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Book of Abstracts

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核技术及应用、医学物理与工程

β-Ga2O3 倾转界面及其电子结构关联性研究

Author: 韦祎[1]

Co-authors: 付恩刚 [1]; 张滋长 [1]; 徐川 [1]

[1] *北京大学*

Corresponding Author: yiwei@stu.pku.edu.cn

摘要: 本研究探讨了单斜晶系 β-Ga2O3（超宽禁带半导体材料）中原子尺度晶体倾斜、缺陷形成与电子结构变化之间的关联，该材料在高功率电子器件和抗辐射应用领域具有重要价值。通过结合高空间分辨率（~2 Å）与能量分辨率（~40 meV）的扫描透射电子显微镜-电子能量损失谱（STEM-EELS）、像差校正 STEM 及密度泛函理论（DFT）计算，我们直接观测到辐照诱导微结构缺陷处的纳米尺度带隙窄化现象（从 4.86 eV 降至 3.98 eV）。实验采用重离子辐照（6 MeV Au3+，1×1015 离子/平方厘米）沿 [010] 晶带轴引入原子级镶嵌式倾斜结构，导致沿块体边界形成排列的镓空位线/团簇。X 射线衍射摇摆曲线展宽与原子分辨率成像共同证实，这些缺陷会引起各向异性晶格畸变。DFT 模拟表明，镓空位（VGa1 和 VGa2）会降低材料带隙，并使载流子迁移率限制因素从本征极性光学声子（POP）散射转变为电离氧原子散射。具体而言，与八面体配位的 VGa2 空位（带隙 4.42 eV，有效质量 0.21 m_0）相比，四面体配位的 VGa1 空位会引发更显著的带隙缩减（3.96 eV）和更低的有效质量（0.10 m_0）。面内倾转界面结构通过破坏长程声子极化，抑制 POP 散射并提升电子迁移率。本工作建立了原子尺度结构形变与电子性能退化之间的直接联系，为极端环境下 β-Ga2O3 的缺陷调控合成与性能优化提供关键理论依据。研究结果凸显了纳米尺度缺陷工程在定制先进功率电子器件与抗辐射半导体材料中的重要作用。

关键词: 宽禁带半导体，扫描透射电子显微镜，电子能量损失谱，马赛克倾转，电子结构，离子辐照

Abstract: Crosslinking structural transformation mechanism at nanoscale to the corresponding anisotropically electronic properties is essential to both the atomic-level controlled synthesis and extreme-conditional applications of the ultrawide bandgap semiconductors. Here, we report the first direct observation of bandgap variation at certain microstructural flaws in monoclinic crystal β-Ga2O3 via scanning transmission electron microscopy-electron energy loss spectrum (STEM-EELS) technology with both high energy and spatial resolution. Atomic-scale tilt of the Mosaic blocks relative to [010] zone axis is demonstrated to cause specific point defects accumulation at block boundaries, resulting in the formation of vacancy lines (or clusters) and then the crystal deformation induced flaws. These as-formed tiny Mosaic tilts observed from both in-plane and out-of-plane geometry are correlated to the corresponding electronic structure obtained by density functional calculations, indicating the carrier mobility limits transferred from intrinsic polar optical phonon scattering to the ionized oxygen atoms
scattering in the defective monoclinic crystal. These findings provide a new insight on these anisotropic

defect formation induced electronic structural variation, paving the way for precise synthesis and development of high-performance ultra-wide bandgap materials.

Keywords: Ultra-wide bandgap semiconductors, STEM-EELS, Mosaic Tilts, Electronic structures, Ion irradiation

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基于 PIC 和 MC 方法的同轴虚阴极反射三极管阵列辐射场数值模拟方法

Authors: 张梦凡[1]; 来定国[2]; 徐启福[2]; 李沫[2]; 邱孟通[2]

[1] *清华大学工程物理系*

[2] *西北核技术研究所*

Corresponding Authors: zhangmf21@mails.tsinghua.edu.cn, laidingguo@nint.ac.cn,xuqifu@nint.ac.cn, limo@nint.ac.cn, qiumengtong@nint.ac.cn

摘要: 同轴虚阴极反射三极管是一种辐射转化效率高、结构简单的新型脉冲硬 X 射线负载，串并联为阵列工作时可产生高能注量、大面积、均匀的硬 X 射线场。数值模拟是同轴虚阴极反射三极管阵列辐射场设计调控的重要技术途径，但由于涉及的物理过程多，电磁、粒子及辐射环境复杂，实现辐射场精确模拟较为困难。本文从同轴虚阴极反射三极管的物理过程出发，对阵列负载工作过程进行分段建模，考虑了阴极等离子体扩散对阻抗负载特性的影响，进行了不同模型之间的电子能量损失校核，改进了辐射场空间叠加方法，建立了基于 PIC 和 MC 方法的同轴虚阴极反射三极管阵列辐射场数值模拟方法。与实验结果相比，能注量模拟结果的平均相对误差为 7.0%，辐射场强度的模拟精度与原有模拟方法相比实现了显著提升。该模拟方法为同轴虚阴极反射三极管阵列型负载的设计提供更准确的依据。

关键词: 同轴虚阴极反射三极管，等离子体，强流电子束，轫致辐射，硬 X 射线源

Abstract: The Cylindrical Virtual Cathode Reflex Triode (CVCRT) is a new type of pulsed hard X-ray load characterized by high radiation conversion efficiency and a simple structure. When connected in series or parallel as an array, it can generate a high-fluence, large-area, uniform hard X-ray field. Numerical simulation is an important technical approach for the design and regulation of the radiation field of CVCRT arrays. However, it is difficult to achieve an accurate simulation of the radiation field due to the multitude of involved physical processes and the complex electromagnetic, particle, and radiation environments. This study presents modifications to the original simulation method: a phased modeling approach for the array load operation was adopted, incorporating the influence of cathode plasma expansion on the impedance load characteristics. Electron energy loss verification was performed across different models, and the spatial superposition method for the radiation field was refined. Consequently, a numerical simulation methodology for the radiation field of CVCRT arrays based on PIC and MC methods was established. Compared with experimental data, the mean relative error for the simulated photon fluence was 7.0%, and the simulation accuracy of the radiation field intensity was significantly enhanced compared to the original simulation method. This improved simulation method provides a more accurate basis for the design of CVCRT array-type loads.

Keywords: cylindrical virtual cathode reflex triode, plasma, high current electron beam, bremsstrahlung, hard X-ray source

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多层平行极板涂硼电离室离子出射率的理论计算

Author: 唐鹏[1]

[1] *清华大学*

Corresponding Author: tp22@mails.tsinghua.edu.cn

摘要: 中文摘要
多层平行极板涂硼电离室是热中子探测的核心器件，离子出射率直接决定探测器探测性能。本研究针对热中子垂直入射场景，聚焦涂层厚度与层数对离子出射率（气隙出射离子与入射中子的比值）的调控机制，通过理论推导与数值仿真开展系统探究。基于热中子与 ^{10}B 的核反应特性，综合中子在硼层的衰减规律及 α 粒子、^{7}Li 重带电粒子的出射行为，建立多层结构离子出射率理论计算模型；利用 Geant4 蒙特卡罗工具构建仿真体系，验证理论模型的准确性。研究表明：随着硼层数增加，离子出射率最优涂硼厚度逐渐减小，且最优条件下的出射率呈显著上升趋势，理论与仿真结果吻合度优异。此外，初步探讨了其他关键因素的影响规律。本研究为多层涂硼电离室的结构参数优化提供了重要理论支撑与数据参考，对提升热中子探测性能具有实际意义。

关键词: 中子探测；硼中子转换；离子出射

Abstract: Multi-layer parallel-plate boron-coated ionization chambers are core devices for thermal neutron detection, and the ion emission rate directly determines the detection performance. Focusing on the regulation mechanism of coating thickness and layer number on ion emission rate (ratio of ions emitted into the gas gap to incident neutrons) under normal incidence of thermal neutrons, this study conducts systematic investigations through theoretical derivation and numerical simulation. Based on the nuclear reaction characteristics between thermal neutrons and ^{10}B, considering the attenuation law of neutrons in boron layers and the emission behavior of heavy charged particles (α particles and ^{7}Li ions), a theoretical calculation model for ion emission rate of multi-layer structure is established. A simulation system is constructed using Geant4 Monte Carlo tool to verify the accuracy of the theoretical model. The results show that with the increase of boron layer number, the optimal boron coating thickness for ion emission rate decreases gradually, and the emission rate under optimal conditions shows a significant upward trend, with excellent consistency between theoretical and simulation results. In addition, the influence laws of other key factors are preliminarily discussed. This study provides important theoretical support and data reference for the optimization of structural parameters of multi-layer boron-coated ionization chambers, and has practical significance for improving the performance of thermal neutron detection.

Keywords: Neutron detection; Boron neutron conversion; Ion emission

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基于 BN 闪烁体的脉冲中子探测技术

Author: 张誉戈[1]

[1] *清华大学*

Corresponding Author: zyg20@mails.tsinghua.edu.cn

摘要: 超快脉冲中子探测技术是诊断核反应时间演化过程特征的重要手段，在核裂变、聚变研究中发挥着不可替代的应用。然而，要对响应时间在纳秒量级的核反应过程准确诊断，就要求探测器必须具有纳秒量级的时间响应、超高的中子伽马分辨能力和合适的灵敏度。目前发展的以同轴法拉第筒和无源介质快中子探测器为代表的电荷收集型强流超快中子探测器，其灵敏度通常在 10^(-25)~10^(-22) C·cm^2 之间，不能满足高灵敏度中子伽马辐射场探测与诊断的需要，因而必须发展能量收集型超快中子探测技术。在能量收集型探测器中，宽禁带半导体探测器最快能实现约 1 纳秒的脉冲响应，然而，其时间响应与探测器面积直接相关，同时它只能对信号进行一级放大，对于强度更低的辐射场，也存在困难和不足。为此，本研究计划探寻新型超快闪烁体，建立新的中子探测技术。通过协同攻关，中山大学生长的以量子限域效应调控缺陷发光而实现高光产额、快响应的氮化硼（BN）闪烁体为解决现有问题提供了可能。经过实验测量，该新型闪烁体对中子灵敏、对伽马不灵敏、时间响应在纳秒量级。将该新型闪烁体应用在薄膜探测器中，可以实现 10^(-16) C·cm^2 的高灵敏度和纳秒量级的时间响应，有效填补了目前探测技术的空白。

关键词: BN 闪烁体；脉冲中子探测；灵敏度；响应时间

Abstract: Ultrafast pulsed neutron detection is a critical diagnostic tool for characterizing the temporal evolution of nuclear reactions, playing an irreplaceable role in nuclear fission and fusion research. However, the accurate diagnosis of nuclear processes with nanosecond-scale reaction times requires detectors to possess nanosecond-level temporal resolution, exceptional neutron-gamma discrimination, and appropriate sensitivity.
Currently, charge-collection type high-intensity ultrafast neutron detectors—represented by coaxial Faraday cups and passive medium fast-neutron detectors—typically exhibit sensitivities in the range of 10^(-25)~10^(-22) C·cm^2. These do not meet the requirements for high-sensitivity detection in neutron-gamma radiation fields, necessitating the development of energy-collection type ultrafast neutron detection technologies. Among these, wide-bandgap semiconductor detectors can achieve a pulse response of approximately 1 ns. However, their temporal response is directly coupled to the detector area. Furthermore, they are limited to primary signal amplification, posing significant challenges when diagnosing lower-intensity radiation fields.
To address these limitations, this research explores novel ultrafast scintillators to establish a new detdctor in neutron detection technology. Through collaborative innovation, Boron Nitride (BN) scintillators—developed by Sun Yat-sen University—leverage quantum confinement effects to regulate defect luminescence, achieving both high light yield and rapid response. Experimental measurements demonstrate that this novel scintillator is sensitive to neutrons while remaining insensitive to gamma radiation, with a temporal response on the nanosecond scale. By integrating this scintillator into thin-film detectors, a sensitivity of 10^(-16) C·cm^2 and nanosecond-level time resolution can be achieved, effectively filling the current technological gap in high-sensitivity ultrafast neutron diagnostics.

Keywords: BN scintillator；Pulsed neutron detection；Sensitivity；Response time

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铀污染土在线 EDXRF 探测系统研制与现场验证

Authors: 王子玚[1]; 张庆贤[1]; 王明[1]; 蒋镖[1]; 谢国昱[1]; 肖鸿飞[1]; 熊茂淋[1]

[1] *成都理工大学*

Corresponding Author: wangziyang201909@163.com

摘要: 铀污染土壤的现场快速筛查与分类，是核设施退役、放射性污染治理以及铀矿冶环境修复中的重要环节。在这些应用场景中，大量土壤通常需要在处置、回填或复用前完成分类。传统实验室分析方法准确性较高，但分析周期较长，难以满足连续化现场筛查和分选的需求。本研究研制了一套用于铀污染土快速筛查的在线能量色散 X 射线荧光（EDXRF）探测系统。该系统可在动态输送条件下开展测量，集成了样品预处理、土层高度控制、高压 X 射线激发、基于硅漂移探测器的荧光测量、X 射线透射成像、密度测量以及软件控制分选等功能，形成了一套适用于现场应用的集成化平台。

系统主要利用铀元素的 L 系特征 X 射线进行识别和定量。现场测量时，X 射线管管压为 130 kV，管流为 300 μA。虽然铀的识别主要依据 L 系特征线，但采用 130 kV 管压可以提高初级 X 射线对动态输送土层的穿透能力和有效激发通量。测试过程中，传送速度设置为 20–30 cm/min；每个测量周期内，EDXRF 能谱累计时间为 1 min，以提高计数统计性，并获得通过探测区域土壤的代表性铀信号。系统还可进行土层高度控制和密度测量，从而计算物料吞吐量。前期选取了三个现场制备样品作为初始标定样，其名义活度分别为 1.00、3.14 和 9.00 Bq/g。后续 ICP-MS 分析表明，这三个样品的实际活度与名义值存在差异，因此在与实验室结果对比前，对现场装置测量结果进行了标定误差修正。

将修正后的现场装置测量结果与 ICP-MS 结果进行对比，共获得 16 组配对数据，决定系数为 R^2 = 0.928，平均绝对相对偏差为 32.1%。系统探测下限估计为 0.7 Bq/g，低于 1.0 Bq/g 的筛查阈值。对于活度低于 0.7 Bq/g 或高于 1.0 Bq/g 的样品，装置未出现误判，说明其在 0.7–1.0 Bq/g 临界区间之外具有较稳定的判别能力。在测试工况下，系统计算吞吐量大于 1 t/h。此外，对相同土壤样品进行压样处理后，采用实验室大荧光设备进行 XRF 测量。压样 XRF 结果与现场装置测量结果之间具有较好的线性关系，决定系数为 R^2 = 0.9454，表明在线 EDXRF 系统获得的铀响应趋势与实验室 XRF 测量结果基本一致。上述结果表明，该在线 EDXRF 系统可用于铀污染土现场快速筛查。后续工作将进一步围绕标准标定样品、基体效应校正，以及土壤水分、粒径和土层厚度变化补偿等方面进行优化。

关键词: 铀污染土；在线 EDXRF；现场探测；快速分选；核设施退役

Abstract: Rapid on-site screening and classification of uranium-contaminated soil are important in nuclear facility decommissioning, radioactive contamination remediation, and uranium mining-related environmental restoration, where large volumes of soil may need to be classified before disposal, backfilling, or reuse. Conventional laboratory analysis provides accurate uranium concentrations but is time-consuming and difficult to apply to continuous field sorting. In this study, an in-line energy-dispersive X-ray fluorescence (EDXRF) detection system was developed for rapid uranium-contaminated soil screening under dynamic conveying conditions. The system integrates sample pretreatment, soil-layer height control, high-voltage X-ray excitation, silicon drift detector-based fluorescence measurement, transmission imaging, density measurement, and software-controlled sorting in a field-deployable platform.

Uranium was identified and quantified mainly using its L-series characteristic X-ray lines. Field measurements were performed at a tube voltage of 130 kV and a tube current of 300 μA. The tube voltage of 130 kV was selected to provide sufficient primary-beam penetration and excitation flux for moving soil layers. The conveying speed was set to 20–30 cm/min. For each measurement interval, the EDXRF spectrum was accumulated for 1 min to improve counting statistics and obtain a representative uranium signal from the soil passing through the detection zone. The system also allowed soil-layer height control and density measurement, enabling the material throughput to be calculated. Three field-prepared samples with nominal activities of 1.00, 3.14, and 9.00 Bq/g were initially used for calibration. Subsequent ICP-MS analysis showed that their actual activities differed from the nominal values; therefore, calibration-error correction was applied before comparison with laboratory results.

The calibration-corrected field-device results were compared with ICP-MS measurements. A total of 16 paired results were obtained after correction, giving a coefficient of determination of $R^2 = 0.928$ and a mean absolute relative deviation of 32.1%. The detection limit of the developed system was estimated to be 0.7 Bq/g, which is below the 1.0 Bq/g screening threshold. The developed system showed no misclassification for samples below 0.7 Bq/g or above 1.0 Bq/g, supporting reliable discrimination outside the borderline range of 0.7–1.0 Bq/g. The system achieved a calculated throughput of more than 1 t/h under the tested operating conditions. In addition, pressed-pellet XRF measurements of the corresponding soil samples were conducted using a laboratory XRF spectrometer. The pressed-pellet XRF results showed a strong linear relationship with the field-device results, with $R^2 = 0.9454$, indicating that the in-line EDXRF system captured a uranium response trend consistent with laboratory XRF measurements. These preliminary results demonstrate the feasibility of the developed in-line EDXRF system for rapid field screening of uranium-contaminated soil. Further improvement will focus on certified calibration samples, matrix-effect correction, and compensation for soil moisture, particle size, and layer-thickness variations.

Keywords: uranium-contaminated soil; in-line EDXRF; field detection; rapid sorting; nuclear decommissioning

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页岩气田环境辐射监测与风险评估

Authors: 丁晨麓[1]; 杨强[1]; 娟翟[1]

[1] *成都理工大学核技术与自动化工程学院*

Corresponding Author: dingchenlu@stu.cdut.edu.cn

摘要: 天然放射性物质（NORM）广泛存在于页岩气钻井作业产生的废弃物中，会对生态环境构成潜在风险，因此受到公众与学者们的日益关注。本研究针对中国西南地区处在不同作业阶段的页岩气田，采集其周围环境土壤土壤、开采废水和污水处理厂处理前后水样。通过结合空气 γ 吸收剂量率、土壤氡浓度、放射性核素活度浓度及常规危害指数，综合评估区域环境放射性水平与从业人员潜在职业暴露风险。研究结果表明，该区域空气 γ 吸收剂量率与土壤放射性水平和国内外其他油气田监测结果基本相当，且放射性水平与铀系核素含量高度相关。土壤中铀-238 与镭-226 呈显著线性相关，说明两种核素在土壤体系中接近放射性平衡；铅-210 与镭-226 比值持续大于 1，且随开采平台运营时长增加而升高，反映出氡子体存在累积效应。现场实测剂量率与理

论计算剂量率存在明显偏差，说明辐射剂量评估工作应优先采用实地直接监测手段。从业人员剂量评估结果显示，页岩气田工作人员年有效剂量低于 1 mSv/a。此外，未经处理的原水中检测出镭-226、镭-228 等核素浓度超标，而现有水处理工艺可有效削减上述放射性核素含量。本研究成果可为页岩气田放射性风险评估提供本底数据支撑，同时凸显了开展长期常态化监测、强化放射性废水管控的必要性。

关键词: 天然放射性物质（NORM）；页岩气开采；环境辐射暴露；放射性核素迁移；放射性废水处理

Abstract: Naturally occurring radioactive materials (NORM) are present in waste generated during shale gas drilling activities and pose potential risks to the environment, drawing increasing public and scientific attention. In this study, soil, wastewater and effluent samples were collected across multiple operational stages of shale gas development in Southwest China. A combination of in-situ gamma absorbed dose rate in air, soil radon concentration, radionuclide activity concentrations, and conventional hazard indices was used to evaluate environmental radioactivity and potential occupational exposure. The results showed that both the gamma absorbed dose rates and soil radioactivity were comparable to those observed in other oil and gas fields, that were strongly correlated with uranium-series nuclides. A strong linear relationship between 238U and 226Ra, indicating the two radionuclides were in near radioactive equilibrium within the soil. The 210Pb/226Ra ratio was consistently greater than 1 and increased with platform operation time, suggesting an accumulation of radon progeny. Discrepancies between measured and calculated dose rates highlighted the need to prioritize direct measurements in dose assessments. Worker dose assessments revealed annual effective doses below 1 $mSvy^{-1}$. Furthermore, elevated concentrations of 226Ra, 228Ra, and 40K were detected in untreated-water, which could be effectively reduced by existing treatment technologies. These findings provide a baseline for radiological risk evaluation in shale gas fields and highlight the necessity for continuous monitoring and wastewater management.

Keywords: Naturally Occurring Radioactive Materials (NORM); Shale Gas Extraction; Environmental Radiation Exposure; Radionuclide Migration; Radioactive Wastewater Treatment

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High-Efficiency Attosecond-Resolution Terahertz Streaking of Relativistic Electron Beams

Authors: 吕鹏[1]; 李任恺[1]

Co-authors: 王志远 [1]; 杨一宁 [1]; 刘卓轩 [1]; 宋柏廷 [1]

[1] *清华大学*

Corresponding Authors: sbt24@mails.tsinghua.edu.cn, lp22@mails.tsinghua.edu.cn, zhiyuan-23@mails.tsinghua.edu.cn, lirk@tsinghua.edu.cn, liuzhuox21@mails.tsinghua.edu.cn, yang-yn21@mails.tsinghua.edu.cn

摘要: 太赫兹偏转是诊断相对论电子束纵向结构的有力工具，这是因为由光学整流方法产生的太赫兹脉冲与加速器的驱动激光是内禀同源的，而且太赫兹波的波长与电子束自身相空间的尺寸高度匹配。然而，受限于可用的太赫兹脉冲能量以及太赫兹-电子相互作用的效率，目前的太赫兹偏转方法的测量精度仅能达到飞秒量级。在本次报告中，我们将介绍一种新型的高效率太赫兹偏转方案以及在清华大学 FORTRESS（超高时空分辨相对论电子源与散射装置）束线上开展的相关实验。利用能量仅几微焦的单周期太赫兹脉冲，束团长度和到达时间的测量精度分别达到了 100 阿秒和 10 阿秒量级。这些结果展示了太赫兹偏转测量可作为一种实用的阿秒级诊断工具及其在下一代超快电子束装置中的应用潜力。

关键词: 阿秒时间分辨；相对论电子束；太赫兹偏转

Abstract: Terahertz (THz) streaking is a powerful technique for ultrafast longitudinal diagnosis of relativistic electron beams, as THz pulses generated via optical rectification are intrinsically synchronized to the driving laser and exhibit wavelengths well matched to the characteristic phase-space dimensions of relativistic electron bunches. However, the temporal resolution of THz streaking is often constrained

to the femtosecond-level by the available THz pulse energy and the efficiency of the THz-electron interaction. In this talk, we introduce a high-efficiency THz streaking scheme and the corresponding experiments conducted at the FORTRESS (Facility Of Relativistic Time-Resolved Electron Source and Scattering) beamline of Tsinghua University. Using single-cycle THz pulses with only a few microjoules of energy, the measurement precisions of 100 as level for bunch length and 10 as level for arrival time have been achieved. These results demonstrate the potential of THz streaking as a practical attosecond-level diagnosis tool for the next-generation ultrafast electron beam facilities.

Keywords: Attosecond timing resolution; Relativistic electron beams; Terahertz streaking

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基于多层阵列闪烁体的康普顿相机搭建

Authors: 田成帅[1]; 曾国强[1]; 杨新宇[1]

[1] *成都理工大学*

Corresponding Author: 854818943@qq.com

摘要: 针对传统双层康普顿相机成像视场受限、散射光子利用率低以及半导体探测器敏感体积不足等问题，本文提出了一种由前、后、左、右四个闪烁体阵列构成的成像结构，探测灵敏体积为 55cm3，实现对入射伽马射线 360° 覆盖并有效提高了探测灵敏体积。最小成像单元采用独立 CsI(Tl) 晶体与单个硅光电倍增管（SiPM）直接耦合的方式，提高了光收集效率并有效改善了能量分辨性能。在读出电子学设计中，为降低系统通道数与整体成本，采用一种串联读出方案，将多个探测单元的输出信号合并为两路进行读出，并结合自主研制的多通道数字化采集系统，构建了一套结构紧凑、通道精简且稳定可靠的康普顿成像电子学系统。
测试结果表明，该系统对 137Cs 实现了 6.2%（FWHM）的总能量分辨率和 12° 的角度分辨率，能够对来自不同方位的放射源进行有效识别与定位。同时，本研究前瞻性地探索了人工智能技术在成像重建中的应用，提出了一种基于多头注意力机制的机器学习直接成像方法，实现了由原始探测数据到成像结果的端到端重建，为提升复杂辐射场条件下的成像效率提供了新的思路。
研究结果表明，所提出的多层阵列闪烁体的康普顿成像系统在实现 360° 全方位成像视场的同时，显著提高了探测灵敏体积。并且在成像灵敏度、响应速度和工程可实现性方面均表现出良好的综合性能，在辐射环境监测、核安全与核应急、放射源快速定位以及核医学成像等领域具有良好的应用前景。

关键词: 康普顿成像；全向视野；闪烁体探测器；串行读出电路；端到端重建

Abstract: Traditional dual-layer Compton cameras face limitations such as a restricted field of view (FOV), low scattered photon utilization, and small sensitive volumes. To overcome these issues, we propose a novel imaging structure consisting of four orthogonally arranged scintillator arrays (front, back, left, and right). This configuration provides a total sensitive volume of 55 cm^3, achieving a 360° omnidirectional coverage for incident gamma rays and effectively expanding the sensitive volume of the detection system. The fundamental imaging unit utilizes an individual CsI(Tl) crystal directly coupled to a single silicon photomultiplier (SiPM), an arrangement that enhances light collection efficiency and significantly improves the energy resolution. In the readout electronics design, to minimize the number of electronic channels and reduce the overall system cost, a multiplexed series readout scheme is implemented, merging the output signals from multiple detection units into two readout channels. Integrated with a custom-developed multi-channel digital data acquisition system, it forms a compact, streamlined, and highly reliable Compton imaging electronics system.
Experimental results demonstrate that the system achieves an overall energy resolution of 6.2% (FWHM) and an angular resolution of 12° for a 137Cs source, proving its capability to effectively identify and localize radioactive sources from various azimuthal directions. Furthermore, this study prospectively explores the application of artificial intelligence in image reconstruction. A machine learning-based direct imaging method utilizing a multi-head attention mechanism is proposed, achieving end-to-end reconstruction from raw detection data to the final imaging results. This approach offers a novel perspective for enhancing imaging efficiency in complex radiation fields.
In conclusion, the proposed multi-layer scintillator array Compton imaging system achieves a 360° omnidirectional field of view while significantly expanding the sensitive volume. The system exhibits excellent comprehensive performance in terms of imaging sensitivity, response speed, and engineering

feasibility, demonstrating highly promising application potential in fields such as radiation environmental monitoring, nuclear safety and emergency response, rapid localization of radioactive sources, and nuclear medicine imaging.

Keywords: Compton imaging; Omnidirectional sensitivity; Scintillator detector; Serial readout circuit; End-to-end reconstruction

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面向核医学单光子成像的钙钛矿半导体 γ 射线探测器

Author: 何旭昌[1]

[1] *苏州大学*

Corresponding Author: 20244020019@stu.suda.edu.cn

摘要: 高能量分辨率、高空间分辨率和高灵敏度的 γ 射线探测器是提升核医学单光子成像性能的关键。传统 NaI(Tl) 闪烁体探测器在能量分辨率方面存在局限，而 CdZnTe 等半导体探测器虽具有较优性能，但其成本和材料制备仍限制了进一步推广。钙钛矿 CsPbBr3 半导体兼具高阻止能力、室温工作能力和潜在低成本优势，为发展新型核医学 γ 相机提供了新的材料基础。本工作围绕像素化 CsPbBr3 半导体探测器，构建了面向 99mTc 单光子 γ 成像的原型探测系统，并通过表面电荷收集优化、像素化电极设计、多通道读出和深度校正，实现了优异的能谱和成像性能。实验结果表明，该探测器在 99mTc 141 keV γ 射线下实现 2.5% 的整体能量分辨率，在 137Cs 662 keV 下实现 1.0% 的整体能量分辨率；点源和线源成像灵敏度达到 0.13%–0.21% cps/Bq，Derenzo phantom 假体成像空间分辨率约为 3.2–3.8 mm，证明了 CsPbBr3 钙钛矿探测器用于核医学单光子 γ 成像的可行性。

进一步地，针对像素化钙钛矿探测器中电荷输运、权重势分布、电荷共享和深度依赖脉冲形状等复杂物理过程，本工作建立了动态电荷感应与信号生成数值模拟框架。该框架集成 Geant4 能量沉积模拟、有限元电场与权重势计算、电子/空穴输运追踪、Shockley–Ramo 感应电荷计算以及 CSA 脉冲和 CR-RC4 成形信号模拟，能够从物理过程出发重建探测器的实时波形和能谱响应。模拟结果与实验脉冲和能谱具有良好一致性，并可用于分析电荷共享事件、作用深度效应和位置依赖的电荷收集损失。基于三维电荷损失校正，模拟能谱的能量分辨率由约 5.5% 改善至 1.5%，显示了该框架在探测器结构优化、信号校正和脉冲处理算法开发中的应用潜力。综上，本研究从器件性能验证和物理机理建模两个层面，展示了钙钛矿半导体 γ 射线探测器在下一代核医学单光子成像系统中的发展前景。

关键词: 钙钛矿半导体；CsPbBr3；γ 射线探测器；核医学成像；单光子成像；电荷感应模拟

Abstract: High energy resolution, spatial resolution, and detection sensitivity are essential for improving single-photon nuclear medicine imaging. Conventional NaI(Tl)-based scintillation cameras are widely used but limited by their moderate energy resolution, while CdZnTe semiconductor detectors provide improved performance but still face challenges related to cost and material growth. $CsPbBr_3$ perovskite semiconductors, featuring strong γ-ray stopping power, room-temperature operation, and potential cost-effectiveness, offer a promising route toward next-generation γ-ray cameras. In this work, we developed a pixelated $CsPbBr_3$ semiconductor detector system for 99mTc single-photon γ-ray imaging. Through surface charge-collection optimization, pixelated electrode design, multichannel readout, and depth correction, the detector achieved excellent spectroscopic and imaging performance. The overall energy resolution reached 2.5% at 99mTc 141 keV and 1.0% at 137Cs 662 keV. Single-photon imaging using point and line 99mTc sources demonstrated sensitivities of 0.13%–0.21% cps/Bq, and Derenzo phantom imaging resolved column sources with a spatial resolution of approximately 3.2–3.8 mm. These results demonstrate the feasibility of $CsPbBr_3$ perovskite detectors for nuclear medicine γ-ray imaging. To further understand and optimize the detector response, we established a numerical framework for dynamic charge induction and signal generation in pixelated perovskite semiconductor detectors. The framework integrates Geant4-based energy deposition, finite-element electric-field and weighting-potential calculations, electron and hole transport tracking, Shockley–Ramo induced-charge modeling, and charge-sensitive amplifier and CR-RC^4 shaping simulations. It enables physics-based reconstruction of real-time waveforms and energy spectra, and provides insight into charge sharing, depth-dependent pulse formation, and position-dependent charge collection loss. The simulated waveforms and spectra show good

agreement with experimental observations. Moreover, by applying three-dimensional charge-loss correction, the simulated energy resolution was improved from approximately 5.5% to 1.5%, indicating the potential of this framework for detector design optimization, signal correction, and pulse-processing algorithm development. Overall, these studies establish a coherent pathway from experimental device demonstration to physics-based signal modeling, supporting the development of high-performance, low-cost perovskite semiconductor γ-ray cameras for future nuclear medicine applications.

Keywords: perovskite semiconductor; $CsPbBr_3$; γ-ray detector; nuclear medicine imaging; single-photon imaging; charge-induction simulation

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99Tc 在北山花岗岩裂隙中的迁移行为研究

Author: 廉冰[1]

[1] *中国辐射防护研究院*

Corresponding Author: lianbing00@sina.com

摘要: 围岩多尺度裂隙及其核素迁移机理的揭示和模拟是核废料地质处置安全保障前提，锝-99 作为长寿命核素，迁移能力强，是处置库安全评价的关键核素。通过锝-99 在花岗岩裂隙系统的迁移扩散实验，阐明裂隙中裂隙填充物及胶体的形成规律、赋存特征及其与核素的相互作用机制，定量评估其对低溶解度、强吸附性核素迁移的影响，为高放废物地质处置库安全评价和长期安全性预测提供理论与工程依据。

关键词: 1. 围岩多尺度裂隙 2. 核素迁移机理 3. 锝-99

Abstract: The revelation and simulation of multi-scale fractures in surrounding rock and radionuclide migration mechanisms are the prerequisite for the safety guarantee of nuclear waste geological disposal. As a long-lived radionuclide, Technetium-99 features strong migration capacity and serves as the critical nuclide for repository safety assessment. Through migration and diffusion experiments of Technetium-99 in granite fracture systems, this study clarifies the formation rule and occurrence characteristics of fracture fillings and colloids in fractures, as well as their interaction mechanisms with radionuclides. It quantitatively evaluates their impacts on the migration of radionuclides with low solubility and strong adsorption, providing theoretical and engineering references for the safety assessment and long-term safety prediction of high-level radioactive waste geological repositories

Keywords: 1.multi-scale fractures of surrounding rock 2.radionuclide migration mechanism 3.Technetium-99 (Tc-99)

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基于 Modelica 语言的同步辐射储存环相对论带电粒子动力学仿真

Author: 张衡[1]

Co-authors: 许时宁; 严佳杰 [1]; 张田 [1]

[1] *哈尔滨工程大学*

Corresponding Authors: tian.zhang@hrbeu.edu.cn, xushining06@outlook.com, beeofcat@outlook.com

摘要: 研究面向同步辐射储存环束流光学设计与辐射物理分析需求，构建了一种基于 Modelica 语言的相对论单粒子动力学仿真平台。该平台旨在利用 Modelica 语言的简洁性、面向对象建模能

力及良好的可扩展性，为储存环磁结构建模、粒子追踪和辐射效应分析提供统一工具。
在物理模型上，平台以 Landau-Lifshitz 辐射反作用方程为核心，在洛伦兹力基础上引入经典辐射阻尼修正项，并通过相对论归一化坐标系减小多数量级物理量并存带来的数值误差，提高计算稳定性与求解精度。在软件架构上，利用 Modelica 的面向对象建模机制和连接器特性，通过星型信息总线实现粒子状态的全局广播与多场自动叠加，借助类继承支持不同类型磁铁元件的即插即用。平台实现了四极磁铁、六极磁铁、射频腔等多类场元件，并内置基于动能定理和总能量平衡的双重能量守恒检验机制。
结果表明，该平台通过了纯磁场回旋、静电偏转、四极和六极聚焦、射频加速及波荡器轨迹等单元测试，并在储存环的多圈追踪仿真中正确再现了辐射阻尼与 RF 补偿之间的动态平衡关系，能量守恒误差保持在合理范围内。
研究表明，该平台能够较完整地实现同步辐射储存环单粒子动力学仿真功能，可为同步辐射光源的晶格设计、算法验证与原型研究提供高效工具。

关键词: 同步辐射；粒子追踪；Modelica；储存环

Abstract: Aiming at the requirements of beam optics design and radiation physics analysis for synchrotron radiation storage rings, this study constructs a relativistic single-particle dynamics simulation platform based on the Modelica language. Leveraging the conciseness, object-oriented modeling capabilities, and excellent extensibility of Modelica, the platform aims to provide a unified tool for storage ring magnetic lattice modeling, particle tracking, and radiation effect analysis.
Regarding the physical model, the platform centers on the Landau-Lifshitz radiation reaction equation. It introduces a classical radiation damping correction term to the Lorentz force and employs a relativistic normalized coordinate system to mitigate numerical errors caused by the coexistence of physical quantities across multiple orders of magnitude, thereby improving computational stability and solving accuracy. In terms of software architecture, the platform utilizes Modelica's object-oriented modeling mechanism and connector features. A star-topology information bus is implemented for the global broadcasting of particle states and the automatic superposition of multiple fields. Additionally, class inheritance is utilized to support the plug-and-play functionality of various magnet components. The platform implements various field components, including quadrupole magnets, sextupole magnets, and radio frequency (RF) cavities, and features a built-in dual energy conservation verification mechanism based on the work-energy theorem and total energy balance.
Results demonstrate that the platform has successfully passed unit tests for pure magnetic cyclotron motion, electrostatic deflection, quadrupole and sextupole focusing, RF acceleration, and undulator trajectories. Furthermore, in multi-turn tracking simulations of the storage ring, it accurately reproduces the dynamic equilibrium between radiation damping and RF compensation, maintaining the energy conservation error within a reasonable range.
Overall, this study indicates that the platform can comprehensively perform single-particle dynamics simulations for synchrotron radiation storage rings, providing an efficient tool for the lattice design, algorithm verification, and prototype research of synchrotron light sources.

Keywords: Synchrotron Radiation; Particle Tracking; Modelica; Storage Ring

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核特色诊疗平台项目全流程设计进度管理优化研究

Author: 李思奇[1]

[1] *哈尔滨工程大学*

Corresponding Author: 1481626832@qq.com

摘要: 随着核技术应用产业的高速发展，医疗领域对核特色诊疗平台建设的需求日益增长。由于常规医院项目设计管理模式难以适配核技术医学应用工程的特殊技术要求与管控逻辑，亟需加大核医疗项目精细化设计管理体系的研究投入。随着核技术在医学领域的应用深度与广度不断拓展，核特色医疗工程建设有望成为核领域新质生产力培育的重要载体，成为我国医疗装备与核技术融合发展进程中不可或缺的核心板块。为了保障核技术医学应用项目按期高质量开工建设，全流程、精细化的设计进度管理在项目工程准备阶段的应用显得尤为重要。现有的核医疗项目设计进度管理大多局限于单一专业领域，即依靠传统线性管理模式开展固定流程的设计任务管控。但上述方法协同性不足，易出现并行设计进度不匹配、工期滞后等问题，对核医疗项目设计中的迭

代增量特性与行政审批不确定性适配性较差。事实上，核技术医学应用项目的设计进度管理是一个多模块、多节点、强耦合的动态管控问题，项目实施过程中无法完全预判行政审批流程波动与设计方案迭代带来的进度风险，传统管理方法存在显著的应用局限。基于上述限制，本文创新性地提出了一种基于混合型开发方法与 WBS 工作分解结构的核技术医学应用项目设计进度管理优化体系。它通过对设计任务进行层级化拆解与模块化管控，实现设计关键节点的精准识别与进度偏差的动态调整，在保障设计成果满足核医疗技术规范与使用要求的同时，可有效提高设计进度管控的稳定性与预见性，并具备全流程闭环优化的管理能力。通过北京核工业医院核技术医学应用项目工程准备阶段全流程设计管理实践，开展上述管理体系的可行性及应用成效验证。结果表明，基于混合型开发方法的 WBS 进度管理体系可以显著提升核医疗项目设计进度管控效率。与传统的线性设计管理模式相比，项目整体设计工期较同类型项目缩短 3 个月，顺利完成全套施工图设计交付与全部行政审批手续办理。通过三大设计模块的分级管控与里程碑节点的动态跟踪，有效化解了设计方案高频迭代、行政审批不确定性带来的进度风险，从而大幅提升了核医疗项目前期设计管理的精细化水平，为核技术医学应用类工程项目的设计进度管控优化与高质量工程建设提供了实践参考与技术支撑。

关键词: 核医疗核特色

Abstract: With the rapid development of the nuclear technology application industry, the demand for the construction of nuclear-featured diagnosis and treatment platforms in the medical field is growing rapidly. Since the conventional design and management mode of hospital projects is difficult to adapt to the special technical requirements and control logic of nuclear technology medical application engineering, it is urgent to increase the research investment in the refined design management system of nuclear medical projects. As the application depth and breadth of nuclear technology in the medical field continue to expand, the construction of nuclear-featured medical engineering is expected to become an important carrier for cultivating new quality productive forces in the nuclear field, and an indispensable core sector in the integrated development of China’s medical equipment and nuclear technology. To ensure the on-time and high-quality commencement of nuclear technology medical application projects, the application of full-process and refined design schedule management in the project preparation stage is particularly critical.

The existing design schedule management of nuclear medical projects is mostly limited to a single professional field, that is, relying on the traditional linear management mode to control design tasks with fixed processes. However, such methods lack synergy, prone to problems such as mismatched parallel design schedules and construction period delays, and are poorly adaptable to the iterative incremental characteristics and administrative approval uncertainties in nuclear medical project design. In fact, the design schedule management of nuclear technology medical application projects is a multi-module, multi-node and strongly coupled dynamic control problem. The schedule risks caused by fluctuations in administrative approval processes and design scheme iterations cannot be fully predicted during project implementation, and traditional management methods have significant application limitations.

Based on the above constraints, this paper innovatively proposes an optimized design schedule management system for nuclear technology medical application projects based on the hybrid development method and Work Breakdown Structure (WBS). Through hierarchical decomposition and modular control of design tasks, it realizes accurate identification of key design nodes and dynamic adjustment of schedule deviations. While ensuring that design results meet nuclear medical technical specifications and application requirements, it can effectively improve the stability and predictability of design schedule control, and has the management capability of full-process closed-loop optimization.

The feasibility and application effectiveness of the above management system are verified through the full-process design management practice in the engineering preparation stage of the nuclear technology medical application project of Beijing Nuclear Industry Hospital. The results show that the WBS schedule management system based on the hybrid development method can significantly improve the efficiency of design schedule control for nuclear medical projects. Compared with the traditional linear design management mode, the overall design period of the project is shortened by 3 months compared with similar projects, and the complete construction drawing design delivery and all administrative approval procedures are successfully completed. Through hierarchical control of three major design modules and dynamic tracking of milestone nodes, the schedule risks caused by high-frequency iteration of design schemes and uncertainties in administrative approval are effectively resolved, thereby greatly improving the refinement level of preliminary design management of nuclear medical projects. It provides practical reference and technical support for the optimization of design schedule control and high-quality engineering construction of nuclear technology medical application engineering projects.

Keywords: nuclear medicine nuclear-featured

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基于光谱融合技术的超细粒级矿石分选技术研究与应用

Author: 周合军[1]

[1] *清华大学工程物理系*

Corresponding Author: zhouhejun@nuctech.com

摘要: 全球矿产的品位越来越低，传统选矿方式带来环境污染和成本高升的困境。智能选矿技术利用物理的方法，对矿石进行预富集，这种方法逐渐被矿山企业认同。该报告围绕半生复杂的难选矿石如何利用 XRT 和双面高清视觉成像技术，针对最小 5mm 的超细粒级矿石分选难题进行研究，实现高准确度识别和高精度分离。

关键词: 矿石，品位，分选，X 射线透射技术，融合

Abstract: The grade of global mineral resources is gradually declining, and traditional mineral processing methods are trapped in the dilemma of severe environmental pollution and rising costs. Intelligent mineral processing technology adopts physical means to pre-concentrate ores, and this approach has been increasingly recognized by mining enterprises. Centering on how to process complex refractory ores, this report conducts research on the separation challenge of ultra-fine particle ores as small as 5 mm by applying XRT and dual-sided high-definition visual imaging technology, so as to realize high-accuracy identification and high-precision separation.

Keywords: Mine, Grade,Sorting,XRT, Fuse

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靶向 GD2 的核素多肽探针的设计优化及应用研究

Authors: 吴梓晗[1]; 王慧[2]; 蔡嘉贤[3]; 陈雨桐[1]; 韩智豪[1]

[1] *中国药科大学*

[2] *中国科学院近代物理研究所*

[3] *华南理工大学*

Corresponding Authors: hanzhihao887@126.com, wzh695843@163.com, 3223081928@stu.cpu.edu.cn, 202410192820@mail.scut.edu.
wangh08@impcas.ac.cn

摘要: 目的：肿瘤作为人类重大健康问题，具有极高发生率和死亡率。精准检测肿瘤进展并通过手术根治性切除病灶，能够极大提高患者的生存率和改善预后。双唾液酸神经节苷脂 GD2 在神经母细胞瘤等多种肿瘤细胞表面表达异常上调，是一种极具潜力的生物标志物。本研究旨在开发 GD2 靶向的核素多肽探针，以实现泛癌种精准诊断。
方法：以那昔妥单抗和伤寒毒素 B 亚基为配体，结合计算机辅助药物设计技术，设计并筛选 GD2 靶向肽。通过细胞实验验证候选肽与 GD2 的结合特异性，并在动物模型中评估其靶向性能。进一步修饰后，将高亲和力优选肽与放射性核素耦合，构建适用于 SPECT 成像的核素多肽探针。
结果：成功设计并筛选出具有高特异性和高亲和力的 GD2 靶向肽，细胞实验证实其能够有效识别并结合表达 GD2 的肿瘤细胞。动物模型研究表明，构建的核素探针在肿瘤部位具有良好的靶向富集和显像效果，能够清晰显示肿瘤病灶。此外，同配体荧光探针能够辅助肿瘤切除手术导航。
结论：本研究成功构建了靶向 GD2 的 SPECT 核素探针，该探针具有泛癌种诊断潜力，可应用于神经母细胞瘤、乳腺癌等多种肿瘤的早期诊断和术中导航，为肿瘤的精准诊疗提供了新的分子影像学工具。

关键词: SPECT，放射性诊断，GD2，多肽探针，肿瘤

Abstract: Objective: Cancer represents a major global health challenge characterized by high incidence and mortality rates. Accurate detection of tumor progression and radical surgical resection of lesions

can significantly improve patient survival and prognosis. Disialoganglioside (GD2) is aberrantly overexpressed on the surface of neuroblastoma and various other tumor cells, representing a highly promising biomarker. This study aims to develop GD2-targeted radiolabeled peptide probes for pan-cancer precise diagnosis.
Methods: Using naxitamab and cholera toxin B subunit as ligands, GD2-targeted peptides were designed and screened through in silico molecular docking and virtual screening. The binding specificity of candidate peptides to GD2 was validated through cellular experiments, and their targeting performance was evaluated in animal models. Subsequently, high-affinity optimized peptides were conjugated with radioactive nuclides to construct radiolabeled peptide probes suitable for SPECT imaging.
Results: GD2-targeted peptides with high specificity and affinity were successfully designed and screened. Cellular experiments confirmed their effective recognition and binding to GD2-expressing tumor cells. Animal model studies demonstrated that the constructed radiotracer exhibited excellent tumor-targeting accumulation and imaging performance, enabling clear visualization of tumor lesions. Additionally, the corresponding fluorescent probe with the same ligand provided effective navigation assistance for tumor resection surgery.
Conclusion: This study successfully developed a GD2-targeted SPECT radiotracer with pan-cancer diagnostic potential. The probe can be applied to precise diagnosis and intraoperative navigation for various tumors including neuroblastoma and breast cancer, providing a novel molecular imaging tool for precision oncology.

Keywords: SPECT, Radionuclide imaging, Disialoganglioside, Peptide probe, Tumor

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小鼠体内 ^{177}Lu-FAP 临床前吸收剂量评估：基于 SPECT-CT 图像的 GATE 蒙特卡洛全粒子输运与 MIRD 近似模型物理差异

Authors: 庞瑞磊[1]; 王鹤霖[1]; 顾月清[1]; 韩智豪[1]

[1] *中国药科大学*

Corresponding Author: 2093497737@qq.com

摘要: 背景：成纤维细胞激活蛋白（FAP）是放射性药物治疗（RPT）的重要靶点，在多种实体瘤中高表达。随着 ^{177}Lu 标记 FAP 药物的快速发展，准确评估临床前模型中的吸收剂量对疗效、安全及临床转化至关重要。目前，基于 MIRD 的器官水平剂量估算与基于蒙特卡罗（MC）的体素水平剂量计算在物理模型上存在本质差异，其一致性尚需系统比较。本研究旨在比较 GATE 蒙特卡罗模拟与 MIRD 方法在荷瘤小鼠中的剂量计算结果，重点探讨 MC 在粒子输运、次级电子沉积、组织非均匀性及边界效应等物理过程中的优势。方法：基于 U87 荷瘤 BALB/c 裸鼠模型，尾静脉注射三种 177Lu-FAP 药物。于注射后进行小动物 SPECT/CT 显像，手动勾画主要器官 VOI，获取各时间点器官放射性活度。采用 OLINDA/EXM、Odam 及 PKAD 算法计算 TIAC 并归一化，结合 S 值获得 MIRD 体系器官吸收剂量。同时，将 SPECT/CT 图像导入 3D Slicer 进行格式转换，利用 Python 进行空间坐标变换，作为 GATE 模拟输入。基于 GATE v9.0（Geant4）进行体素级 MC 模拟，以 CT 图像（0.25 mm 体素）构建体素化体模，SPECT 图像定义体素化源。物理过程包含光电效应、康普顿散射、韧致辐射，无能量削减及方差减少。放射源为 177Lu，DoseActor 输出能量沉积与剂量分布。模拟时间为实际采集的 1/10–1/100，统计不确定性 <5%，每只小鼠耗时 3.5 小时。基于 VOI 计算各器官剂量率，积分拟合得总吸收剂量，并分析能量剖面及剂量等高线。结果：三种放射性药物在肿瘤中均显示出较高的放射性摄取与滞留。在器官吸收剂量方面，基于 MIRD 方法（OLINDA/EXM、Odam、PKAD）计算得到的肾脏和肿瘤吸收剂量分别为 19.78—45.94Gy/GBq 和 670.27—744.43 Gy/GBq，不同计算工具之间结果较为接近/存在一定差异。GATE 蒙特卡罗模拟获得的体素级剂量分布显示，肿瘤内剂量呈现明显异质性，平均吸收剂量为 713.51—840.10Gy/GBq，与 MIRD 方法相比差异为 12%—25%。肾脏剂量在体素水平同样表现出局部热点，最高与平均剂量比值可达 2.5。结论：MIRD 方法提供器官平均水平剂量，适用于快速评估，但无法反映内部剂量异质性。GATE-MC 通过精确模拟粒子输运、次级电子沉积及边界效应，揭示肿瘤及肾脏内部的剂量异质性，更接近真实物理分布。两者物理本质互补，联合使用可为 RPT 药物临床前剂量学表征及临床转化提供更全面的物理依据。

关键词: 吸收剂量；MIRD；蒙特卡洛；辐射剂量学；医学物理

Abstract: Background: Fibroblast activation protein (FAP) is an important target for radionuclide radiotherapies (RPT) and is highly expressed in various solid tumors. With the rapid development of ^{177}Lu-labeled FAP agents, accurate assessment of absorbed dose in preclinical models is essential for efficacy, safety, and clinical translation. Currently, MIRD-based organ-level dosimetry and Monte Carlo (MC)-based voxel-level dose calculations have fundamental differences in physical models, and their consistency requires systematic comparison. This study aims to compare GATE Monte Carlo simulations with MIRD-based methods for dose calculation in tumor-bearing mice, with an emphasis on the advantages of MC in physical processes such as particle transport, secondary electron deposition, tissue heterogeneity, and boundary effects. Methods: Based on a U87 tumor-bearing BALB/c nude mouse model, three ^{177}Lu-FAP agents were injected via the tail vein. Small-animal SPECT/CT imaging was performed at multiple time points post-injection, and VOIs of major organs were manually delineated to obtain organ radioactivity at each time point. OLINDA/EXM, Odam, and the PKAD algorithm were used to calculate TIACs followed by normalization, and organ absorbed doses were obtained based on the MIRD framework combined with S-values. Meanwhile, SPECT/CT images were imported into 3D Slicer for format conversion, and spatial coordinate transformation was performed using Python to generate input for GATE simulations. Voxel-level MC simulations were performed using GATE v9.0 (Geant4). CT images (0.25 mm voxel size) were used to construct a voxelized phantom, and SPECT images were used to define a voxelized source. The physical processes included photoelectric effect, Compton scattering, and bremsstrahlung, without energy cuts or variance reduction. The radioactive sources were ^{177}Lu. DoseActor was used to output energy deposition and dose distributions. The simulation time was set to 1/10–1/100 of the actual acquisition time, with statistical uncertainty <5%. Each mouse simulation took 3.5 hours on a computing cluster. Based on the delineated VOIs, dose rates of each organ were calculated, and total absorbed doses were obtained by integral fitting. Energy profiles and dose contour lines were also analyzed. Results: All three radiopharmaceuticals showed high radioactive uptake and retention in tumors. In terms of organ absorbed doses, the kidney and tumor absorbed doses calculated by the MIRD-based methods (OLINDA/EXM, Odam, PKAD) were 19.78–45.94 Gy/GBq and 670.27–744.43 Gy/GBq, respectively. The results from different calculation tools were relatively close / showed some differences. Voxel-level dose distributions obtained from GATE Monte Carlo simulations revealed significant intratumoral dose heterogeneity, with mean absorbed doses ranging from 713.51 to 840.10 Gy/GBq, showing a difference of 12%–25% compared to the MIRD-based methods. At the voxel level, the kidneys also exhibited local hotspots, with a maximum-to-mean dose ratio reaching 2.5. Conclusion: The MIRD-based methods provide organ-level mean doses suitable for rapid assessment but fail to reflect internal dose heterogeneity. GATE-MC, by accurately simulating particle transport, secondary electron deposition, and boundary effects, reveals dose heterogeneity within tumors and kidneys, which is closer to the true physical distribution. The two approaches are physically complementary, and their combined use can provide a more comprehensive physical basis for preclinical dosimetry characterization and clinical translation of RPT agents.

Keywords: Absorbed dose; MIRD; Monte Carlo; Radiation dosimetry; Medical physics

Chapter 2

核能科学与工程

补偿磁路对永磁涡流限速器的制动性能影响研究

Author: 吴泓宇[1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Author: wu-hy23@mails.tsinghua.edu.cn

摘要: 对于高温气冷堆控制棒落棒限速系统，提出了一种新型永磁涡流限速器，其输出的阻尼转矩具有在宽温度范围内对运行温度不敏感的优点。通过采用铁镍合金材料的永磁体包壳，建立了一条补偿磁分路，以抑制永磁体剩磁和导体盘电导率的负温度敏感性对阻尼转矩的不利影响。基于三维有限元仿真方法，验证了补偿磁分路对转矩的运行温度敏感性的抑制作用，并研究了结构参数的影响。此外，在不同的转速和运行温度范围内，对于应用补偿包壳的永磁涡流限速器开展了系列实验。实验结果验证了仿真模型的准确性，实测的转矩温度敏感性小于 0.023%/◦C。本研究对于同类装置提高宽运行温度范围内的转矩稳定性具有重要意义。

关键词: 涡流制动器，有限元分析，磁路，敏感性分析，温度补偿

Abstract: A novel permanent magnet eddy current retarder (PMECR), with a characteristic of temperature-insensitive damping torque over a wide range of operating temperatures, is proposed for speed limit systems. A compensating magnetic shunt is accomplished by utilizing the magnet cladding composed of iron–nickel (Fe–Ni) alloy, and it is used to equalize the adverse effects of temperature sensitivity of the magnet remanence and the conductor disk conductivity on damping torque. Based on the 3-D finite element method, the suppression effect of compensating magnetic shunt design on the sensitivity of torque to operating temperature has been verified, and the influence of main structural parameters is studied. Moreover, experiments with different compensation structures are conducted, varying the rotational speed and changing the operating temperature within the range of 20 ◦C–150 ◦C. The experimental results validate the accuracy of the simulation model, and the achieved quantitative indicator of torque temperature sensitivity is less than 0.023%/◦C. Additionally, compensating capabilities are determined for the potential range of cladding thickness in engineering. With the compensating magnetic shunt, similar devices can maintain torque stability with the dynamic wide change of the operating temperature.

Keywords: Eddy current brake, finite element analysis, magnetic shunt, sensitivity analysis, temperature compensation

沸腾现象中近壁面过热边界层的实验测量方法

Authors: 韩晋玉[1]; 赵陈儒[1]; 涵亮薄[1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Authors: hjy23@mails.tsinghua.edu.cn, zhaochenru@tsinghua.edu.cn, bohl@tsinghua.edu.cn

摘要: 沸腾现象广泛存在于核能系统的多元场景。目前关于沸腾过程中径向温度分布和过热层厚度特性的研究相对不足，现有研究多沿用单相流热边界层定义，对沸腾特有的过热边界层厚度界定标准不一导致壁面法向温度梯度及边界层演化规律尚缺乏统一共识，影响了汽泡边界层内能量传递与相变传热机制的定量描述。为解决上述问题，本文开发近壁面流体精细化测温的微型热电偶（Micro Thermocouple，简称 MTC）实验方法，以及微米级空间分辨率与毫秒级时间分辨率的高精度同步测量手段，提出基于物理机制的汽/液相分离算法，获得纯液相温度分布和局部空泡份额。

关键词: 过热边界层；微型热电偶；沸腾传热

Abstract: Boiling phenomena are widely encountered in various scenarios of nuclear energy systems. However, studies on radial temperature distributions and superheated layer thickness characteristics during boiling remain relatively insufficient. Existing research mostly follows the definition of single-phase thermal boundary layers, and inconsistent criteria for defining the superheated boundary layer thickness unique to boiling have led to a lack of unified consensus on wall-normal temperature gradients and boundary layer evolution dynamics. This inconsistency hinders the quantitative description of energy transfer and phase-change heat transfer mechanisms within the bubble boundary layer. To address these issues, this study develops a micro-thermocouple (MTC) experimental method for fine-scale temperature measurement of near-wall fluids, along with high-precision synchronized measurement techniques featuring micron-scale spatial resolution and millisecond-level temporal resolution. Furthermore, a vapor/liquid phase separation algorithm based on physical mechanisms is proposed to obtain the pure liquid-phase temperature distribution and local void fraction.

Keywords: superheated boundary layer; micro-thermocouple; boiling heat transfer

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空间闭式布雷顿循环氦氙工质泄漏对离心压气机性能的影响机制研究

Author: 许日升[1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Author: xrs23@mails.tsinghua.edu.cn

摘要: 针对空间闭式布雷顿循环中 He-Xe 二元混合工质长期非等比例泄漏问题，本文建立了“泄漏演化—物性漂移—压气机性能变化—系统匹配迁移”的耦合分析框架，研究 He 优先泄漏对离心压气机全寿期性能和运行裕度的影响。首先，通过等效泄漏模型获得系统压力、工质组成和平均摩尔质量随服役时间的变化规律；随后，结合变组分真实气体物性模型和三维 CFD 计算，分析不同服役阶段下压气机性能图的演化特征；最后，引入压气机—涡轮系统匹配模型，揭示运行线和实际工作点的迁移机制。结果表明，长期 He 优先泄漏会导致系统总压非线性下降、混合工质平均摩尔质量升高和气体常数降低，进而推动压气机工作点向大折合流量侧迁移并逐渐偏离高效区。寿期末叶轮通道内高相对马赫数区域扩大，局部阻塞趋势和吸力面—轮盖角区分离增强，是效率下降和阻塞裕度收缩的重要原因。研究表明，长寿命 He-Xe 闭式布雷顿循环压气机设计应考虑工质泄漏引起的全寿期边界漂移和运行裕度变化。

关键词: 闭式布雷顿循环；He-Xe 混合工质；离心压气机；非等比例泄漏；真实气体物性；系统匹配；运行裕度

Abstract: This study investigates the influence of long-term non-proportional leakage of He-Xe binary working fluid on the lifetime performance and operating margin of a centrifugal compressor in a space closed Brayton cycle. A coupled analysis framework of “leakage evolution–property drift–compressor performance variation–system matching migration”is established. First, an equivalent leakage model is developed to predict the temporal evolution of system pressure, mixture composition, and mean molar mass. Then, a variable-composition real-gas property model is coupled with three-dimensional CFD simulations to obtain compressor performance maps at different service stages. Finally, a compressor–turbine system matching model is introduced to determine the migration of the operating line and actual operating point. The results show that preferential helium leakage leads to a nonlinear decrease in system pressure, an increase in mean molar mass, and a reduction in the gas constant. These variations drive the compressor operating point toward the high corrected-flow-rate region and gradually away from the initial high-efficiency zone. At the end of service life, the high relative Mach number region expands inside the impeller passage, accompanied by local choking tendency and enhanced separation near the suction-surface/shroud corner. These flow mechanisms contribute to efficiency degradation and choking-margin reduction. The results indicate that the design of long-life He-Xe centrifugal compressors should account for lifetime boundary drift and operating-margin redistribution induced by working-fluid leakage.

Keywords: closed Brayton cycle; He-Xe working fluid; centrifugal compressor; non-proportional leakage; real-gas properties; system matching; operating margin

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基于栅格法的随机堆积球床几何全六面体网格生成算法

Author: 赖桂桦[1]

[1] *清华大学核能与新能源技术研究院*

Co-author: 王宏

Corresponding Authors: hongw@mail.tsinghua.edu.cn, lgh22@mails.tsinghua.edu.cn

摘要: 随机堆积球床具有复杂的孔隙结构，其颗粒间接触和狭窄流道给热工水力分析中的计算网格生成带来了较大困难，尤其容易在接触点附近产生低质量网格。针对这一问题，本文提出了一种面向随机堆积球床几何的基于栅格法的全六面体网格生成算法。该方法以笛卡尔网格作为初始背景网格，通过边界识别、网格投影和几何贴合，使网格逐步贴合到球体及容器壁面边界；同时在网格生成过程中引入自动化接触处理策略，以改善颗粒-颗粒及颗粒-壁面接触区域的网格质量。在此基础上，进一步结合缓冲层插入和网格质量优化方法，提高边界附近及局部复杂区域的网格正交性和鲁棒性。两个代表性球床几何算例表明，该方法能够稳定生成高质量全六面体网格，并在网格质量和生成效率方面优于商业软件 Fluent Meshing。结果表明，本文提出的算法能够较好地适应随机堆积球床复杂多孔几何，为复杂多孔介质中的高精度 CFD 模拟提供可靠的网格生成方法。

关键词: 六面体网格；网格生成算法；随机堆积球床；接触点处理

Abstract: The complex porous geometry of randomly packed pebble beds poses significant challenges for thermal-hydraulic analysis in industrial applications. In particular, the presence of inter-particle contact points often hinders the generation of high-quality computational grids for computational fluid dynamics (CFD) simulations. To address this issue, this paper presents a grid-based, all-hexahedral meshing algorithm designed specifically for randomly packed pebble beds. The method begins with a Cartesian base mesh, which is subsequently projected and conformed to the geometric boundaries. Automated contact treatments are integrated into the meshing process and refinements to the algorithm include insertion of a buffer layer and mesh optimization. Two representative cases for the pebble bed geometry demonstrates the advantage of the hexahedral mesh and the robustness of the algorithm. Furthermore, the algorithm shows a better computational efficiency compared to commercial software Fluent Meshing. Results show that the proposed hexahedral meshing algorithm is capable to handle the complex, porous geometries of randomly packed pebble beds, which establishes a foundation for high-fidelity CFD simulations in complex porous media.

Keywords: Hexahedral mesh; Mesh generation; Packed pebble bed; Contact points

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格子玻尔兹曼方法：基于聚结效应的脊状超疏水表面液滴跳跃研究

Author: 孙奥[1]

[1] *北京市海淀区清华大学*

Corresponding Author: suna25@mails.tsinghua.edu.cn

摘要: 聚结诱导液滴跳跃（CIDJ）是超疏水表面上一类高效的被动液滴去除机制，在冷凝传热、自清洁及防冰等领域具有重要应用前景。然而，针对介观尺度液滴在脊状结构及脊状晶格系统中的聚结行为，尤其是多液滴排列方式与能量转换机制的协同调控，仍缺乏系统分析。本研究采用三维多弛豫时间（MRT）伪势格子玻尔兹曼方法（D3Q19），系统模拟了脊状及脊状晶格超疏水表面上液滴的聚结跳跃过程，分析了结构参数、液滴排列方式及尺寸比对动力学行为与能量演化路径的影响。结果表明，脊高是主导跳跃性能的关键几何参数，高脊结构可有效约束液桥扩展，提升垂直动量转化效率；脊状晶格系统在无量纲脊高 $h^*= 0.83$ 时可使跳跃速度提升 10.1%。液滴排列对称性显著影响能量转换效率，非对称排列易引发水平振荡，而晶格结构可补偿其动能损失，对 V 型排列液滴提升幅度达 98.68%。本研究对 CIDJ 现象的解释从单脊、双液滴系统拓展至脊状晶格、多液滴场景，明确了结构参数、液滴排列及尺寸比对跳跃行为的调控机制，为超疏水表面结构设计及介观液滴操控提供了理论依据与技术支撑。

关键词: 格子玻尔兹曼方法；聚结诱导液滴跳跃；超疏水表面；脊状晶格系统；液滴排列对称性

Abstract: Coalescence-induced droplet jumping (CIDJ) is a highly efficient passive droplet removal mechanism on superhydrophobic surfaces, which has important application prospects in fields such as condensation heat transfer, self-cleaning, and anti-icing. However, there is still a lack of systematic analysis of the coalescence behavior of mesoscale droplets in ridge structures and ridge lattice systems, especially the collaborative regulation of the multi-droplet arrangement and the energy conversion mechanism. In this study, the three-dimensional multi-relaxation time (MRT) pseudo-potential lattice Boltzmann method (D3Q19) was used to systematically simulate the coalescence and jumping process of droplets on ridge and ridge lattice superhydrophobic surfaces, and the influence of structural parameters, droplet arrangement, and size ratio on the dynamic behavior and energy evolution path was analyzed. The results show that the ridge height the geometric key is parameter governing the jumping performance. The high-ridge structure can effectively constrain the expansion of the liquid bridge and improve the vertical momentum conversion efficiency. The ridge lattice system can increase the jumping velocity by 10.1% when the dimensionless ridge height $h^* = 0.83$. The symmetry of droplet arrangement significantly affects the energy conversion efficiency. Asymmetric arrangement is prone to cause horizontal oscillations, while the lattice structure can compensate for its kinetic energy loss, with an improvement amplitude of 98.68% for V-shaped arranged droplets. This study extends the explanation of the CIDJ phenomenon from single-ridge and two-droplet systems to ridge lattice and multi-droplet scenarios, clarifies the regulatory mechanism of structural parameters, droplet arrangement, and size ratio on the jumping behavior, and provides a theoretical basis and technical support for the structural design of superhydrophobic surfaces and the manipulation of mesoscale droplets.

Keywords: Lattice Boltzmann method, Coalescence-induced droplet jumping, Superhydrophobic surface, Ridge lattice system, Droplet arrangement symmetry

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基于协同边界调控的载荷可调式准零刚度隔振器

Authors: 张宸[1]; 许华航[1]; 李笑天[1]; 顾永鹏[1]

[1] *清华大学*

Corresponding Author: c-zhang23@mails.tsinghua.edu.cn

摘要: 准零刚度（QZS）隔振器在低频隔振方面具有显著优势，但其工程应用往往受限于对承载载荷的高度敏感性。针对这一问题，本文提出了一种基于协同边界调控的额定载荷可调式准零刚度隔振器。该隔振器由特定构型的曲梁与集成调节机构组成，可实现额定载荷的连续调节。通过协同调控曲梁端部的横向位移和转角，隔振器的准零刚度特性能够被重构，从而适应设计范围内的任意载荷。
本文首先采用非线性有限元分析，揭示边界条件对曲梁载荷-位移特性的协同影响机制；随后建立多目标优化设计策略，在满足预设载荷调节需求的同时兼顾结构强度约束。优化算例表明，该隔振器能够在一定载荷范围内通过结构重构保持准零刚度特性，例如优化设计可覆盖名义载荷 50% 至 150% 的变化范围。进一步地，本文开展了非线性动力学分析，评估不同边界条件和载荷工况下的隔振性能，结果表明协同边界调控能够有效恢复系统的低频隔振能力。最后，本文制作了 3D 打印样机，并通过静态和动态实验进行了验证。实验结果表明，借助额定载荷调节策略，该隔振器在三种显著不同载荷下均能保持基本一致的低截止频率。所提出的准零刚度隔振器兼具结构紧凑性、被动可靠性和载荷适应性，可为复杂工程环境中的高性能低频振动控制提供一种有效方案，尤其适用于有效载荷难以精确预测的应用场景。

关键词: 准零刚度隔振器；低频振动隔离；非线性动力学；曲梁；额定载荷调节；边界条件调控

Abstract: Quasi-zero-stiffness (QZS) vibration isolators offer a superior solution for low-frequency vibration isolation; however, their application remains constrained by an inherent sensitivity to the supported load. To address this limitation, this paper proposes a novel QZS isolator comprising specifically shaped curved-beams and integrated regulation mechanisms to achieve a continuously tunable rated load. Through the synergistic regulation of the lateral displacement and the rotation angle at the curved-beam boundaries, the isolator's QZS characteristic can be reconfigured to accommodate arbitrary payloads within a design range. The research first employs nonlinear finite element analysis to elucidate the synergistic effects of boundary conditions on load–displacement characteristics of the curved-beam. Subsequently, a multi-objective optimization strategy is developed for designing the curved-beam, aiming to satisfy the predefined load-tuning requirements while adhering to strength constraints. In the optimization case presented herein, the isolator can be reconfigured to maintain QZS characteristics across a payload range–as exemplified by an optimized design spanning 50% to 150% of the nominal load. Nonlinear dynamic analysis is further conducted to evaluate the isolation performance under different boundary conditions and payloads, demonstrating the effectiveness of the synergistic regulation in restoring system performance. Finally, a 3D-printed prototype was fabricated and validated through comprehensive static and dynamic experiments. The results demonstrate that the isolator maintains a consistent low cut-off frequency under three significantly different loads through the rated-load tuning strategy. The proposed QZS isolator offers a compact and robust solution for high-performance passive vibration control in complex engineering environments, with its QZS characteristic reconfigurability ensuring practical viability in scenarios where precise payload prediction is challenging.

Keywords: Quasi-zero-stiffness isolator; Low-frequency vibration isolation; Nonlinear dynamics; Curved-beam; Rated-load tuning; Boundary-condition regulation

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兆瓦级车载移动式热管冷却反应堆核能系统特性分析

Author: 林恒隆[1]

Co-authors: 李泽光[1] ; 王侃[1] ; 诸葛伟林; 余纲林[1] ; 江泓升; 李景康; 杨俊; 苏子麟[1] ; 王慧富[1]

[1] *清华大学工程物理系*

Corresponding Author: linhl22@mails.tsinghua.edu.cn

摘要: 热管冷却反应堆（Heat pipe cooled reactor, HPR）具有体积小、安全性高的特点，可用于车载移动等特殊应用场景。本文选择基于 HPR 的移动核电系统 MNPS-1000 进行研究和分析，该系统旨在产生输出 1MWe。根据设计，建立了一个完整的系统模型，包括反应堆模型、高温热管模型、热管换热器模型和能量转换系统模型等。利用 MATLAB/SIMULINK，搭建了适用于该核电系统的分析平台。基于该平台，对系统的稳态和瞬态性能进行了仿真。在稳态分析中，模型关键节

点的模拟值与参数匹配的计算值基本一致，最大相对误差不超过 6%，验证了基于所建平台开展系统分析的有效性。在瞬态分析中，分别对典型的反应堆系统事故和能量转换系统事故进行了模拟和分析。这些事故中燃料组件的最高温度不超过 1550K，低于选定的材料温度安全限值，讨论了该系统的固有安全特性。

关键词: 热管冷却反应堆，联合循环，车载移动，系统分析

Abstract: Heat pipe cooled reactor (HPR) has the characteristics of small size and high safety, and can be used in special application scenarios such as vehicle-mounted mobility. In this paper, the Mobile Nuclear Power System based on HPR named MNPS-1000, which is designed to generate 1MWe, is selected for research and analysis. Ac cording to the design, a whole system model is established, which includes the reactor model, high-temperature heat pipe model, heat pipe heat exchanger model and energy conversion system model, etc. Using MATLAB/ SIMULINK, the analysis platform suitable for this nuclear power system is built. Based on this platform, the steady state and transient performance of the system are characterized. In the steady state analysis, the simulated values of key nodes of the model are in general agreement with the calculated values of parameter matching, and the maximum relative error does not exceed 6 %. The effectiveness of characteristic analysis based on the built platform is verified. In the transient analysis, typical reactor system accidents and energy conversion system accident are simulated and analyzed respectively. The maximum temperature of the fuel assemblies in these accidents does not exceed 1550 K, which is lower than the selected material temperature safety limit. The inherent safety feature of the system is discussed.

Keywords: Heat pipe cooled reactor, Combined cycle, Vehicle-mounted mobile, System analysis

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清华大学高通量反应堆两相热力学特性研究

Authors: 张杰[1]; 衡解[1]; 石磊[1]

[1] *清华大学*

Corresponding Author: zhangjie22@mails.tsinghua.edu.cn

摘要: 清华高通量反应堆（THFR）燃料元件的窄流道及局部堵塞事故是影响堆芯安全的核心问题之一。本研究采用计算流体力学（CFD）方法，分析了高通量反应堆内局部流道堵塞引发的热工水力现象。研究结果表明：堵塞物尾迹区的热量积聚贡献了开启核态沸腾（ONB）所需过热度的 90% 以上，其影响远超压力降效应。研究识别出一种关键的“涡旋捕获”机制：蒸汽团被截留在再循环涡流中，形成持久的蒸汽包覆层。这种热屏蔽效应将包壳与过冷主流隔离，从而急剧增加了偏离核态沸腾（DNB）的风险。研究结论认为，决定堵塞期间反应堆安全裕度的是微观尺度下的多相动力学特征，而非宏观的压力波动。本研究揭示的物理机制可为高通量反应堆的堵塞事故监测报警系统提供理论支撑，并为先进燃料组件的流道优化设计提供参考依据。

关键词: 窄流道，局部流道堵塞，多相动力学

Abstract: The narrow flow channel and local blockage accidents in the fuel elements of the Tsinghua High-Flux Reactor are one of the key issues affecting core safety. This study uses CFD to analyze thermal-hydraulic phenomena induced by local flow blockages in a high-flux reactor. Results show that heat accumulation in the blockage wake contributes over 90% of the superheat required for Onset of Nucleate Boiling, far outweighing pressure-drop effects. A critical “vortex trapping” mechanism was identified, where vapor clusters are sequestered in recirculating eddies, forming a persistent vapor blanket. This thermal-shielding effect isolates the cladding from the subcooled mainstream, drastically increasing Departure from Nucleate Boiling (DNB) risks. The study concludes that micro-scale multiphase dynamics, not macroscopic pressure fluctuations, govern reactor safety margins during blockages.The physical mechanisms revealed in this study provide a theoretical foundation for monitoring and alarm systems for blockage accidents in high-flux reactors and offer a reference for the optimized channel design of advanced fuel assemblies.

Keywords: Narrow flow channel，Local flow blockage，Multiphase flow dynamics

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A Robust Smith-like Predictor-Enhanced Passivity-Based Control Method for the HTR-PM Reactor Module Subject to Large Hot Helium Temperature Response Delay

Author: 游照旭[1]

Co-author: Zhe Dong [1]

[1] *清华大学*

Corresponding Authors: dongzhe@tsinghua.edu.cn, yzx24@mails.tsinghua.edu.cn

摘要: 全球首座商业化球床模块式高温气冷堆核电站——高温气冷堆核电站示范工程（HTR-PM）于 2023 年 12 月 6 日投入商业运行。为验证反应堆协调控制策略的可行性，开展了功率斜坡升降、汽轮机跳闸、反应堆跳闸等多项全厂试验，获取了关键过程变量的宝贵现场数据。数据分析表明，热氦温度存在显著响应滞后，显著影响了单模块协调控制性能。
针对该工程问题，本文面向热氦温度响应滞后工况下的 HTR-PM 反应堆模块，提出一种鲁棒型类史密斯预估器增强无源控制方法。设计时域类史密斯预估器，用于估计无滞后热氦温度，并将其融入无源控制框架。该方法可补偿热响应滞后的不利影响，同时保留无源控制的稳定性优势。与传统无源控制（PBC）相比，该方法提升了系统瞬态调节性能，增大了闭环稳定的允许滞后裕度，能够在传统无源控制失稳的大滞后工况下维持系统稳定运行。本文对闭环系统的渐近稳定性进行了理论分析，并基于 HTR-PM 单模块协调控制场景开展仿真，验证了所提方法的有效性与鲁棒性。

关键词: HTR-PM；协调控制；大时延系统；类史密斯预估器；无源性控制

Abstract: The HTR-PM demonstration project, the world's first commercial high-temperature gas-cooled reactor pebble-bed module nuclear power plant, entered commercial operation on December 6, 2023. Several plant-wide tests, including power ramping, turbine trip, and reactor trip tests, were conducted to verify the feasibility of the reactor coordinated control strategy and provided valuable field data on key process variables. Analysis of these data reveals a pronounced response delay in the hot helium temperature, which significantly degrades the performance of single-module coor-dinated control. Motivated by this engineering issue, this paper proposes a robust Smith-like predictor-enhanced passivity-based control method for the HTR-PM reactor module with large hot helium temperature response delays. A time-domain Smith-like predictor is developed to estimate the delay-free hot helium temperature and incorporated into the passivity-based control framework. The proposed method compensates for delayed thermal response while preserving the stability advantages of passivity-based control. Compared with conventional PBC, it improves transient regulation performance and increases the allowable delay margin for closed-loop stability, maintaining stable operation under large-delay conditions where conventional PBC becomes unstable. Closed-loop asymptotic stability is theoretically analyzed, and simulations based on the HTR-PM single-module coordinated control scenario verify the effectiveness and robustness of the proposed method.

Keywords: HTR-PM; coordinated control; large time-delay system; Smith-like predictor; passivity-based control

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基于 RMC/Fluent 的高参数堆组件核-热-燃耗耦合特性分析

Author: 何颖[1]

Co-authors: 刘国栋 [1]; 赵星宇 [1]; 陈海升 [1]; 侯任郡 [1]; 邱美铭 [1]; 黄善仿 [1]

[1] *清华大学*

Corresponding Author: he-y22@mails.tsinghua.edu.cn

摘要: 高保真、高分辨率模拟让堆芯挖掘裕量成为可能。高功率密度压水堆在传统压水堆基础上提高堆芯功率密度，堆芯内可能出现泡状流甚至弹状流。功率分布、热工参数分布的不均匀性增加，给堆芯寿期设计带来挑战。本文基于 RMC、Fluent 开发了一套核-热-燃耗耦合工具，对功率映射方法进行改进，最终用于不同功率水平下组件的多场耦合特性分析。结果表明本文提出的功率映射算法能兼容板、帮的计算需求，具有较好的网格兼容性和几何兼容性。核-热-燃耗耦合程序通过单棒的验证，得到 235U、241Pu 的相对偏差小于 1%。Fluent 两相流模型也通过 Martin 实验的验证。从不同功率水平组件的耦合结果来看，keff、功率峰因子、235U 等重要核素浓度、燃料温度、冷却剂温度等参数变化趋势一致，但两相流的引入导致功率峰因子显著增大、寿期燃料最高温度变化幅度增大，同时会导致计算时间增加约 1.7 倍。

关键词: 蒙卡；CFD；高参数堆；核-热-燃耗耦合

Abstract: High-fidelity, high-resolution simulation enables nuclear reactor margin exploration. High-Power-Density Pressurized Water Reactors (PWRs) increase power density compared to conventional PWRs, potentially leading to bubbly or even slug flow in the core. The increased non-uniformity of power and thermal-hydraulic parameter distributions poses challenges to core lifetime design. In this paper, a neutronics-thermal-hydraulic-burnup coupling tool is developed based on RMC and Fluent, with an improved power mapping method, and is subsequently applied to the multi-field coupling analysis of fuel assemblies under various power levels. Results show that the proposed power mapping algorithm can accommodate both rod-type and plate-type computational requirements, exhibiting good mesh and geometric compatibility. The coupled neutronics/thermal-hydraulic/burnup code is validated against a single-pin cell, yielding relative deviations for ^{235}U and ^{241}Pu density of less than 1%. The Fluent two-phase flow model is also validated against the Martin experiment. From the coupling results for assemblies at different power levels, the trends of key parameters such as keff, power peaking factor, concentrations of important nuclides (e.g., ^{235}U), fuel temperature, and coolant temperature are consistent. However, the introduction of two-phase flow leads to a significant increase in the power peaking factor and a larger variation in the maximum fuel temperature over the fuel lifetime, while also increasing the computational time by approximately 1.7 times.

Keywords: Monte Carlo; CFD; High power density PWR; neutronics/thermal-hydraulics/burnup coupling

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清华高通量堆全堆输运计算 GPU 加速研究

Author: 左天赢 [1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Author: zty23@mails.tsinghua.edu.cn

摘要: 为提高清华高通量堆（THFR）全堆中子输运计算效率，充分利用单机 CPU-GPU 异构系统的计算资源，研究并实现了三维中子输运计算全流程的 GPU 加速。全堆输运计算基于 2D/1D 方法，径向采用二维特征线方法（MOC），轴向采用一维 MOC，并实现了三维粗网有限差分（CMFD）加速。通过 C5G7 3D 扩展基准题和 THFR 3D 简化模型进行精度验证和效率分析，使用单块 NVIDIA 3090 GPU 和采用 32 核并行及 SIMD 向量化并行的 CPU 进行计算。结果表明：GPU 计算精度良好，完全单精度适用于全堆输运计算；C5G7 3D 扩展基准题的计算加速比达到 40 倍以上，THFR 3D 简化模型的计算加速比达到 5.6 倍，计算效率大幅提升。

关键词: 高通量堆；中子输运计算；2D/1D 方法；GPU

Abstract: To improve the efficiency of whole-core neutron transport calculations for Tsinghua High Flux Reactor and fully utilize the computational resources of single-machine CPU-GPU heterogeneous systems, the GPU acceleration of entire three-dimensional neutron transport calculations has been studied and implemented. Whole-core transport calculation is based on the 2D/1D method, and the radial calculation employs the two-dimensional method of characteristics(MOC), while the axial calculation

uses one-dimensional MOC, and three-dimensional coarse mesh finite difference(CMFD) acceleration has been implemented. Accuracy verification and efficiency analysis were performed using the C5G7 3D extension benchmark and the THFR 3D simplified model, with computations carried out on a single NVIDIA 3090 GPU and a CPU utilizing 32-core parallel processing and SIMD vectorization. The results indicate that the GPU achieves good computational accuracy, with full single-precision performance being fully suitable for whole-core transport calculations; the computational speedup for the C5G7 3D extension benchmark exceeded 40x, while that for the THFR 3D simplified model reached 5.6x, demonstrating a significant improvement in computational efficiency.

Keywords: High flux reactor, Neutron transport calculation, 2D/1D method, GPU

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Nb 在 Mo-Nb 合金辐照诱导硬化中关键作用的原子尺度研究

Author: 杨业鑫[1]

Co-authors: 孟云龙; 佟振峰; 龚翱翔; 马雁

[1] *华北电力大学*

Corresponding Author: yangyexin0116@163.com

摘要: 钼铌（Mo-Nb）合金因其优异的抗蠕变性和高真空功函数特性，被认为是空间热离子反应堆能量转换部件的首选材料。然而，溶质 Nb 原子引起的辐照硬化基本机制仍不明确。本研究通过分子动力学（MD）模拟，探究了刃位错与 Nb 修饰辐照缺陷的相互作用，并与辐照缺陷及富 Nb 团簇的作用进行了对比。模拟结果表明：Nb 在位错环上的偏析会显著影响这些环与刃位错的相互作用。当位错环被 Nb 修饰后，特别是当环的取向平行于滑移面且相对于位错的伯氏矢量倾斜时（<11-1> 型环），这些环会从弱障碍转变为强障碍。Nb 修饰的 <11-1> 型环对滑移位错的钉扎强度还取决于 Nb 浓度。一旦 Nb 浓度超过临界值，位错将无法吸收或剪切 <11-1> 型环。此外，临界 Nb 浓度随 <11-1> 型环尺寸增大而升高，这是因为 Nb 原子与位错环的平均结合强度随环尺寸增大而降低，需要更高 Nb 浓度进行补偿。这些发现为理解 Mo-Nb 体系辐照硬化机制提供了新见解。

关键词: Mo-Nb 合金；铌聚集；辐照硬化；刃位错滑移；临界分切应力

Abstract: Molybdenum-niobium (Mo-Nb) alloys are considered the preferred materials for energy conversion components in space thermionic reactors because of their excellent creep resistance and high vacuum work function. However, the fundamental mechanism of irradiation hardening caused by solute Nb atoms remains unclear. Here, the interaction between edge dislocations and Nb-decorated irradiation-induced defects was studied using molecular dynamics (MD) simulations, and the results were compared to interactions with irradiation-induced defects and Nb-rich clusters. The simulation results showed that Nb segregation to loops greatly affects the interaction between these loops and edge dislocations. The loops can change from weak barriers to strong obstacles when decorated with Nb, especially when the loop orientation is parallel to the glide plane and inclined relative to the Burgers vector of the dislocation ($< 11\bar{1} >$ loops). The pinning strength of Nb-decorated <11-1> loops on gliding dislocations also depends on Nb concentration. Once the Nb concentration exceeds a certain critical level, the <11-1> loops can no longer be absorbed or sheared by the dislocations. Additionally, the critical Nb concentration increases with <11-1> loop size. This happens because the average binding strength between Nb atoms and loops decreases as <11-1> loop size grows, requiring a higher Nb concentration to compensate. These findings offer new insights into the mechanisms behind irradiation hardening in the Mo-Nb system.

Keywords: Mo-Nb alloys; Nb aggregation; Irradiation hardening; Edge dislocation glide; Critical resolved shear stress

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基于 CUDA 的三维 Random Ray 多群中子输运求解器及 GPU 加速机制研究

Author: 沈绍宁[1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Author: shensn25@mails.tsinghua.edu.cn

摘要: Random Ray Method 是一种将特征线法的确定性沿线积分与随机射线抽样相结合的中子输运数值方法，具有几何处理简单、天然适合大量独立射线并行推进等特点。针对三维非均匀反应堆物理问题中的射线追踪、源迭代和多群通量累积开销，本文研究基于 CUDA 的 Random Ray 多群中子输运求解思路。方法上采用裂变源幂迭代求解有效增殖因子 keff，GPU 端将主要计算分解为按 cell-group、ray 和 ray-group 粒度组织的多个 kernel，将几何追踪、沿线衰减积分、标量通量统计和裂变源更新组织为适合 GPU 的并行计算流程。最后通过 Takeda 与 C5G7 基准问题验证方法的可行性和加速效果。

关键词: Random Ray Method；中子输运；CUDA；GPU 加速；多群方法；Takeda；C5G7

Abstract: The Random Ray Method is a neutron transport numerical method that combines the deterministic line integration of the characteristic line method with random ray sampling. It has the characteristics of simple geometric processing, low memory requirements, and is naturally suitable for the parallel advancement of a large number of independent rays. Aiming at the overhead of Ray tracing, source iteration and multi-group flux accumulation in three-dimensional non-uniform reactor physics problems, this paper studies the solution idea of Random Ray multi-group neutron transport based on CUDA. Methodologically, the fission source power iteration is adopted to solve the effective proliferation factor k_eff. At the GPU end, the main computation is decomposed into multiple kernels organized according to the granularity of cell-group, ray, and Ray-group. Organize geometric tracing, along-line attenuation integration, scalar flux statistics, and fission source updates into a parallel computing process suitable for GPUs. Finally, the feasibility and acceleration effect of the method are verified through the benchmark problems of Takeda and C5G7.

Keywords: Random Ray Method; neutron transport; CUDA; GPU acceleration; multigroup transport; Takeda; C5G7

基于 RMC 的自主蒙卡子通道核热耦合系统开发

Author: 李耀东[1]

[1] *清华大学*

摘要: 高保真核热耦合分析是研究反应堆复杂物理行为的重要手段。为建立自主可控的核热耦合分析体系，本文基于自主开发的蒙特卡罗中子输运程序 RMC 与热工水力子通道程序 RTH-SC，构建了以 Python 脚本为驱动的核热耦合计算系统 RMC/RTH-SC。
本工作的主要内容涵盖两个方面：一是 RTH-SC 程序全堆 pin-by-pin 分析能力的开发与实现；二是耦合计算平台的设计与搭建。针对商用压水堆全堆 pin-by-pin 精细化建模的复杂性，开发了预处理工具 SC-Pre，实现了全堆几何模型的自动化构建；在此基础上，建立了基于 Picard 迭代的耦合计算框架，并完成了中子物理网格与热工水力网格之间的映射关系处理。
为验证系统的计算精度，以 VERA7 基准题反应堆为对象开展了全堆模拟，并与 RMC/CTF 耦合结果进行对比。结果表明：有效增殖因子的相对偏差为 7.1 pcm；堆芯组件功率分布的平均偏差约为 1.4%；慢化剂温度的平均偏差为 0.74 ℃；慢化剂密度的平均偏差为 0.83×10^{-3} g·cm^{-3}。上述结果表明，所建立的 RMC/RTH-SC 耦合系统具有良好的计算准确性，可为压水堆精细化核热耦合分析提供有效支撑。

关键词: RMC；核热耦合；RTH-SC

Abstract: High-fidelity neutronics–thermal-hydraulics coupled analysis is an essential approach for investigating the complex physical behavior of nuclear reactors. To establish an independently developed and fully controllable coupled analysis framework, this study presents the RMC/RTH-SC coupled system, which is built upon the in-house Monte Carlo neutron transport code RMC and the thermal-hydraulic subchannel code RTH-SC, with Python scripts serving as the coupling driver.
The scope of this work encompasses two primary aspects: first, the development and implementation of full-core pin-by-pin analysis capability within the RTH-SC code; and second, the design and construction of the coupled computational platform. To address the complexity inherent in full-core pin-by-pin modeling of commercial pressurized water reactors (PWRs), a preprocessing tool, SC-Pre, was developed to enable automated construction of the full-core geometric model. On this basis, a coupled computational framework based on Picard iteration was established, along with the implementation of mesh mapping between the neutronics and thermal-hydraulic domains.
To verify the computational accuracy of the coupled system, a full-core simulation was performed for the VERA Benchmark Problem 7 reactor, and the results were compared against those obtained from the RMC/CTF coupled solution. The comparison shows that the relative deviation in the effective multiplication factor is 7.1 pcm, the mean deviation in assembly-wise power distribution is approximately 1.4%, the mean deviation in moderator temperature is 0.74 ℃, and the mean deviation in moderator density is 0.83×10^{-3} g·cm^{-3}. These results demonstrate that the developed RMC/RTH-SC coupled system possesses satisfactory computational accuracy and can serve as an effective tool for high-fidelity neutronics–thermal-hydraulics coupled analysis of PWRs.

Keywords: RMC; Neutronics/thermal-hydraulics coupling; RTH-SC

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高温气冷堆甲烷蒸汽重整系统中氚渗透行为研究

Authors: 华强银[1]; 李昊翔[1]; 刘瑞洋[1]; 张璜[1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Author: liury23@mails.tsinghua.edu.cn

摘要: 高温气冷堆（HTGR）甲烷蒸汽重整（MSR）制氢是中短期内最有希望实现的核能制氢技术。由反应堆产生的氚的渗透行为在系统安全分析时极为重要。目前有两种方法可以将核反应堆与氢气生产系统连接起来：直接耦合或通过中间热交换器（IHX）间接耦合。为了分析两种耦合方式的氚渗透差异，比较不同 IHX 合金和运行条件下氚渗透行为，本研究考虑放射性元素氚不同源项的产生速率、释放分数，以及衰变减少等情况，分析了氚浓度、分压、温度和不同合金等参数，建立了氚在 IHX 发生渗透的计算模型。结果表明，氚的渗透速率主要受到 IHX 合金指前因子的限制，并且受温度变化影响较大，稳定状态下温度由 750℃ 增加为 950℃ 时，氚的渗透速率可增大近 3 倍。核能制氢系统通过中间换热器间接耦合，使得二回路中氚的分压较一回路下降约 90%。这些结果将有助于设计一个有效和安全的高温气冷堆甲烷蒸汽重整制氢系统，并为核能制氢系统的安全和高效运行提供宝贵的信息。

关键词: 高温气冷堆，核能制氢，氚，氚渗透，系统安全性分析

Abstract: Hydrogen production system by Methane Steam Reforming (MSR) using High Temperature Gas Cooled Reactor (HTGR) is the most promising technology for nuclear hydrogen production in the near future. The tritium permeation behavior produced by the reactor is extremely important when analyzing the system safety. It is currently possible to connect a nuclear reactor to a hydrogen production system by direct coupling or indirect coupling through an intermediate heat exchanger (IHX). In this study, parameters such as partial pressure, temperature and different alloys were analyzed in steady state and unsteady state. Then a calculational model for the permeation of tritium occurring at the IHX is established. The results show that the permeation rate of tritium can increase nearly two times as the temperature increases from 750 to 950℃ in the steady state. The nuclear hydrogen production system is indirectly coupled through an intermediate heat exchanger, which results in an approximately 90% decrease in the partial pressure of tritium in the second circuit compared to the first circuit. These works will contribute to the design of an efficient and safe nuclear hydrogen production system by MSR using HTGR.

Keywords: High-Temperature gas-cooled reactor, Hydrogen production using nuclear energy, Tritium, Tritium permeation, System safety

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基于多尺度小波残差注意力网络的低分辨率弱峰伽马能谱全能峰预测模型

Authors: Xiyu Yang[1]; Hui Yang[1]; Jian Shan[1]

[1] *南华大学*

Corresponding Author: 361814621@qq.com

摘要: 基于 $LaBr_3(Ce)$ 探测器的伽马能谱现场快速测量是核应急响应与环境辐射监测的关键技术手段，但其较低的能量分辨率导致复杂放射性场景中出现严重谱峰重叠与弱峰淹没，传统分步进行平滑-本底扣除流程的谱分析方法及商用解谱软件 GammaVision 在低峰康比及低信噪比条件下存在显著的弱峰面积丢失问题，制约了动态工况下的核素快速定性定量分析。本研究提出的 4-Level-Wavelet ResAttention 模型将离散小波变换（DWT）多尺度分解嵌入端到端深度学习框架，通过 LevelNetRes 残差模块实现弱峰层级特征高维提取，Level-attention Transformer 实现跨尺度特征自适应融合，并针对弱峰能谱分析的峰型特征保留关键需求，设计了联合约束峰位精度、峰型对称性及峰面积误差的多目标加权损失函数，提升低峰康比条件下的弱峰提取精度与鲁棒性。实验表明，与传统方法相比，新模型在低峰康比条件下净峰谱均方误差与峰型变形程度分别降低 95.82% 和 97.71%，峰面积误差降低 89.33%；在重叠峰分析中面积比误差降低 91.76%；在峰康比低至 1.34—2.97 的极端实测场景中，峰形保真度为传统方法的 7.94%，峰面积误差降低 17.47%。该模型为低能量分辨率探测器的复杂弱峰能谱解析提供了高精度、高鲁棒性的技术方案，可有效支撑复杂放射性核素的现场快速识别与定量分析。

关键词: 伽马能谱分析；弱峰提取；离散小波变换；ResNet；Transformer；净谱预测；现场快速测量；环境辐射监测

Abstract: Rapid in-situ gamma spectroscopy based on $LaBr_3(Ce)$ detectors is critical for nuclear emergency response and environmental radiation monitoring. However, their limited energy resolution leads to severe peak overlap and weak-peak masking in complex radioactive scenarios. Conventional stepwise smoothing and background subtraction methods, as well as the commercial spectrum analysis software GammaVision, suffer from significant weak-peak area loss under low Peak-to-Compton ratio and low signal-to-noise ratio conditions, hindering rapid nuclide identification and quantification in dynamic environments. To address this issue, this study proposes a 4-Level Wavelet ResAttention model that embeds Discrete Wavelet Transform (DWT) multi-scale decomposition into an end-to-end deep learning framework. The LevelNetRes module extracts high-dimensional hierarchical features of weak peaks, while the Level-attention Transformer enables adaptive cross-scale feature fusion. A multi-objective weighted loss function is further designed to jointly constrain peak position accuracy, peak symmetry, and peak area error, thereby improving extraction accuracy and robustness. Experimental results demonstrate that, compared with conventional methods, the proposed model reduces the relative mean squared error and peak shape distortion of net spectra by 95.82% and 97.71%, respectively, and decreases peak area error by 89.33% under low peak-to-Compton conditions. In overlapping peak analysis, the area ratio error is reduced by 91.76%. In extreme measured scenarios with peak-to-Compton ratios as low as 1.34–2.97, peak fidelity reaches 7.94 times that of conventional methods, while peak area error is reduced by 17.47%. This model provides a high-precision and robust solution for analyzing complex weak-peak spectra from low-resolution detectors, supporting rapid in-situ identification and quantification of radioactive nuclides.

Keywords: Gamma-ray spectral analysis; Weak-peak extraction; Discrete Wavelet Transform; ResNet; Transformer; Net spectrum prediction; Rapid in-situ measurement; Environmental radiation monitoring

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钇及钇基合金氢化过程中的相转变机制及热力学性质的第一性原理研究

Author: 周楠[1]

Co-authors: 施展泽 [1]; 李翔 [1]; 胡逊祥 [1]; 赵苛衣 [1]; 闫国庆 [2]; 黄贵洋 [1]; 龚模超 [3]

[1] *四川大学物理学院*

[2] *有色金属研究总院*

[3] *江西理工大学稀土学院*

Corresponding Authors: zhounan0202@stu.scu.edu.cn, huxx@scu.edu.cn

摘要: 氢化钇（YHx）因其优异的中子慢化能力和热稳定性，在高温反应堆中具有广阔的应用前景。然而，金属氢化物固有的脆性，以及金属吸氢过程中因氢致相变引发的开裂，使得无裂纹氢化钇的制备面临挑战。微合金化是缓解氢致开裂的有效手段。本研究采用第一性原理计算方法，系统研究了钇基合金中的氢扩散行为、氢致相变及压力-组分-温度（PCT）曲线。结果表明，微合金化提高了氢在钇基合金中的扩散系数，而低浓度掺杂不会阻碍 YHx 沿 {0001}HCP/{111}FCC 路径发生的相结构转变；同时，本研究基于纯计算方法准确描述了钇及钇基合金的 PCT 曲线。

关键词: 氢化钇；第一性原理计算；扩散；相变；PCT

Abstract: Yttrium hydride (YHx) exhibits excellent neutron moderating capability and thermal stability, giving it broad application prospects in high-temperature reactors. However, the inherent brittleness of metal hydrides, along with cracking induced by hydrogen-induced phase transformation during the hydrogen absorption process, poses challenges to the fabrication of crack-free yttrium hydride. Microalloying is an effective approach to mitigate hydrogen-induced cracking. In this study, first-principles calculations were employed to systematically investigate hydrogen diffusion behavior, hydrogen-induced phase transformation, and pressure–composition–temperature (PCT) curves in yttrium-based alloys. The results show that microalloying increases the diffusion coefficient of hydrogen in the yttrium-based alloy, while low-concentration doping does not hinder the phase transformation of YHx along the {0001}HCP/{111}FCC path. Moreover, this study accurately describes the PCT curves of yttrium and yttrium-based alloys using a purely computational approach.

Keywords: Yttrium hydride; first-principles calculations; diffusion; phase transformation; PCT

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基于最速下降法的堆芯物理库子群参数调整方法研究

Author: 陈莹[1]

Co-authors: 温丽丽 [1]; 吴海成 [1]

[1] *中国原子能科学研究院*

Corresponding Author: chenying@ciae.ac.cn

摘要: 反应堆物理计算是核反应堆设计的核心技术之一，其计算精度直接影响反应堆设计可靠性。堆芯物理库为反应堆物理计算提供截面数据、裂变产额和衰变数据，因此堆芯物理库的准确度是保障反应堆物理计算精度的前提。此前中国核数据中心研制了 45 群能群结构的堆芯物理库 TPEX，临界基准检验后发现其预测的 keff 在能谱较硬的铀系统实验中存在系统性低估的现象。为提高 TPEX 库准确度，本课题创新的提出了一种基于逃脱截面的共振积分与子群参数调整方法，建立了基于最速下降法建立了一套自动化共振积分与子群参数调整系统 ADJ_RI 并研制了调整库 TPEX_adj，解决了 TPEX 库的缺陷，为堆芯物理库的工程应用提供数据与技术支撑。

关键词: 堆芯物理；子群参数；调整方法

Abstract: Reactor physics calculation is a core technology in nuclear reactor design, and its computational accuracy directly influences the reliability of the reactor design. The core physics library provides cross-section data, fission yields, and decay data for reactor physics calculations; therefore, the accuracy of the core physics library is a prerequisite for ensuring the precision of reactor physics computations. Previously, the China Nuclear Data Center developed the TPEX core physics library with a 45-group energy structure. Criticality benchmark verification revealed that the predicted effective multiplication factor (keff) in harder-spectrum uranium-fueled systems was systematically underestimated. To enhance the accuracy of the TPEX library, a resonance integral and subgroup parameter adjustment methodology based on escape cross sections is proposed in this study. An automated resonance integral and subgroup parameter adjustment system, designated ADJ_RI, has been established using the steepest descent method, and an adjusted library, TPEX_adj, has been developed. This work resolves the identified deficiencies of the TPEX library and provides essential data and technical support for the engineering application of core physics libraries.

Keywords: Reactor Core Physics; Subgroup Parameters; Adjustment Method

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具有伽利略不变性的含热质量源热-流耦合 MRT 格子 Boltzmann 模型

Author: 宋江川[1]

Co-authors: 桂南 [1]; 姜胜耀 [1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Authors: shengyaojiang@sina.com, guinan@mail.tsinghua.edu.cn, songjc24@mails.tsinghua.edu.cn

摘要: 针对含质量注入/抽吸及其携热效应的复杂热流问题，本文发展了一种具有伽利略不变性的热-流耦合多松弛时间格子 Boltzmann 模型。首先，基于含质量源的连续性方程和动量方程，在 MRT 框架下构造了满足伽利略不变性的质量源项矩空间形式，并通过 Chapman-Enskog 多尺度分析证明该模型能够正确恢复含质量源的 Navier-Stokes 方程。在一维质量源验证中，数值误差随网格加密近似满足 N_LB^(-2) 衰减，并随质量源强度近似满足 q_0^2 关系，表明模型具有二阶空间精度。进一步地，在单组分、常物性、低马赫数弱可压假设下，本文从质量守恒、动量守恒和总能量守恒方程出发，推导了含热质量源的守恒型温度控制方程，并建立了与流场源项一致耦合的温度分布函数 MRT 模型。为保证温度方程在存在体力、空间变热源及背景输运时仍能正确恢复，本文在温度源项一阶矩中引入温度-体力耦合项和速度-源项耦合项修正。数值结果表明，所提出模型能够有效消除参考系平移引起的非物理振荡和各向异性误差条纹，在移动质量源算例中全局相对误差保持在 10^(-6) 量级以内，相比未修正模型降低约两个数量级；在高波数质量源稳定性测试中，可承受的质量源扰动幅值超过传统 SRT 模型的 3 倍；在全局压力调控算例中，平均压力的相对误差低于 10^(-13) 量级。对于含热质量源的二维制造解算例，u_x、u_y 和 T 的观测收敛阶分别约为 2.08、1.87 和 2.10，密度扰动收敛阶约为 2.48，验证了模型对质量源、动量交换和热源项耦合效应的近二阶恢复能力。本文工作为相变传热、反应流、注入/抽吸流动及压力调控等含质量与能量交换问题提供了一种统一、稳定且物理一致的格子 Boltzmann 建模方法

关键词: 格子 Boltzmann 方法；多松弛时间模型；质量源；热质量源；伽利略不变性；热-流耦合；二阶精度

Abstract: A Galilean-invariant thermal-flow coupled multiple-relaxation-time lattice Boltzmann model is developed for complex flows involving mass injection/suction and the associated heat transport. First, based on the continuity and momentum equations with a mass source, a Galilean-invariant mass-source formulation is constructed in moment space within the MRT framework. Chapman-Enskog multiscale analysis demonstrates that the proposed formulation correctly recovers the Navier-Stokes equations with mass source terms. In the one-dimensional benchmark test, the numerical error decreases approximately as N_LB^(-2) under grid refinement and scales approximately with q_0^2with respect to the source strength, confirming the second-order spatial accuracy of the model. The formulation is then extended to thermally coupled mass-source flows. Under the assumptions of a single-component fluid, constant properties, and low-Mach-number weak compressibility, a conservative temperature equation

with a heated mass source is derived from the conservation laws of mass, momentum, and total energy. A corresponding MRT lattice Boltzmann model for the temperature field is established and consistently coupled with the flow-field source formulation. To ensure the correct recovery of the target temperature equation in the presence of body forces, spatially varying heat sources, and background advection, two correction terms are introduced into the first-order moments of the thermal source term, namely the temperature-force coupling term and the velocity-source coupling term. Numerical results show that the proposed model effectively eliminates non-physical oscillations and anisotropic error stripes induced by reference-frame translation. In moving mass-source tests, the global relative error remains at or below the order of 10^(-6), corresponding to an approximately two-order-of-magnitude reduction compared with the uncorrected model. In high-wavenumber mass-source stability tests, the tolerable amplitude of mass-source perturbations is more than three times that of the conventional SRT model. In the global pressure-regulation test, the relative error of the average pressure remains below the order of 10^(-13). For the two-dimensional manufactured solution with heated mass sources, the observed convergence orders of u_x, u_y, and Tare approximately 2.08, 1.87, and 2.10, respectively, while the perturbation-based density error gives an observed order of approximately 2.48. These results demonstrate the nearly second-order recovery capability of the proposed model for coupled mass-source, momentum-exchange, and heat-source effects. The present work provides a unified, stable, and physically consistent lattice Boltzmann framework for thermally coupled flows with mass and energy exchange, such as phase-change heat transfer, reactive flows, injection/suction flows, and pressure-regulation problems.

Keywords: Lattice Boltzmann method; multiple-relaxation-time model; mass source; heated mass source; Galilean invariance; thermal-flow coupling; second-order accuracy

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先进小型一体化全自然循环压水堆关键安全特性整体性能试验研究

Authors: 曹克美[1]; 胡培政[1]; 杨江子[1]; 戚展飞[1]; 任文星[1]; 刘镝[1]

[1] *上海核工程研究设计院股份有限公司*

Corresponding Author: sloppyman@163.com

摘要: 针对国家电投集团开发的先进小型一体化全自然循环压水堆（供热堆），为满足安全审评对整体性能试验的验证要求，本文介绍基于多级双层比例分析方法（H2TS）设计建造的整体性能试验台架及典型工况试验。该台架在几何布置、系统配置及专设安全设施方面与原型堆保持高度一致，能够准确表征反应堆的热工水力现象。本文选取了典型设计基准工况开展试验研究。结果表明：在稳压器顶部破口（LOCA）工况下，非能动应急堆芯冷却系统（JNG）能够按预设逻辑自动触发，自动卸压与直接注射的协同动作，确保了堆芯在整个事故进程中处于淹没状态，有效缓解了事故后果；在丧失三回路热阱（非 LOCA）工况下，非能动二次侧余热排出系统（NCR）能够及时投入并建立稳定的自然循环，有效导出堆芯衰变热，防止系统超压。试验数据充分验证了供热堆专设安全系统容量配置的充裕性及事故缓解逻辑的正确性，为该类反应堆的安全审评提供了关键的试验依据。

关键词: 一体化全自然循环；小堆；非能动安全；整体性能试验；安全特性验证

Abstract: This paper presents an integral effect test facility designed and constructed based on the Hierarchical Two-Tiered Scaling (H2TS) methodology to meet the verification requirements for the integral performance test of an advanced small modular integral pressurized water reactor (heating reactor) developed by SPIC. The test facility maintains high fidelity to the prototype in geometric configuration, system layout, and engineered safety features, enabling accurate simulation of its key thermal-hydraulic phenomena. Experimental studies on typical design-basis conditions were carried out. The results demonstrate that: (1) For a pressurizer top LOCA, the passive Emergency Core Cooling System (JNG) is automatically activated as designed; the coordinated operation of the Automatic Depressurization System and the Direct Vessel Injection system ensures core submergence throughout the transient, effectively mitigating the accident consequences. (2) For a loss of tertiary heat sink accident (non-LOCA), the Passive Residual Heat Removal system (PRHRS) engages promptly and establishes stable natural circulation, successfully removing core decay heat and preventing system overpressure. The test data

fully validate the sufficient capacity of the reactor’s engineered safety systems and the correctness of the accident mitigation logic, providing essential experimental evidence for the safety review of this reactor type.

Keywords: Integral full natural circulation; Small Modular Reactor (SMR); Passive safety; Integral effect test; Safety characteristic validation

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球床式高温气冷堆一回路硼酸类物质研究

Author: 聂瑞[1]

Co-authors: 刘学刚 [1]; 魏利强 [1]; 张乃哲 [1]; 董玉杰 [1]; 曹建主 [1]; 谢锋 [1]

[1] *清华大学*

Corresponding Authors: weilq@tsinghua.edu.cn, liu-xg@tsinghua.edu.cn, caojz@tsinghua.edu.cn, dongyj@tsinghua.edu.cn, znz23@mails.tsinghua.edu.cn, nier25@mails.tsinghua.edu.cn, fxie@tsinghua.edu.cn

摘要: 高温气冷堆一回路冷却剂化学环境复杂，杂质的来源、形态及沉积行为对系统运行可靠性与安全监测具有重要影响。本文针对 HTR-10 尘埃过滤器中发现的白色结晶沉积物开展了物相鉴定与成因分析。采用 X 射线衍射、拉曼光谱和傅里叶变换红外光谱对样品进行了表征，结果表明该沉积物主要由 $NH_4B_5O_8·4H_2O$、$(NH_4)_3[B_{15}O_{20}(OH)_8]·4H_2O$ 和 H_3BO_3 组成，通过 SEM 观察了沉积物的形貌，通过 EDS 和 ICP-MS 分析了 B 含量，并通过 STA 对晶体的热行为进行测试。结合 HTR-10 的结构特征与运行条件分析，推测沉积物中的硼主要来源于堆芯含硼碳砖，而铵根则可能与二回路联胺或其分解产物经微量跨壁迁移进入一回路有关。研究首次在高温气冷堆一回路中识别出硼酸类沉积物，揭示了一回路中含硼杂质迁移转化与沉积的新现象，可为异常化学过程识别、杂质来源追踪以及冷却剂化学监测与净化策略优化提供参考。

关键词: 高温气冷堆、硼酸、腐蚀、结构表征

Abstract: The primary-circuit coolant chemistry of high-temperature gas-cooled reactors is highly complex, and the sources, chemical states, and deposition behavior of impurities are of great importance to system reliability and safety monitoring. In this study, the white crystalline deposits found in the HTR-10 dust filter were investigated through phase identification and formation mechanism analysis. The samples were characterized by X-ray diffraction, Raman spectroscopy, and Fourier transform infrared spectroscopy. The results showed that the deposits were mainly composed of $NH_4B_5O_8·4H_2O$, $(NH_4)_3[B_{15}O_{20}(OH)_8]·4H_2O$, and H_3BO_3. The morphology of the deposits was observed by SEM, the boron content was analyzed by EDS and ICP-MS, and the thermal behavior of the crystals was examined by STA. Based on the structural characteristics and operating conditions of HTR-10, it is inferred that the boron in the deposits mainly originated from the boron-containing carbon bricks in the core, while the ammonium species were likely related to trace migration of hydrazine or its decomposition products from the secondary circuit into the primary circuit through micro-leakage across the heat-transfer boundary. This study reports for the first time the identification of borate deposits in the primary circuit of a high-temperature gas-cooled reactor, revealing a new phenomenon involving the migration, transformation, and deposition of boron-containing impurities in the primary circuit. The findings can provide reference for the identification of abnormal chemical processes, impurity source tracing, and the optimization of coolant chemistry monitoring and purification strategies.

Keywords: High-temperature gas-cooled reactor; boric acid; corrosion; structural characterization

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先进反应堆风险指引的堆型评价方法

Author: 雷蕾[1]

[1] *核能与新能源技术研究院*

Corresponding Author: leileisjtu@qq.com

摘要: 当前我国先进反应堆技术发展活跃，涉及铅铋快堆、钠冷快堆、高温气冷堆、溶液堆、熔盐堆等不同堆型，采用多样化冷却剂，可用于多种应用场景。一直以来，我国先进反应堆的安全评价主要参考了引进国同堆型的既有内容，未能形成系统化的开发方法。一方面，现行核安全监管框架及评价方法主要以确定论为基础，适用对象为传统水冷反应堆，不能完全反映和适应先进反应堆的设计特征，对核安全监管带来挑战。另一方面，缺少系统性的与先进堆安全特点相适应的评价方法，制约了新技术的发展和工程落地。目前，国家核安全局正在探索与当前核能发展形势相适应的堆型评价方法，针对先进反应堆积极推动风险指引的方法应用。近年来，美国应对新型堆发展的需要，开展了风险指引基于性能（RIPB）的方法论研究，通过许可基准事件选取和评估、构筑物系统和设备安全功能识别、纵深防御充分性评估等工作，采用可预期的方法在概要性问题上达成共识。本报告参考美国 RIPB 的分析方法，结合我国核安全监管形势研究了风险指引的先进反应堆堆型评价方法，包括风险指引的设计基准选取方法，风险指引的构筑物系统和设备安全功能分级，先进堆关键设计承诺研究，并拟就典型先进堆开展案例研究，为我国先进反应堆的堆型评价提供参考。

关键词: 堆型评价；设计基准；风险指引；基于性能；设计基准事故；许可基准事故；关键设计承诺；先进反应堆。

Abstract: Currently, the development of advanced reactor technology in China is thriving, encompassing various reactor types such as lead-bismuth fast reactors, sodium-cooled fast reactors, high-temperature gas-cooled reactors, liquid-cooled reactors and molten salt reactors, which utilise diverse coolants and can be applied in a wide range of scenarios. Historically, safety assessments of advanced reactors in China have primarily relied on existing content from the countries of origin for the same reactor types, failing to establish a systematic development methodology. On the one hand, the current nuclear safety regulatory framework and assessment methods are predominantly based on deterministic approaches, designed for conventional water-cooled reactors; consequently, they cannot fully reflect or adapt to the design characteristics of advanced reactors, posing challenges for nuclear safety regulation. On the other hand, the absence of systematic assessment methods tailored to the safety characteristics of advanced reactors has constrained the development of new technologies and their engineering implementation. Currently, the National Nuclear Safety Administration is exploring reactor evaluation methods suited to the current nuclear energy development landscape, and is actively promoting the application of risk-informed approaches for advanced reactors. In recent years, in response to the development of new reactor types, the United States has conducted methodological research on Risk-Informed Performance-Based (RIPB) approaches. Through the selection and assessment of licence-defining events, the identification of safety functions in building systems and equipment, and the evaluation of the adequacy of defence-in-depth, a consensus has been reached on overarching issues using a predictable methodology. This research report draws upon the analytical methods of the US RIPB and, in light of China's nuclear safety regulatory context, examines risk-informed evaluation methods for advanced reactor designs. This includes the selection of design bases for risk-informed approaches, the classification of safety functions for building systems and equipment, and the study of key design commitments for advanced reactors. Furthermore, the report proposes case studies on typical advanced reactors to provide a reference for the evaluation of advanced reactor designs in China.

Keywords: Reactor Design Review; Design Basis; Risk-informed; Performance-based; Design Basis Accident; Licensing Basis Accident; Key Design Commitments; Advanced Reactors.

Chapter 3

环、化、材、技、能源战略

限域插层调控范德华层状材料的超导性及涌现量子物态

Author: 吴俊杰[1]

[1] *中国科学技术大学*

Corresponding Author: junjiewu@mail.ustc.edu.cn

摘要: 我们以过渡金属硫族化合物为研究体系，聚焦层间限域客体插层对其磁电物性的精准调控，系统探索原子排布、能带结构及有机-无机客体空间构型的协同调控机制。围绕决定磁电性能的核心自由度—电荷、自旋、轨道与晶格，通过对客体种类、构型、分布及浓度的原子级调控，诱导出伊辛超导、量子相变等新奇物性。结合原子分辨的结构与电子态表征手段，建立起"结构-物性"定量关联，并揭示了器件界面电子态调制的微观机制。例如，通过有机/无机分子或离子限域插层，有效解耦范德华层间，使块体展现出单层结构特有的伊辛超导物性；首次在钽-硫基材料体系中观察到量子格里菲斯奇异性；衍生铁磁序和超导态共存；潜在拓扑超导体的发现等。

关键词: 量子材料；超晶格；伊辛超导；拓扑超导

Abstract: This study employs transition metal chalcogenides as a research platform to precisely modulate their magnetoelectric properties via interlayer-confined guest intercalation. We systematically investigate the synergistic regulation mechanisms governing the atomic arrangement, band structure, and spatial configuration of organic–inorganic guests. By targeting the core degrees of freedom that control magnetoelectric performance—charge, spin, orbital, and lattice—we implement atomic-scale control over guest species, configuration, distribution, and concentration to induce emergent physical phenomena such as Ising superconductivity and quantum phase transitions. Combined with atomic-resolved structural and electronic characterization techniques, we establish quantitative structure–property relationships and elucidate the microscopic mechanisms underlying interfacial electronic state modulation in devices. For instance, confined intercalation of organic/inorganic molecules or ions effectively decouples van der Waals interlayer interactions, enabling bulk crystals to exhibit Ising superconducting behavior characteristic of monolayer structures. The quantum Griffiths singularity is observed for the first time in tantalum–sulfur-based materials. The coexistence of emergent ferromagnetic order and superconductivity is realized, and topological superconductor candidates are identified in these systems.

Keywords: Quantum materials; Superlattice; Ising superconductivity; Topological superconductivity

Robust Ga2O3 Memristor with Sharp Stable Negative Differential Resistance for Energy Efficient Reliable Analog Resistive Switching and Artificial Synapse Applications

Author: 粟兴莉[1]

[1] *四川大学物理学院*

Corresponding Author: 1822500028@qq.com

摘要: 如今，忆阻器主要依赖外部电路来管理功耗，尤其是在高电场下，这增加了系统复杂性并降低了能效。为解决这一问题，人们希望实现具有内在限流机制的忆阻器，使其能够在高电场下高效工作。在此，我们展示了一种稳健的掺锡 β-氧化镓（β-Ga2O3）忆阻器，该忆阻器在毫伏（MV）级别展现出显著的负微分电阻（NDR）效应，能够有效自我限制过冲电流。NDR 效应与电阻切换特性的共存归因于氧空位的可逆迁移和肖特基势垒的动态调制。重要的是，该忆阻器在已报道的同类产品中展现了创纪录的 NDR 性能指标，包括高达 3.55 的最陡峭斜率和长达 103 个周期和 104 秒的最长耐久性。此外，该忆阻器还表现出典型的模拟电阻切换和基本的人工突触行为。在高电场下最陡峭且最稳定的 NDR 效应的辅助下，这种稳健的 Ga2O3 忆阻器为高性能、节能的多功能应用提供了一个有前景的平台。

关键词: β-Ga2O3、负微分电阻、节能、模拟电阻切换、人工突触

Abstract: Nowadays, memristors mainly rely on external circuits to manage power consumption, especially under high electric fields,which increases system complexity and reduces
energy efficiency. To solve this problem, it is desirable to achieve memristors with an intrinsic current-limiting mechanism that can energy-efficiently work under high electricfields. Here,we demonstrate a robust Sn-doped β-Ga2O3 memristor that exhibits aprominent negative differential resistance(NDR) effectat the MVm−1 level, which enables effective self-limiting of over shoot current.The coexistence of the NDR and resistive switching characteristics is attributed to the reversible migration of oxygen vacancies and dynamic modulation of the Schottky barrier. Importantly, thememristor demonstrates record breaking NDR performance metrics, including the sharpest slope up to 3.55 and the longest endurance up to 103 cycles and 104 seconds, among the reported ones.Furthermore, the memristor exhibits typical an alog resistive switching and essential artificial synapse behaviors. Assisted with the sharpest and stablest NDR effect under high electricfield, the robust Ga2O3 memristor offers apromising plat form toward high-performance energy-efficient multifunctional applications.

Keywords: β-Ga2O3, negative differential resistance, energy efficient, analog resistive switching, artificial synapse

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未来气候条件下基于数据驱动预测的净零电力系统充裕性评估

Authors: 吕晋宁[1]; 陈文颖[1]

[1] *清华大学*

Corresponding Authors: lvjn24@mails.tsinghua.edu.cn, chenwy@tsinghua.edu.cn

摘要: 随着全球能源系统向碳中和转型，可再生能源发电波动性的不断增强以及负荷对气候变化的敏感性上升，正对净零电力系统的充裕性带来重大挑战。然而，现有评估通常缺乏一种能够在未来气候条件下，同时刻画高时空分辨率长期负荷变化以及输电与储能约束的分析框架。为此，本研究构建了一个综合评估框架，通过耦合高分辨率负荷预测与电力系统模拟，对净零电力系统的充裕性进行评估。首先，我们为中国开发了一个基于神经网络的小时电力负荷模型（HELM），用于预测不同社会经济与气候情景下的省级电力负荷。随后，将预测结果嵌入一个覆盖 30 个省份、8760 小时的模拟模型中，在每种碳中和转型情景下，通过超过 300 组跨省输电与储能配置方案评估系统运行表现。结果表明，到 2060 年，全国电力需求将达到 23262.59 TWh，夏季峰值负荷将达到 3234 GW，显示出未来电力系统在负荷波动加剧和峰值负荷攀升方面面临的挑战。在以风

电和光伏为主导的电力系统中，显著的时空错配将导致最高达 59.54% 的潜在电力短缺。针对性扩张输电和储能可有效缓解这些缺口，使全国系统充裕性提高 16.25%，并在浙江等受电省份实现超过 50% 的提升。这些发现通过强调跨省基础设施、灵活性资源和市场化支持机制的协同发展，为中国能源转型提供了战略性路线图。

关键词: 净零电力系统，电力负荷预测，机器学习，系统充裕性，跨省电力传输，储能

Abstract: As global energy systems transition toward carbon neutrality, the increasing variability of renewable generation and climate-sensitive load poses significant challenges to net-zero power system adequacy. However, current assessments often lack a framework that captures high-resolution, long-term load dynamics alongside transmission and storage constraints under future climate conditions. This study constructs an integrated assessment framework to evaluate the adequacy of a net-zero power system by coupling high-resolution load forecasting with power system simulations. We first developed a neural network-based Hourly Electricity Load Model (HELM) for China to forecast provincial load under diverse socioeconomic and climate scenarios. These forecasts were then integrated into an 8760-hour simulation model encompassing 30 provinces to assess system performance under more than 300 configurations of interprovincial transmission and energy storage for each carbon-neutral transition scenario. Results show that national electricity demand will reach 23262.59 TWh in 2060, with a summer peak of 3234 GW, revealing the challenges ahead in demand volatility and rising peak loads. In a power system dominated by wind and solar power, substantial spatiotemporal mismatches lead to potential electricity deficits of up to 59.54%. Targeted expansion of transmission and storage can mitigate these gaps, enhancing national system adequacy by 16.25% and exceeding 50% in power-importing provinces such as Zhejiang. These findings provide a strategic roadmap for China’s energy transition by emphasizing the coordinated development of interprovincial infrastructure, flexible resources, and market-based support mechanisms.

Keywords: Net-zero power system, Electricity load forecasting, Machine learning, System adequacy, Interprovincial transmission, Energy storage

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过冷液体非线性流变学与动力学的理论与模拟研究

Author: 曾轲祺[1]

[1] *清华大学工程物理系*

Corresponding Author: 362441662@qq.com

摘要: 过冷液体表现出复杂的动力学行为：在微观层面，其动力学特质在空间上是不均匀的，即所谓的动态不均匀性。在宏观层面，其剪切粘度随剪切速率的增加而呈幂律下降，即所谓的剪切变稀。然而两者之间的具体关联尚不明确。通过在二维、三维中几类不同体系进行模拟分析，我们发现剪切变稀与动态不均匀可以通过局部弹性来定量地联系起来，这种局部弹性体现为对剪切产生弹性响应的瞬态团簇。当这些团簇发生大规模屈服后，紧接着就会出现动态不均匀性，其由剪切转变去引发，并由弹性介导的相互作用促进。基于这一物理图景，我们找到了一个将剪切变稀与动态不均匀性的特征长度联系起来的标度关系。

关键词: 过冷液体；动态不均匀；剪切变稀；分子模拟

Abstract: Supercooled liquids exhibit complicated dynamical behaviors: At the microscopic level, the dynamics is heterogeneous spatially, known as dynamic heterogeneity. At the macroscopic level, the shear viscosity decreases as shear rate increases with a power law, known as shear thinning. The relation between these two universal dynamical phenomena remains elusive. With simulations of several model liquids in two and three dimensions, we show that they are quantitatively bridged by localized elasticity embodied as transient clusters that elastically respond to shear. Prominent dynamic heterogeneity emerges right after the massive yielding of these clusters, which is initiated by shear transformation zones and facilitated by elasticity-mediated interaction. With this picture, a scaling law relating shear thinning to the characteristic length of dynamic heterogeneity is found.

Keywords: supercooled liquids; dynamical heterogeneity; shear thinning; molecular simulation

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从表观熔合线到真实熔合区：F91/ERNiCr-3 堆焊界面分区及 PMZ 高温风险

Authors: 胡梦佳[1]; 雒晓卫[1]

Co-author: 罗温伟 [1]

[1] *清华大学核能与新能源技术研究院 104 室*

Corresponding Author: luoww23@mails.tsinghua.edu.cn

摘要: F91/ERNiCr-3 异种金属堆焊界面存在显著的成分、组织、相结构及热物理性能梯度，是接头高温服役过程中的潜在薄弱区域。从微观尺度看，该界面并非单一几何线，而是具有一定空间尺度的熔合区或成分过渡区。其中，真实熔合线代表熔合区最靠近未熔化 F91 母材一侧的边界，是界定界面热历史、冶金分区及碳迁移行为的重要空间基准。然而，现有研究通常依据金相腐蚀或电解抛光后观察到的表观界面标定熔合线，其是否等同于真实熔化边界仍缺乏验证。
本研究结合 $FeCl_3$ 腐蚀、电解抛光、硬度坑空间标记、EDS、EBSD、JMatPro 计算和高温原位实验，分析了 F91/ERNiCr-3 堆焊界面的宏观偏析特征、真实熔合线位置及 PMZ 高温相稳定性。结果表明，TIG 堆焊界面并非均匀单一结构，而主要由无 PMZ 的普通界面和含 PMZ 的宏观偏析界面组成，二者沿界面长度占比分别约为 24.2% 和 75.8%。$FeCl_3$ 腐蚀界面主要反映腐蚀响应差异，电解抛光界面主要对应 bcc/fcc 相界，二者均不应直接等同于真实熔合线。
通过硬度坑定位、EBSD 晶粒形貌和 EDS 的 Ni 分布的联合分析发现，真实熔合线位于传统腐蚀界面更靠近 F91 母材的一侧，并揭示了 CGHAZ 与 PMZ/TZ 之间常被忽略的 F91 UMZ。该区域具有凝固组织特征，其形成源于熔池边界层混合不足。进一步研究表明，PMZ 虽在室温下保持 bcc 结构，但因 Ni 渗入导致 Ac1 降低至约 300–400 ℃，低于典型服役温度 541℃，并在高温原位实验中观察到疑似固态相变行为。该研究澄清了表观腐蚀界面、相界和真实熔合边界之间的差异，为 F91/镍基焊材异种金属接头界面组织识别、碳迁移分析、高温铁素体残留机制解释及服役风险评估提供了更准确的冶金依据。

关键词: 异种金属焊接、熔合线、界面宏观偏析、部分混合区

Abstract: F91/ERNiCr-3 dissimilar metal buttering interfaces exhibit pronounced gradients in composition, microstructure, phase constitution, and thermophysical properties, making them potential weak regions during high-temperature service. At the microscale, such an interface should not be regarded as a geometrically sharp line, but rather as a fusion region or compositional transition zone with a finite spatial extent. The true fusion line, defined as the boundary of this region closest to the unmelted F91 base metal, provides an essential spatial reference for interpreting the interfacial thermal history, metallurgical zoning, and carbon-migration behaviour. However, in previous studies, the fusion line has commonly been identified from the apparent boundary revealed by metallographic etching or electropolishing, although whether this boundary truly corresponds to the actual melting boundary remains insufficiently verified.
In this study, $FeCl_3$ etching, electropolishing, microhardness-indent spatial marking, EDS, EBSD, JMatPro calculations, and in-situ high-temperature observation were combined to investigate interfacial macrosegregation, the location of the true fusion line, and the high-temperature phase stability of the partially mixed zone (PMZ) in F91/ERNiCr-3 TIG buttering. The results show that the TIG-buttered interface is not a uniform single structure, but mainly consists of PMZ-free ordinary interface segments and PMZ-containing macrosegregated interface segments, which account for approximately 24.2% and 75.8% of the interfacial length, respectively. The boundary revealed by $FeCl_3$ etching mainly reflects differences in corrosion response, whereas the boundary observed after electropolishing primarily corresponds to the bcc/fcc phase boundary. Therefore, neither boundary should be directly equated with the true fusion line.
By correlating microhardness-indent markers with EBSD grain morphology and EDS Ni distributions, the true fusion boundary was found to lie on the F91 base-metal side of the conventionally etched boundary. This finding further reveals a previously overlooked F91 unmixed zone (UMZ) between the CGHAZ and the PMZ/TZ. This zone exhibits solidification-related microstructural features, and its formation can be attributed to insufficient mixing within the molten-pool boundary layer. Further analysis

indicates that, although the PMZ retains a bcc structure at room temperature, local Ni enrichment lowers its Ac1 temperature to approximately 300–400 ℃, below the typical service temperature of 541 ℃. In-situ high-temperature observation also revealed microstructural changes indicative of possible solid-state transformation. This study clarifies the differences among the apparent etched boundary, the phase boundary, and the true fusion line, providing a more accurate metallurgical basis for interfacial microstructure identification, carbon-migration analysis, interpretation of retained high-temperature ferrite, and service-risk assessment of F91/Ni-filler dissimilar metal joints.

Keywords: Dissimilar metal welding, Fusion line, Interfacial macrosegregation, Partially mixed zone (PMZ)

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建筑需求侧转型如何缓解中国深度脱碳中的能源、材料与土地约束

Author: 吴紫琪[1]

[1] *清华大学*

Corresponding Author: wu-zq24@mails.tsinghua.edu.cn

摘要: 在全球气候变化背景下，以可再生能源扩张和终端电气化为核心的供给侧脱碳路径正逐渐受到关键矿产、土地空间及生态承载能力等资源约束的限制，使气候问题从“碳排放约束”转向“资源与系统规模约束”。在此背景下，需求侧转型被重新审视为实现深度脱碳的重要路径。尤其在中国，建筑部门正处于存量快速累积与集中更新并存的关键阶段，其规模与使用方式将长期锁定能源与材料需求。然而，现有研究多将需求侧简化为能效提升或减排潜力，缺乏对其如何通过跨部门传导重塑供给侧扩张路径及资源约束的系统性分析。本文构建建筑存量物质流模型（MFA）与能源系统优化模型（China-More 3.0）的顺序耦合框架，从“需求—系统规模—资源约束”的链条出发，系统评估建筑需求侧转型的宏观影响。结果表明，建筑需求侧转型在 2022–2060 年间可累计减排约 37 Gt CO_2-eq，其中相当部分来源于通过控制建筑存量规模与优化空间利用所带来的需求收缩效应。在温室气体中和约束下，需求侧协同路径通过压缩终端能源需求，从源头降低系统规模，使 2060 年电力装机需求减少约 23%（约 2.3 TW），并显著缓解钢铁、水泥等难减排行业的转型压力。同时，需求侧转型通过避免供给侧扩张，在关键矿产、土地占用及系统成本等方面产生系统性资源缓解效应。总体而言，建筑需求侧转型的核心作用在于通过改变服务提供方式，从源头决定能源与材料系统规模，从而避免供给侧扩张并释放资源约束压力。这一机制为资源约束趋紧背景下实现深度脱碳提供了新的系统性路径。

关键词: 建筑部门；需求侧转型；深度脱碳；物质流；能源系统优化

Abstract: In the context of global climate change, supply-side decarbonization pathways centered on renewable energy expansion and electrification are increasingly constrained by critical minerals, land availability, and ecological limits. As a result, the climate challenge is shifting from carbon mitigation alone to one shaped by resource availability and system scale. Demand-side transformation has therefore emerged as a critical but underexplored pathway for deep decarbonization. This is particularly important for China, where rapid building stock accumulation and large-scale renewal create a crucial window for shaping long-term energy and material demand. However, existing studies largely reduce demand-side interventions to efficiency improvements, overlooking their role in reshaping system-scale dynamics and resource constraints. Here, we develop a sequentially coupled framework integrating a building stock-based Material Flow Analysis (MFA) model with an energy system optimization model (China-More 3.0) to assess demand-side transformation along the chain of demand, system scale, and resource constraints. We find that building demand-side transformation can deliver approximately 37 Gt CO_2-equivalent cumulative emission reductions over 2022–2060, with a substantial share arising from demand reduction effects rather than efficiency improvements alone. By reducing final energy demand at the source, demand-side transformation fundamentally reshapes decarbonization pathways, lowering power system capacity requirements by about 23% (2.3 TW) by 2060 and alleviating transition pressures in hard-to-abate sectors such as steel and cement. Importantly, demand-side transformation generates systemic benefits by avoiding supply-side expansion. It reduces critical mineral demand, mitigates land use pressures by avoiding 17,800–32,500 km^2 of renewable energy deployment, and yields cumulative

net system savings of approximately 9 trillion RMB. Overall, the primary value of demand-side transformation lies not only in emissions reduction, but in its ability to determine system scale by altering service provision, thereby alleviating multiple resource constraints simultaneously. These findings highlight the importance of shifting from supply-driven decarbonization strategies toward system-level approaches in which demand plays a central role.

Keywords: Building sector; Demand-side transformation; Deep decarbonization; Material flow analysis; Energy system optimization

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T91 钢辐照损伤与动态铅铋腐蚀耦合行为研究

Author: 杨凌峰[1]

Co-authors: 管琦 [1]; 朱卉平 [1]; 牛雷风 [1]

[1] *华北电力大学*

Corresponding Authors: fanbuqie717499@163.com, 2093822820@qq.com, zhuhuiping@ncepu.edu.cn, niufenglei@ncepu.edu.cn

摘要: T91 铁素体/马氏体钢因其良好的高温强度、导热性能和抗辐照肿胀能力，被认为是铅冷快堆包壳及堆内结构件的重要候选材料之一。然而，在实际服役环境下，T91 不仅要承受高温流动铅铋共晶（LBE）引起的持续腐蚀，还将同步积累辐照诱导位移损伤及气体相关缺陷，因此其服役行为本质上受“辐照损伤—保护层形成—动态腐蚀失稳”共同控制。围绕这一问题，本工作结合 T91 在动态高氧 LBE 中的腐蚀行为与 He 预注入后 Fe 自离子辐照的损伤演化结果，构建其在铅冷快堆相关条件下的结构演化与性能退化认识。

在动态腐蚀方面，T91 在 500 ℃、饱和氧浓度和 3 m/s 动态 LBE 条件下表现出典型的分层氧化特征。1000 h 时表面形成粗糙且不均匀的颗粒状腐蚀产物层，截面总厚度约为 14–19 μm；到 2000 h，腐蚀层增厚至约 21–30 μm，表面背景趋于细化和均匀；至 3000 h，总厚度约为 24–30 μm，净增厚速率明显放缓，但表面三维起伏和方向性失稳显著增强。结合截面 EDS 与 XRD 可知，腐蚀层由外层富铁氧化物和内层富铬氧化层共同构成，表面主导相属于磁铁矿/尖晶石。这说明 T91 在动态高氧 LBE 中并非简单经历氧化层持续增厚，而是在后期进入了外层氧化物生长、剥落与再生并存的竞争阶段。

在辐照损伤方面，T91 在 450 ℃ 下经 2000 或 6000 appm He 预注入后，再接受 3.25 MeV Fe 自离子辐照。结果表明，He 预注入显著改变了后续缺陷演化行为：随着预注入 He 浓度由 2000 appm 提高至 6000 appm，He 泡平均尺寸由约 3.42 nm 降至约 2.91 nm，而数密度由约 0.71x1023m-3 增加至 2.42x1023m-3，提升约 3.4 倍；同时，位错环密度相较 Fe-only 条件提高近一个数量级，且高 He 条件下大量形成环泡复合体。纳米压痕结果显示硬化行为具有明显非单调性：在 100–200 nm 深度范围内，Fe-only、Fe+2000 appm He 和 Fe+6000 appm He 条件下的相对硬化增量分别约为 207.2%、187.9% 和 263.8%，即中等 He 水平下硬化略低于 Fe-only，而高 He 水平下硬化最强。该结果说明，中等 He 含量下 He-V 团簇和稀疏气泡主要作为空位陷阱，削弱了位错环主导的硬化；而高 He 条件下，致密纳米气泡与环泡复合体共同构成更强障碍场，从而显著增强辐照硬化。

综合来看，动态高氧 LBE 决定了 T91 表层保护层的形成、分层与后期失稳方式，而 He 泡、位错环及其复合缺陷则改变了近表层扩散条件、缺陷俘获能力和局部力学响应，进而可能影响氧化膜的早期建立与后期稳定性。尽管当前辐照实验采用的是 He 预注入—Fe 自离子辐照路径，但其揭示的“缺陷结构转变—障碍场重构—力学响应变化”规律，对于理解铅冷快堆条件下 T91 的辐照-腐蚀耦合行为具有重要启发意义，也为后续开展“预辐照后短时动态腐蚀”研究提供了基础。

关键词: T91 钢；铅冷快堆；动态腐蚀；辐照硬化

Abstract: T91 ferritic/martensitic steel is regarded as one of the most important candidate structural materials for lead-cooled fast reactors because of its good high-temperature strength, thermal conductivity, and resistance to irradiation swelling. Under actual service conditions, however, T91 is subjected not only to continuous corrosion in flowing lead-bismuth eutectic (LBE), but also to irradiation-induced displacement damage and gas-related defects. Therefore, its long-term performance should be understood from the combined effects of irradiation damage, oxide-scale evolution, and dynamic corrosion instability rather than from corrosion or irradiation alone.

In this work, the dynamic corrosion behavior of T91 in oxygen-saturated flowing LBE and the microstructural evolution induced by sequential helium implantation and Fe self-ion irradiation were jointly considered in order to establish an integrated understanding of T91 degradation under lead-cooled fast reactor-relevant conditions. Under dynamic LBE corrosion at 500 ℃, saturated oxygen concentration, and 3 m/s, T91 exhibited a typical layered oxidation structure. After 1000 h, a rough and non-uniform corrosion layer had already formed on the surface, with a total thickness of about 14-19 μm. After 2000 h, the corrosion layer thickened to about 21-30 μm, while the surface background became relatively finer and more uniform. At 3000 h, the total thickness remained in the range of about 24-30 μm, indicating that the net thickening rate had markedly decreased. Nevertheless, three-dimensional surface topography revealed a pronounced increase in height fluctuation and directional instability at the late stage. Combined cross-sectional EDS and XRD analyses showed that the corrosion scale consisted of an Fe-rich outer oxide and a Cr-enriched inner oxide, and that the dominant surface phases belonged to the magnetite/spinel family. These results indicate that the late-stage corrosion behavior of T91 in flowing oxygen-saturated LBE is no longer governed by simple oxide thickening, but rather by a competition between oxide growth and outer-layer degradation, exfoliation, and regeneration.
To characterize the irradiation-induced near-surface defect state, T91 was pre-implanted with 2000 or 6000 appm He at 450 ℃, followed by 3.25 MeV Fe self-ion irradiation. The results showed that helium pre-implantation significantly altered the subsequent defect evolution. When the He content increased from 2000 to 6000 appm, the average bubble diameter decreased from about 3.42 nm to about 2.91 nm, whereas the bubble number density increased from about 0.71 × 1023 m-3 to about 2.42 × 1023 m-3, i.e., by a factor of about 3.4. Meanwhile, the dislocation-loop density increased by nearly one order of magnitude compared with the Fe-only condition, and abundant bubble-loop complexes were formed in the high-He sample. Nanoindentation measurements further revealed a non-monotonic hardening response. In the 100-200 nm depth range, the normalized hardness increments for the Fe-only, Fe + 2000 appm He, and Fe + 6000 appm He conditions were about 207.2%, 187.9%, and 263.8%, respectively, meaning that the 2000 appm He sample was slightly softer than the Fe-only sample, whereas the 6000 appm He sample exhibited the strongest hardening. This behavior suggests that, at a moderate helium level, He-V clusters and sparse bubbles mainly act as vacancy traps and mitigate loop-controlled hardening, whereas at a high helium level, dense nanoscale bubbles and bubble-loop complexes become the dominant obstacle field and significantly enhance irradiation hardening.
Taken together, the present results suggest that the service degradation of T91 under lead-cooled fast reactor-relevant conditions should be interpreted through the coupling of two interconnected processes. Dynamic high-oxygen LBE determines the formation, stratification, and late-stage instability of the protective oxide scale, while irradiation-induced bubbles, dislocation loops, and their coupled complexes modify the near-surface defect structure, diffusion pathways, and local mechanical response, thereby potentially affecting oxide nucleation, growth, and scale stability. Although the current irradiation experiments follow a helium pre-implantation plus Fe self-ion irradiation route, the observed defect evolution and hardening behavior provide important implications for understanding the irradiation-corrosion coupling of T91 in lead-cooled fast reactor systems and provide a basis for future work on pre-irradiation-assisted short-term dynamic corrosion experiments.

Keywords: T91 steel; lead-cooled fast reactor; dynamic corrosion; irradiation hardening

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Operational Resilience Value of EV Flexibility under Historically Grounded Climate Stress

Authors: 陈文颖[1]; 丁琪[1]

[1] *清华大学能源环境经济研究所*

Corresponding Authors: bl9632795@gmail.com, dingq23@mails.tsinghua.edu.cn

摘要: 电动汽车在增加电力需求的同时，也为电力系统提供了可调度的负荷灵活性。本文评估了在短时历史极端气候压力事件下，电动汽车有序充电与车网互动（V2G）对未来电力系统运行韧性的影响。研究基于中国 2060 年省级小时尺度 PyPSA-China-TIMES 电力系统模型，在年度基准情景确定发电装机、固定储能功率与能量容量、以及省间输电容量后，将三个持续 48–72 小时的历史气候压力事件施加到固定资产系统上，并比较无序充电、有序充电和有序充电叠加 V2G 的运行结果。结果表明，在事件天气与无序充电条件下，三个事件窗口内全国未满足电力需求达到 5.50–19.49 TWh。有序充电可降低 1.08–3.40 TWh 的未满足电力需求，V2G 进一步提供 0.24–0.58

TWh 的额外削减。综合有序充电与 V2G 后，事件窗口内未满足电力需求相对于无序充电降低 20.4%–23.9%。结果说明，在短时极端气候导致集中供需紧张时，电动汽车充电灵活性能够提供可量化的运行韧性价值，其中有序充电是主要贡献来源，V2G 提供较小但稳定的增量贡献。

关键词: 电动汽车；有序充电；车网互动；极端气候；电力系统韧性；

Abstract: Electric vehicles (EVs) are increasingly relevant to power-system resilience because they add electricity demand while also creating flexible load. This study estimates the operating value of EV charging flexibility in a 2060 Chinese power system exposed to short historical climate-stress events. Three 48–72 hour climate-stress events are imposed on a provincial PyPSA-China-TIMES power-system model after installed generation capacity, stationary-storage power and energy capacity, and inter-provincial transfer capacity have been fixed from an annual baseline. Under event weather with uncontrolled charging, national unserved electricity demand reaches 5.50–19.49 TWh within the historical event windows. Smart charging reduces these shortfalls by 1.08–3.40 TWh, and V2G provides a further 0.24–0.58 TWh reduction. The combined smart-charging-plus-V2G response lowers event-window unserved electricity demand by 20.4–23.9%, indicating that EV flexibility can provide measurable operating resilience when short-duration climate stress creates concentrated scarcity.

Keywords: electric vehicles; smart charging; vehicle-to-grid; climate extremes; power-system resilience;

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F91/ERNiCr-3 堆焊界面真实熔合线识别及冶金分区重构

Author: 罗温伟[1]

Co-authors: 胡梦佳 [1]; 雒晓卫 [1]

[1] *清华大学核能与新能源技术研究院 104 室*

Corresponding Author: luoww23@mails.tsinghua.edu.cn

摘要: F91/ERNiCr-3 异种金属堆焊界面存在显著的成分、组织、相结构及热物理性能梯度，是接头高温服役过程中的潜在薄弱区域。从微观尺度看，该界面并非单一几何线，而是具有一定空间尺度的熔合区或成分过渡区。其中，真实熔合线代表熔合区最靠近未熔化 F91 母材一侧的边界，是界定界面热历史、冶金分区及碳迁移行为的重要空间基准。然而，现有研究通常依据金相腐蚀或电解抛光后观察到的表观界面标定熔合线，其是否等同于真实熔化边界仍缺乏验证。
本研究结合 $FeCl_3$ 腐蚀、电解抛光、硬度坑空间标记、EDS、EBSD、JMatPro 计算和高温原位观察，系统分析了 F91/ERNiCr-3 TIG 堆焊界面的结构特征。结果表明，该堆焊界面并非均匀单一结构，而主要由无 PMZ 的普通界面和含 PMZ 的宏观偏析界面组成，二者沿界面长度占比分别约为 24.2% 和 75.8%。$FeCl_3$ 腐蚀界面主要反映腐蚀响应差异，而电解抛光后观察到的界面可能主要受 Ni 含量及其梯度所控制。两类表观界面均不同于实际熔合线。
结合硬度坑空间标记、EBSD 晶粒分析和 EDS 的 Ni 扩散特征，确认实际熔合线位于传统腐蚀界面更靠近 F91 母材的一侧约 20μm 处。这一结果揭示了 CGHAZ 与 PMZ/TZ 之间存在一层以往容易被忽略的 F91 UMZ。该区域具有与凝固相关的组织特征，可能来源于熔池边界层内液态金属混合不足。上述结果澄清了传统基于腐蚀得到的表观界面并非实际熔合线，完善了 F91/ERNiCr-3 bcc/fcc 异种金属界面的冶金分区认识，并为后续界面碳迁移分析和高温铁素体残留机制解释提供了更准确的冶金分析依据。

关键词: 异种金属焊接、熔合线、界面宏观偏析、部分混合区

Abstract: F91/ERNiCr-3 dissimilar metal buttering interfaces exhibit pronounced gradients in composition, microstructure, phase constitution, and thermophysical properties, making them potential weak regions during high-temperature service. At the microscale, such an interface should not be regarded as a single geometrical line, but rather as a fusion region or compositional transition zone with a finite spatial extent. The true fusion line represents the boundary of this fusion region closest to the unmelted F91 base metal, and therefore provides an important spatial reference for defining the interfacial thermal history, metallurgical zoning, and carbon-migration behaviour. However, in previous studies, the fusion line has commonly been identified from the apparent interface revealed by metallographic etching

or electropolishing, while whether such an apparent interface corresponds to the true melting boundary remains insufficiently verified.
In this study, $FeCl_3$ etching, electropolishing, microhardness-indent spatial marking, EDS, EBSD, JMatPro calculations, and in-situ high-temperature observation were combined to systematically investigate the interfacial structure of F91/ERNiCr-3 TIG buttering. The results show that the buttered interface is not a uniform single structure, but mainly consists of PMZ-free ordinary interface segments and PMZ-containing macrosegregated interface segments, which account for approximately 24.2% and 75.8% of the interfacial length, respectively. The interface revealed by $FeCl_3$ etching mainly reflects differences in corrosion response, whereas the interface observed after electropolishing may be largely governed by the local Ni content and its compositional gradient. Neither type of apparent interface corresponds to the actual fusion line.
By combining microhardness-indent spatial marking, EBSD grain analysis, and EDS-based characterization of Ni diffusion/enrichment, the actual fusion line was confirmed to be located approximately 20 μm on the F91 base-metal side of the conventionally etched interface. This finding reveals a previously overlooked F91 unmixed zone between the CGHAZ and the PMZ/TZ. This region exhibits solidification-related microstructural features and is likely associated with insufficient mixing of liquid metal within the molten-pool boundary layer. These results clarify that the apparent interface conventionally identified by etching is not the actual fusion line, refine the metallurgical zoning of the F91/ERNiCr-3 bcc/fcc dissimilar metal interface, and provide a more accurate metallurgical basis for subsequent analyses of interfacial carbon migration and the mechanism of retained high-temperature ferrite.

Keywords: Dissimilar metal welding，Fusion line，Interfacial macrosegregation，Partially mixed zone (PMZ)

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Photocatalytic Removal and Mechanistic Investigation of U(VI) Using BaTiO3/g-C3N4 Heterojunctions with Enhanced Efficiency

Author: 彭炜[1]

[1] *东华理工大学*

Corresponding Author: 502307614@qq.com

摘要: 随着核能的广泛部署，铀污染——尤其是六价铀 U(VI)——已对水生生态系统构成日益严峻的威胁。光催化还原技术作为一种绿色且可持续的环境修复策略应运而生。然而，如何实现高光催化效率并有效利用太阳能，目前仍是一个巨大的挑战。本研究通过简便的水热法，基于合理的能带排列，合成了一系列 BaTiO3/g-C3N4 (BTO/CN) II 型异质结光催化剂，并评估了不同 BTO/CN 配比对 U(VI) 去除效率的影响。在测试的组分中，BaTiO3/g-C3N4-4 表现出最佳的光催化性能，在可见光照射 20 分钟内，U(VI) 的去除效率高达 96.2%，显著优于单一组分及其他复合配比。这种优化的异质结有效地调控了电子能带结构，促进了光生电子 - 空穴 (e−h+) 对的快速分离。此外，异质结界面的协同效应与 BaTiO3 固有的铁电特性，显著抑制了电荷载流子的复合，并拓宽了可见光吸收范围，从而大幅提升了系统的整体光催化效率。BaTiO3/g-C3N4 异质结的合理设计，为开发用于铀修复的高效光催化剂提供了极具前景的策略和坚实的实验基础。

关键词: 石墨相氮化碳；钛酸钡；光催化；铀 (VI)；环境修复

Abstract: With the extensive deployment of nuclear energy, uranium contamination—particularly in the hexavalent form U(VI)—has become an escalating threat to aquatic systems. Photocatalytic reduction, has emerged as a green and sustainable strategy for environmental remediation. However, achieving high photocatalytic efficiency and effective solar energy utilization remains a significant challenge. In this study, a series of BaTiO3/g-C3N4 (BTO/CN) type-II heterojunction photocatalysts were synthesized through a simple hydrothermal method with rational band alignment. The effect of different BTO/CN ratios on U(VI) removal efficiency was evaluated. Among the tested compositions, BaTiO3/g-C3N4-4 exhibited the highest photocatalytic performance, achieving a U(VI) removal efficiency of 96.2% within 20 minutes of visible light irradiation—significantly outperforming both individual components and other composite ratios. The optimized heterojunction effectively modulated the electronic band structure, facilitating the rapid separation of photogenerated electron-hole (e−h+) pairs. Furthermore,

the synergistic effect between the heterojunction interface and the intrinsic ferroelectric properties of BaTiO3 significantly suppressed charge carrier recombination and extended the visible-light absorption range. This, in turn, substantially enhanced the overall photocatalytic efficiency of the system. The rational design of BaTiO3/g-C3N4 heterojunctions offers a promising strategy and a robust experimental basis for the development of high-efficiency photocatalysts of uranium remediation.

Keywords: Graphitic carbon nitride; Barium titanate; Photocatalytic; Uranium (VI); Environmental remediation

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辐照诱导氢化钇损伤演化与变形行为

Authors: 赵苛衣[1]; 李翔[1]; 周楠[1]; 杨宗达[2]; 李博[3]; 晋宇恒[1]; 胡逊祥[1]; 崔丽娟[1]

[1] *四川大学物理学院*

[2] *东京大学核工程与管理系*

[3] *北京科技大学材料科学与工程学院*

Corresponding Authors: huxx@scu.edu.cn, keyizhao0822@163.com

摘要: 氢化钇是一种有望应用于先进微型反应堆的高温中子慢化剂，但其在亚化学计量氢含量条件下的辐照响应仍缺乏充分认识。本文采用透射电子显微镜（TEM）表征，并结合密度泛函理论（DFT）计算，系统研究了 $YH_{1.58}$ 在 2.5 MeV Fe^{2+} 离子辐照条件下的微观结构演化行为，辐照温度范围为 50–465 ℃，辐照剂量为 0.1 和 1.5 dpa。

在 0.1 dpa 条件下，辐照损伤主要表现为缺陷团簇，并呈现出明显的温度依赖性：随着辐照温度升高，缺陷团簇尺寸增大而密度降低；空洞仅在 465 ℃ 条件下可被观察到。在 1.5 dpa 条件下，损伤形貌发生显著变化，包括低温下微裂纹的形成以及较高温度下带状变形结构的出现。50 ℃ 条件下形成的开口微裂纹富集氧元素，这与氧化钇（Y_2O_3）的形成有关。DFT 计算表明，裂纹形成可产生由空位辅助的迁移通道，促进氢向裂纹表面迁移，从而推动氢脱附及后续氧元素掺入。本研究揭示了温度、辐照剂量、变形行为与化学元素再分布在氢化钇辐照响应中的耦合作用，为理解氢化钇在先进核反应堆中的应用行为提供了新的认识。

关键词: 氢化钇；离子辐照；微裂纹；微观结构演化

Abstract: Yttrium hydride is a promising high-temperature neutron moderator for advanced microreactor applications, yet its irradiation response at substoichiometric hydrogen concentrations remains insufficiently understood. In this work, the microstructural evolution of YH1.58 under 2.5 MeV Fe2+ ion irradiation was systematically investigated over a wide range of temperatures (50-465 ℃) and doses (0.1 and 1.5 dpa), using transmission electron microscopy (TEM), complemented by density functional theory (DFT) calculations. At 0.1 dpa, irradiation damage is dominated by defect clusters, with a clear temperature dependence: defect clusters increase in size and decrease in density as temperature rises, and cavities become observable only at 465 ℃. At 1.5 dpa, pronounced changes in damage morphology are observed, including microcrack formation at low temperatures and band-shaped deformation structures at elevated temperatures. At 50 ℃, open microcracks are oxygen-enriched due to the formation of yttrium oxide (Y2O3), with DFT calculations indicating that crack formation creates vacancy-assisted pathways that facilitate hydrogen migration towards crack surfaces, promoting hydrogen desorption and subsequent oxygen incorporation. These findings provide new insights into the coupled roles of temperature, irradiation dose, deformation, and chemical redistribution in the irradiation response of yttrium hydride, which is crucial for its application in advanced nuclear reactors.

Keywords: Yttrium hydride; ion irradiation; microcracks; microstructural evolution

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全球光伏组件生产与贸易的一般均衡分析

Author: 刘心怡[1]

[1] *清华大学*

Corresponding Author: xyliu24@mails.tsinghua.edu.cn

摘要: 光伏发电是推动能源结构绿色转型、实现减排目标的关键技术。光伏组件作为光伏发电设施的核心部件，近年来生产技术不断突破，制造成本持续下降，成为光伏发电大规模部署的关键支撑。而组件生产过程消耗大量电力，其碳排放水平与当地电力结构密切相关。目前，全球光伏组件生产与贸易高度集中于中国，引发部分国家对供应安全的担忧，并采取以贸易壁垒为主的产业保护政策，而该类政策对全球光伏组件生产贸易格局的影响，及其经济环境效应尚不明晰。
本研究首先构建涵盖光伏组件生产相关信息的数据集，据此从电子设备制造部门中拆分出光伏组件部门，在一般均衡模型中详细刻画其生产、贸易与能耗，得到单独刻画光伏组件生产部门的一般均衡模型（C-GEM_PV），并将基年更新校核至 2023 年；进而设计减排政策与贸易限制情景并进行模拟，探究减排目标下贸易限制增加对全球光伏组件生产与贸易格局及经济与环境产生的影响。
研究表明：（1）无额外贸易限制的减排政策情景下，光伏发电需求驱动全球光伏组件产量持续增长，2035 年接近 1,000GW。中国仍占据生产贸易的核心枢纽地位，印度增长潜力较大，将超过越南成为第二大生产国。（2）全球贸易限制将压低全球光伏组件产量，最高限制程度下 2035 年降幅约 10.9%。净出口国产量下降，净进口国产量增加；同时全球光伏发电量显著减少；美国受影响最大，最高限制程度下 2035 年降幅达 24.4%。同时净出口国碳价水平下降，净进口国碳价上升，且主要国家均承受不同程度的福利损失。（3）全球贸易限制使光伏组件贸易额大幅下降，但中国在全球贸易中占比有所提升。中国出口结构趋于多元化，对欧盟市场依赖程度降低；美国减少对越南的进口依赖，转而增加从其他亚洲国家的进口。（4）若仅美国实施进口贸易限制，全球光伏组件生产、贸易、光伏发电量及福利水平所受影响显著减小，中国在全球生产与贸易中的占比进一步提升。相比于全球贸易限制情景，美国将面临更高的福利损失，其他国家的福利损失有所减轻。
基于上述结论，本研究建议：（1）主要出口国应积极拓展国内光伏应用市场并推动出口市场多元化，以增强抵御外部贸易风险的能力。（2）主要进口国应审慎评估贸易政策与减排目标的一致性，以效率驱动型措施替代贸易壁垒。（3）各国应以协商替代贸易限制政策，借助全球贸易与气候治理的多边对话平台达成共识与合作，防止贸易摩擦延缓全球气候治理进程。

关键词: 全球减排；光伏组件；贸易限制；政策分析；一般均衡模型

Abstract: Photovoltaic (PV) power generation is a key technology for advancing the green tran- sition of the energy system and achieving emission reduction targets. As the core com- ponent of PV systems, PV modules have experienced rapid technological progress and continuous cost reductions in recent years, providing critical support for large-scale PV deployment. However, module production is electricity-intensive, and its carbon emis- sions are closely linked to the local power generation mix. Currently, global PV module production and trade are highly concentrated in China, prompting some countries to adopt protectionist policies, primarily in the form of trade barriers. The implications of such policies for the global production and trade patterns of PV modules, as well as related economic and environmental impacts, remain insufficiently understood.
This study develops a computable general equilibrium model with an explicit PV module sector (C-GEM_PV). Based on a detailed dataset covering module production and energy use, the PV module sector is disaggregated from the electronic equipment manu- facturing sector to explicitly characterize its production, trade, and energy consumption, with the base year updated and calibrated to 2023. Using C-GEM_PV, this study designs multiple trade restriction scenarios to examine how increasing trade barriers under emis- sion reduction targets reshape the global PV module production and trade patterns, as well as associated economic and environmental impacts.
The main findings are summarized as follows. (1) Under emission reduction sce- narios without additional trade restrictions, global PV module production continues to expand, driven by growing demand for PV power, and is projected to approach 1,000 GW by 2035. China remains the central hub of global production, while India exhibits strong growth potential and is expected to surpass Vietnam as the second-largest pro- ducer. (2) Global trade restrictions significantly reduce PV module production, with a maximum decline of approximately 10.9% in 2035, and lower production concentration. Module output decreases in major exporting regions but increases in importing regions. Meanwhile, global PV power generation declines markedly, with the United States being most affected, experiencing a reduction of up to 24.4% in 2035. Trade restrictions lower marginal abatement costs in net exporting countries

while increasing them in net import- ing countries, and result in welfare losses across all regions. (3) Global trade restrictions

substantially reduce the total value of PV module trade, while further increasing China’s share in global trade. China’s export structure becomes more diversified, with reduced dependence on the European Union market, whereas the United States decreases its re- liance on imports from Vietnam and shifts toward other Southeast Asian suppliers. (4) When trade restrictions are imposed solely by the United States, their impacts on global PV module production, trade, power generation, and welfare are significantly mitigated, while China’s share in global production and trade further increases. The United States experiences greater welfare losses than under global trade restriction scenarios, whereas other countries face relatively smaller losses.
Based on above findings, several policy implications emerge. (1) Major exporting countries should expand domestic PV application markets and diversify export markets to strengthen resilience against external trade risks. (2) Major importing countries should align trade policies with emission reduction targets and substitute trade barriers with efficiency-driven measures. (3) Countries should replace trade restrictions with multi- lateral consultations, leveraging global trade and climate governance platforms to foster cooperation and prevent trade frictions from impeding global climate governance.

Keywords: Global emissions mitigation; Photovoltaic modules; Trade restrictions; Policy analysis; Computable General Equilibrium Model

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基于 Blockage 的离心压缩机扩压器优化

Author: 程成[1]

[1] *清华大学*

Corresponding Author: chengc23@mails.tsinghua.edu.cn

摘要: 离心式压缩机的性能受限于喘振和阻塞这两种失速情况，失速不仅导致压比和效率急剧下降，还可能引发叶片损坏。失速现象根源在于非设计工况下气体入射角与扩压器叶片安装角的不匹配，引发叶片吸力面流动分离，形成低能流体团并堵塞流道。为抑制分离、拓宽稳定裕度，本文提出了一种基于前缘开槽的扩压器结构改进方案，优化了传统扩压器稳定工况范围较窄的问题，并将该方法应用在 Radiver 叶轮中，通过数值模拟验证了该方法可以有效改善扩压器性能。为精准优化三角形槽的几何参数，本研究引入 Blockage 模型量化流道堵塞程度，分别以近喘振与近阻塞工况为优化目标，使用 NSGA-II 多目标遗传算法进行自动寻优。通过对优选方案（OP）的详细分析表明：前缘开槽能显著扩大压缩机的稳定工作裕度，并在近喘振与近阻塞工况下有效抑制扩压器内的边界层分离。本研究同时验证了以 Blockage 作为优化目标可有效表征系统的稳定裕度，为离心压缩机的气动优化设计提供了新思路与可靠方法。

关键词: 楔形扩压器；前缘开槽；边界层分离；Blockage

Abstract: The performance of centrifugal compressors is limited by two conditions: surge and choke, which not only lead to a sharp decline in pressure ratio and efficiency but may also cause blade damage. The stall phenomenon fundamentally arises from the mismatch between the gas incidence angle and the diffuser vane angle under off-design conditions, which triggers flow separation on the suction surface of the vanes, leading to the formation of low-energy fluid regions that block the flow path. To suppress flow separation and widen the stability margin, this paper proposes an improved diffuser structure based on a kind of leading-edge slot. This approach addresses the narrow stable operating range of conventional diffusers and has been applied to the Radiver impeller. Numerical simulations demonstrate that the proposed method effectively enhances diffuser performance. To precisely optimize the geometric parameters of the triangular slots, this study introduces a Blockage model to quantify the flow path obstruction level, with the optimization objectives set as near-surge and near-choke conditions. An automated optimization is performed using the NSGA-II multi-objective genetic algorithm. Detailed analysis of the optimized design (OP) reveals that introducing appropriately sized slots at the leading edge significantly expands the compressor’s stable operating margin and effectively suppresses boundary layer separation within the diffuser under both near-surge and near-choke conditions. This study also demonstrates that utilizing Blockage as an optimization objective can effectively characterize the

system’s stability margin, offering a new perspective and a reliable methodology for the aerodynamic optimization design of centrifugal compressors.

Keywords: Vane Diffuser; Leading-Edge Slot; Boundary Layer Separation; Blockage

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空间解析建模评估碳中和目标下我国抽水蓄能与水电发展布局

Authors: Hanjie Mao[1]; Da Zhang; Ziheng Zhu

Co-authors: Xiaogang He ; Shuo Zhang

[1] *清华大学*

Corresponding Author: maohj25@mails.tsinghua.edu.cn

摘要: 中国承诺到 2060 年实现碳中和，这需要整合 5000 至 8000 吉瓦的可变可再生能源，可能对电网稳定性带来前所未有的挑战。本研究采用具有时空高分辨率的模型，对风-光-水混合系统的容量扩张和系统运行进行协同优化，量化了脱碳电网中抽水蓄能（PHS）和梯级水电的灵活性需求。结果表明，部署 205 吉瓦的开环抽水蓄能可使系统年成本降低 810 亿元人民币，同时将可变可再生能源弃电率降低 11% 。通过对闭环抽水蓄能进行水库级别的精细化建模，我们发现，传统方法由于未能捕捉实际运行的灵活性，系统性地高估了 30% 的容量需求，并导致每年成本虚高 360 亿元人民币。关键在于，以可再生能源为主导的电力市场中的价格波动能产生足够的套利收益，使抽水蓄能无需补贴即可具备商业可行性——这一发现对全球能源转型的融资具有重要指导意义。此外，优化水电梯级运行每年可额外节省 1160 亿元人民币的成本。多年气候模拟进一步证实了该系统在多变气象条件下的强韧性。对抽水蓄能和水电灵活性进行高保真建模，对于设计大型电力系统深度脱碳的经济可行路径至关重要。

关键词: 碳中和；抽水蓄能；梯级水电；电力系统扩展规划；可再生能源并网；系统灵活性

Abstract: China’s commitment to carbon neutrality by 2060 requires 5000–8000 GW integration of variable renewable energy, which may pose unprecedented grid stability challenges. Using spatial-temporally resolved modeling to co-optimize capacity expansion and system operation for hybrid wind-solar-hydropower systems, we quantify the flexibility requirements of pumped hydro storage (PHS) and cascaded hydropower in a decarbonized grid. We demonstrate that deploying 205 GW of open-loop PHS reduces system costs by 81 billion yuan (about 11.6 billion USD) annually while decreasing VRE curtailment by 11%. Through reservoir-level modeling of closed-loop PHS, we reveal that conventional approaches systematically overestimate capacity requirements by 30% and inflate costs by 36 billion yuan (about 5.2 billion USD) annually by failing to capture operational flexibility. Crucially, price volatility in renewable-dominated markets generates arbitrage revenues sufficient to enable the commercial viability of PHS without subsidies—a finding with global implications for financing energy transitions. Optimizing hydropower cascade operations yields an additional 116 billion yuan (about 16.6 billion USD) in annual savings. Multi-year climate simulations confirm system resilience across diverse weather conditions. Sophisticated modeling of pumped storage and hydropower flexibility is essential for designing economically viable pathways to deep decarbonization in large-scale power systems.

Keywords: Carbon neutrality; Pumped hydro storage; Hydropower cascade; Power system expansion modeling; Renewable energy integration; System flexibility

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二维材料基疏松纳滤膜制备及其有机小分子/二价盐分离性能研究

Authors: 石硕青[1]; 赵璇[1]; 李福志[1]; 张薛[1]

[1] *清华大学*

Corresponding Author: ssq25@mails.tsinghua.edu.cn

摘要: 轻工行业的快速发展使含染料、氨基酸及抗生素等有机小分子的高盐废水排放不断增加。实现有机小分子与无机盐（二价及高价盐）的高效分离，对废水资源化及零排放具有重要意义。本研究聚焦高性能疏松纳滤（LNF）膜的构建，以缓解“渗透-分离”的“trade-off”效应。基于界面聚合优化，系统考察二维材料氧化石墨烯（GO）与二硫化钼（MoS_2）插层对膜结构与性能的影响。通过正交试验确定 PVDF 基膜最优界面聚合条件：PIP 浓度 4 w/v.%、停留 300 s，TMC 浓度 0.05 w/v.%、停留 90 s，热处理 30 min，可获得稳定 NF 膜。在 GO 改性中，对比铸膜液添加、插层及水相添加三种方式，发现以多巴胺（DA）为桥连的插层结构最优，制得 PVDF/PDA-GO LNF 膜。该膜通量为 10.45 L/(m²·h·bar)，PEG2000 截留率 76.05%，Mg2SO4 截留率 4.88%。机理分析表明分离主要受空间位阻与 Donnan 效应协同控制。进一步以低成本 MoS_2 替代 GO，通过真空抽滤结合原位限域界面聚合，构建 H-PVDF/MoS2 LNF 膜。该膜纯水通量达 830.42 L/(m²·h·bar)，刚果红/Mg2SO4 分离系数达 52.01，显著削弱 trade-off。其高通量源于亲水性与较大孔结构，而负电表面及 0.63 nm 层间距实现高效选择性分离。同时，膜在酸性条件下通量恢复率达 95.92%，并可在 0.08 MPa 低压下稳定运行，展现出良好的工业应用潜力。

关键词: 有机小分子；无机盐；界面聚合；疏松纳滤膜；机理探究

Abstract: The rapid development of the light industry has led to an increasing discharge of high-salinity wastewater containing small organic molecules such as dyes, amino acids, and antibiotics. Achieving efficient separation of small organic molecules and inorganic salts (divalent and multivalent salts) is of great significance for wastewater resource utilization and zero discharge. This study focuses on the construction of high-performance loose nanofiltration (LNF) membranes to alleviate the “permeation-separation”trade-off effect. Based on interfacial polymerization optimization, the effect of intercalation of two-dimensional materials—graphene oxide (GO) and molybdenum disulfide (MoS_2)—on membrane structure and performance was systematically investigated. Through orthogonal experiments, the optimal interfacial polymerization conditions for the PVDF base membrane were determined: PIP concentration 4 w/v.%, standing time 300 s, TMC concentration 0.05 w/v.%, standing time 90 s, and thermal treatment for 30 min, which can yield a stable NF membrane. In GO modification, three methods—addition into casting solution, intercalation, and addition into aqueous phase—were compared, and the intercalated structure bridged with dopamine (DA) was found to be the best, resulting in the PVDF/PDA-GO LNF membrane. This membrane exhibits a flux of 10.45 L/(m²·h·bar), PEG2000 rejection of 76.05%, and Mg2SO4 rejection of 4.88%. Mechanism analysis indicates that the separation is mainly controlled synergistically by size exclusion and the Donnan effect. Furthermore, using low-cost MoS2 to replace GO and combining vacuum filtration with in-situ confined interfacial polymerization, an H-PVDF/MoS2 LNF membrane was constructed. This membrane achieves a pure water flux of 830.42 L/(m²·h·bar), a Congo red/$Mg2SO_4$ separation factor of 52.01, and significantly weakens the trade-off effect. Its high flux is attributed to hydrophilicity and a larger pore structure, while the negatively charged surface and 0.63 nm interlayer spacing enable efficient selective separation. At the same time, the membrane achieves a flux recovery rate of 95.92% under acidic conditions and can operate stably under low pressure (0.08 MPa), demonstrating good potential for industrial application.

Keywords: small organic molecules, inorganic salts, interfacial polymerization, loose nanofiltration membranes, mechanism study

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Polyvinylidene fluoride-based loose nanofiltration membrane with graphene oxide intercalation for efficient desalination of small organic molecules

Authors: 石硕青[1]; 赵璇[1]; 李福志[1]; 张薛[1]

[1] *清华大学*

Corresponding Author: ssq25@mails.tsinghua.edu.cn

摘要: 有机物小分子与无机盐的分离对实现工业废水资源化利用至关重要。通过对三种不同氧化石墨烯 (GO) 掺杂方式制备的纳滤膜进行通量、截留率及有机小分子和无机盐分离测试，得到以 GO 和多巴胺 (DA) 涂层形成的 PDA-GO 插层的方式效果最好，从而制备了一种新型的疏松纳滤膜材料 (PVDF/PDA-GO-TFN)，旨在提高有机小分子和无机盐分离性能的同时增强膜表面的稳定和抗污染性能、降低“trade-off”效应。本研究探明了形成 PDA-GO 插层的最优条件和在此基础上界面聚合的最佳组合。通过 SEM-EDS、AFM 以及 FT-IR 确定了插层结构的产生。PVDF/PDA-GO-TFN 疏松纳滤膜纯水通量高达 10.45 L/(m2·h·bar)，对标准物 PEG 2000 的截留率高达 88%，对无机盐 NaCl、Na2SO4 的截留率分别低至 11% 和 6.8%。通过对膜表面接触角 (亲水性)、荷电性 (Zeta 电位) 以及孔径 (BET) 进行相关性分析，确定分离机理为 Donnan 效应和空间位阻效应。经过四个循环有机小分子和无机盐混合溶液冲洗过滤后，膜的 FRR 均值为 99.06%，表明膜抗污染能力较强，且通过 SPSS 对无机盐截留率进行显著性差异分析，指出膜稳定性能优异。综上，PVDF/PDA-GO-TFN 膜材料的制备为高效分离有机小分子和无机盐纳滤膜的制备提供新思路。

关键词: 氧化石墨烯; 多巴胺; 疏松纳滤膜; 有机废水脱盐

Abstract: The separation of small organic molecules and inorganic salts is crucial for achieving industrial wastewater resource utilization. Through flux, rejection rate, and separation tests of small organic molecules and inorganic salts using nanofiltration membranes prepared by three different doping methods of graphene oxide (GO), it was found that the method of forming a PDA-GO interlayer using GO and a dopamine (DA) coating performed the best. Consequently, a novel type of loose nanofiltration membrane material (PVDF/PDA-GO-TFN) was prepared, aiming to improve the separation performance of small organic molecules and inorganic salts, enhance surface stability and anti-fouling properties of the membrane, and reduce the “trade-off” effect. This study identified the optimal conditions for forming the PDA-GO interlayer and, on this basis, the best combination for interfacial polymerization. The formation of the interlayer structure was confirmed by SEM-EDS, AFM, and FT-IR. The pure water flux of the PVDF/PDA-GO-TFN loose nanofiltration membrane reached as high as 10.45 L/(m2·h·bar), the rejection rate for the standard PEG 2000 molecule was as high as 88%, and the rejection rates for inorganic salts NaCl and Na2SO4 were as low as 11% and 6.8%, respectively. By performing correlation analysis on surface contact angle (hydrophilicity), charge (Zeta potential), and pore size (BET) of the membrane, it was determined that the separation mechanism is the Donnan effect and steric hindrance effect. After four cycles of washing and filtration with a mixed solution of small organic molecules and inorganic salts, the average FRR of the membrane was 99.06%, indicating strong anti-fouling ability. In addition, a significance analysis of the inorganic salt rejection rate using SPSS showed that the membrane has excellent stability. In summary, the preparation of PVDF/PDA-GO-TFN membrane material provides a new approach for the efficient separation of small organic molecules and inorganic salts by nanofiltration membranes.

Keywords: Graphene oxide; Dopamine; Loose nanofiltration membrane; Desalination of organic wastewater

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碘化铯负载基体石墨氧化动力学及释放行为研究

Author: 丘阳晨[1]

[1] *清华大学*

Corresponding Author: qiuyc25@mails.tsinghua.edu.cn

摘要: 面向未来低碳能源体系，核能在保障能源安全与实现深度脱碳中具有重要战略意义；而核燃料材料服役行为的可靠性，是支撑核能安全高效利用的关键基础。其中，高温气冷堆燃料元件中的基体石墨兼具慢化剂、结构材料和裂变产物滞留屏障等多重功能，其氧化机制及裂变产物释放行为是事故工况安全评价中的核心科学问题之一。一旦高温气冷堆发生进气事故，高温氧化氛围可能导致 TRISO 包覆颗粒破损率升高，使更多裂变产物释放至基体石墨中；与此同时，基体石

墨自身也会发生氧化，滞留其中的裂变产物不仅可能改变石墨氧化动力学过程，还可能在氧化过程中发生化学形态转化并进一步释放至一回路中。因此，开展含裂变产物基体石墨的氧化过程及释放行为研究，对反应堆事故状态下释放源项评估和核燃料安全分析具有重要意义。

本研究以稳定碘化铯作为模拟裂变产物，通过溶液浸渍法将其负载于基体石墨中，用以模拟辐照后燃料元件中含裂变产物的基体石墨环境；进一步结合热重-质谱-傅里叶红外联用分析、水平管式炉氧化实验及第一性原理计算，系统研究碘化铯负载对基体石墨高温氧化行为的影响，以及氧化过程中碘、铯元素的释放、迁移与残留特征。

TG-MS-FTIR 结果表明，碘化铯负载显著降低了基体石墨开始氧化阶段的反应活化能，并对石墨氧化生成二氧化碳和一氧化碳的反应过程均表现出明显促进作用；但在本研究所涉及的负载量范围内，碘化铯负载量差异对反应活化能的影响并不显著。水平管式炉氧化实验结果显示，在 600 ℃、700 ℃ 和 800 ℃ 条件下，大部分铯和几乎全部碘均可从碘化铯负载基体石墨中释放，仅少量铯以碳酸盐或氧化物形式残留于氧化灰分中，且随氧化温度升高，灰分中铯残留量进一步降低。释放出的铯中，少部分在石英管近样品端随未燃尽石墨片层共同沉降，大部分则以碘化铯气溶胶形式释放和迁移；碘元素中部分被氧化为气态碘并被碱液吸收，大部分同样以碘化铯气溶胶形式释放和传输。

第一性原理计算进一步表明，在石墨表面尤其是缺陷石墨表面，铯原子相较碘原子具有更低的吸附能，说明负载于基体石墨中的碘化铯可能更倾向于通过铯与缺陷石墨发生相互作用。该相互作用一方面可能增强缺陷石墨的化学活性，从而促进基体石墨氧化；另一方面也可能解释铯相较于碘更易在氧化灰分中残留的现象。上述结果揭示了模拟裂变产物碘化铯对基体石墨氧化动力学及碘、铯差异化释放行为的影响机制，可为高温气冷堆进气事故工况下基体石墨氧化行为分析、裂变产物释放源项评估以及核燃料材料安全性研究提供实验依据和理论支撑。

关键词: 高温气冷堆；基体石墨；进气事故；碘化铯；氧化动力学；裂变产物释放；铯碘释放行为；第一性原理计算

Abstract: In the context of future low-carbon energy systems, nuclear energy plays a strategically important role in ensuring energy security and achieving deep decarbonization. The reliability of nuclear fuel materials under service conditions is a fundamental basis for the safe and efficient utilization of nuclear energy. In high-temperature gas-cooled reactors, matrix graphite in fuel elements serves simultaneously as a moderator, structural material, and final barrier against the release of fission products into the primary circuit. Its oxidation mechanism and associated fission product release behavior are therefore among the key scientific issues in accident-condition safety assessment. In the event of an air ingress accident, the high-temperature oxidizing atmosphere may increase the failure probability of TRISO-coated fuel particles, resulting in the release of more fission products into the matrix graphite. Meanwhile, the matrix graphite itself undergoes oxidation, during which retained fission products may not only affect graphite oxidation kinetics but also experience chemical transformation and further release into the primary circuit. Therefore, investigating the oxidation process and release behavior of fission-product-containing matrix graphite is of great significance for source term evaluation and nuclear fuel safety analysis under reactor accident conditions.

In this study, stable cesium iodide was used as a simulated fission product and loaded into matrix graphite by solution impregnation to represent the fission-product-containing matrix graphite environment in irradiated fuel elements. Thermogravimetry-mass spectrometry-Fourier transform infrared spectroscopy, horizontal tube furnace oxidation experiments, and first-principles calculations were combined to systematically investigate the effect of cesium iodide loading on the high-temperature oxidation behavior of matrix graphite, as well as the release, transport, and retention characteristics of iodine and cesium during oxidation.

The TG-MS-FTIR results show that cesium iodide loading significantly reduces the activation energy at the initial oxidation stage of matrix graphite and markedly promotes the oxidation reactions of graphite to carbon dioxide and carbon monoxide. However, within the loading range investigated in this study, the variation in cesium iodide loading has no significant influence on the activation energy. The horizontal tube furnace oxidation experiments indicate that, at 600 ℃, 700 ℃, and 800 ℃, most cesium and nearly all iodine are released from cesium-iodide-loaded matrix graphite. Only a small fraction of cesium remains in the oxidation ash in the form of carbonates or oxides, and the residual cesium further decreases with increasing oxidation temperature. Among the released cesium, a minor fraction deposits near the sample end of the quartz tube together with unburned graphite flakes, whereas the majority is released and transported in the form of cesium iodide aerosols. Part of the iodine is oxidized into gaseous iodine and absorbed by alkaline solution, while most iodine is also released and transported as

cesium iodide aerosols.

First-principles calculations further reveal that cesium atoms exhibit lower adsorption energies than iodine atoms on graphite surfaces, especially on defective graphite. This suggests that cesium iodide loaded in matrix graphite may preferentially interact with defective graphite through cesium. Such interaction may enhance the chemical activity of defective graphite and thereby promote graphite oxidation; it may also explain why cesium is more likely than iodine to remain in the oxidation ash. These results reveal the influence mechanism of simulated fission product cesium iodide on the oxidation kinetics of matrix graphite and the differential release behavior of iodine and cesium, providing experimental evidence and theoretical support for graphite oxidation analysis, fission product source term assessment, and nuclear fuel material safety evaluation under air ingress accident conditions in high-temperature gas-cooled reactors.

Keywords: High-temperature gas-cooled reactor; matrix graphite; air ingress accident; cesium iodide; oxidation kinetics; fission product release; cesium and iodine release behavior; first-principles calculations

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等离子弧切割过程中气溶胶的时空演变及形成机制

Author: 周菲[1]

[1] *清华大学*

Corresponding Author: zhouf23@mails.tsinghua.edu.cn

摘要: 随着全球越来越多核反应堆进入退役阶段，退役过程中放射性气溶胶的防控已成为辐射防护与环境安全中的关键问题。等离子体切割作为核反应堆退役中广泛采用的热切割技术，在作业过程中会快速产生大量粒径分布动态变化显著的气溶胶。然而，目前对该过程中气溶胶的时序演化规律及形成机制仍缺乏系统认识，导致源项评估及污染控制存在较大不确定性。本研究采用双极电迁移率粒径谱仪（bSMPS）与光学粒子计数器（OPS）联用，对等离子体切割过程中 10 nm–20 μm 范围内的气溶胶进行高时间分辨率（≤1.5 min）监测。结果表明，亚微米气溶胶呈现典型的双峰粒径分布特征，包括小于 30 nm 的成核模态和 100–500 nm 的积聚模态。气溶胶动力学分析表明，蒸发–冷凝和凝并过程主导了颗粒生长，而成核模态颗粒的形成与等离子体环境中高浓度离子诱导成核密切相关。不同材料及工艺参数对气溶胶特征具有显著影响。其中，碳钢切割产生的颗粒物数浓度最高，峰值粒径最大，而铝材切割产生的颗粒物浓度最低。对于碳钢切割，板材厚度对粒径分布影响较小，而较高切割电流（100 A）会显著提高成核模态颗粒的占比。通风条件可使气溶胶数浓度降低近一个数量级，并有效抑制颗粒进一步生长。本研究为核反应堆退役过程中放射性气溶胶的形成机制认识及控制策略优化提供了理论依据，可为通风时机选择、切割参数优化及作业现场辐射防护提供参考。

关键词: 核反应堆退役；等离子体切割；放射性气溶胶；颗粒数浓度粒径分布（PNSD）；蒸发–冷凝与凝并机制

Abstract: As many reactors around the world are decommissioning, the prevention and control of radioactive aerosols during this process have emerged as a key challenge. Plasma arc cutting or simplified as plasma cutting is a widely-used decommissioning technique, during which aerosols are generated rapidly and variably. However, the temporal evolution and formation mechanisms of these aerosols are usually unknown, leading to uncertainties in aerosol pollution control. This study comprised a combination of a bipolar electric mobility particle sizer and optical particle sizer to measure aerosols in the size range of 10 nm–20 μm with high time resolution (≤1.5 min). The submicron aerosols show a bimodal particle number size distribution (PNSD) with the coexistence of a nucleation mode (<30 nm) and an accumulation mode (100–500 nm). Aerosol modeling indicates that evaporation-condensation and coagulation dominate particle growth, and nucleation-mode particles can be caused by ion-induced nucleation due to high concentration of ions in the plasma. The number concentration of aerosols produced by cutting carbon steel is the highest, while cutting aluminum is the lowest. The peak particle diameter from cutting carbon steel is the largest, and the aluminum the lowest in the size range of 100–200 nm. For carbon steel, the thickness of the plate exerts a negligible influence on the PNSDs, while the percentage of nucleation-mode particles is found to be significantly higher at 100 A current than at 50 A current. The ventilation can reduce the aerosol number concentration by one order of magnitude and

suppress the growth of aerosols. The study provides a theoretical basis for the optimization of the radioactive aerosol control (e.g., ventilation timing, current parameters, etc.) during the decommissioning cutting process.

Keywords: Nuclear decommissioning; Plasma cutting; Radioactive aerosols; Particle number size distribution; Evaporative-condensation and coagulation

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Driving Out Bad Money with the Good: Policy Design for Retired Electric Vehicle Batteries

Author: 商辰宣[1]

[1] *清华大学*

Corresponding Author: shangcx24@mails.tsinghua.edu.cn

摘要: 问题定义：在发展中国家，大多数退役电动汽车电池（REVB）由非正规电池回收商（IBR）回收，而非正规电池回收商（FBR），这反映了“劣币驱逐良币”式的市场失灵。我们探究了这种市场失灵的根源，并评估了现有政策工具——即政府资助的回收补贴政策和基于制造商的延伸生产者责任（EPR）政策——在解决该问题上的有效性。我们还尝试提出一种结合两种政策优点的责任共担政策，旨在为这一市场失灵提供更全面的解决方案。

方法论/结果：我们构建了一个考虑 IBR 与 FBR 之间回收价格竞争的闭环供应链模型。考虑了四种政策情景：无政策、回收补贴、EPR 以及责任共担政策。结果表明，在没有政策干预的情况下，由电池制造商决定的 IBR 与 FBR 之间的回收成本差距会持续扩大，从而加剧市场失灵。当 IBR 仍然活跃于回收市场时，三种政策均无法有效激励制造商缩小成本差距。然而，当 FBR 回收具有社会效率时，责任共担政策能够首先将 IBR 逐出市场，进而激励电池制造商降低回收成本差距，从而为 EPR 政策和单独的回收补贴政策的有效性创造条件。

管理启示：考虑到发展中国家回收成本差距较大，政府应首先实施责任共担政策。在 IBR 退出市场且回收成本差距缩小后，可以转向 EPR 政策，最终过渡到回收补贴政策。

关键词: 退役电动汽车电池；回收竞争；回收补贴政策；生产者延伸责任政策；责任共担政策

Abstract: Problem definition：In developing countries, most retired electric vehicle batteries (REVBs) are recycled by informal battery recyclers (IBRs) rather than by formal battery recyclers (FBRs), reflecting a market failure described as “Bad money drives out good money”. We investigate the root causes of this market failure and evaluate the effectiveness of existing policy instruments—namely, government-funded recycling subsidy policy and manufacturer-based EPR policy—in addressing the problem. We also try to propose responsibility-sharing policy that combines the strengths of both policies, aiming to offer a more comprehensive solution to this market failure.
Methodology/results：We develop a closed-loop supply chain model with recycling price competition between the IBR and FBR. Four policy scenarios are considered: No policy, recycling subsidy, EPR and responsibility-sharing policies. Results show that without policy intervention, the recycling cost gap between IBR and FBR—determined by battery manufacturers—continues to increase, driving the market failure. When IBRs remain active in the recycling market, none of the three policies effectively incentivize manufacturers to lower the cost gap. However, the responsibility-sharing policy can first drive IBRs out of the market when FBR recycling is socially efficient and subsequently incentivizes battery manufacturers to reduce the recycling cost gap, which establishes the conditions under which EPR and stand-alone recycling subsidies can be effective.
Managerial implications：Given the large recycling cost gap in developing countries, the government should first implement the responsibility-sharing policy. After IBR exit the market and the recycling cost gap narrows, it can shift to EPR, and finally to recycling subsidy.

Keywords: Retired electric vehicle battery; Recycling competition; Recycling subsidy Policy; EPR Policy; Responsibility-Sharing Policy

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缠结高分子熔体非线性拉伸流变中的“缠结-堆积”转变

Author: 王寅[1]

[1] *清华大学*

Corresponding Author: yin-wang23@mails.tsinghua.edu.cn

摘要: 管道模型（Tube model）通过将多链缠结的相互作用简化为单链图像，实现了对聚合物材料力学行为的定量描述，并为从聚合物加工到生命科学等领域的应用奠定了基础。然而，在强拉伸流场中，该理论表现出系统性的失效。本文通过对缠结聚合物的分子动力学模拟，揭示了链间构型中存在一种由应变诱导的、从缠结态向堆积态（Packed state）的转变。在原始链（Primitive chain）拉伸达到饱和后，对流解缠结和链取向作用促使体系重新组织为由取向链段构成的二维堆积构型。这种转变从根本上改变了非线性拉伸流中应力的来源，从而解释了管道模型在上述条件下的失效，并实现了对大拉伸应变下力学响应的定量预测。这项研究结果清晰地阐明了链间集体重组是如何主导非线性拉伸行为的。

关键词: 高分子物理，软物质凝聚态，复杂流体物理，分子动力学模拟

Abstract: The tube model, which reduces the interaction of many-chain entanglement to a single-chain picture, has enabled quantitative descriptions of the mechanical behaviors of polymeric materials and underpins applications from polymer processing to life sciences. In strong extensional flows, however, this theory systematically fails. Herein, through molecular dynamics simulations of entangled polymers, we reveal a strain-induced crossover from the entangled state to a packed state in the inter-chain configuration. Following the saturation of primitive chain stretch, convective disentanglement and chain alignment reorganize the system into a packed configuration of aligned segments. This crossover fundamentally alters the origin of the stress in nonlinear extensional flows, which explains the breakdown of the tube model under such conditions, and leads to a quantitative prediction to the mechanical response at large extensional strains. These findings clearly show how the collective inter-chain reorganization governsthe nonlinear extensional behaviors.

Keywords: Polymer physics, soft matter condensed matter, complex fluid physics, molecular dynamics simulation

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$UO_2(111)$ 表面高覆盖度下水分子吸附与解离的密度泛函理论研究

Author: 朱林松[1]

[1] *成都理工大学核技术与自动化工程学院*

Corresponding Author: 1498053911@qq.com

摘要: 本研究采用密度泛函理论（DFT+U），研究了水分子在 $UO_2(111)$ 表面的行为，重点关注其吸附与解离过程。我们确定了单个水分子的吸附构型，发现其表现出解离吸附趋势，具有较低的解离能垒。在多水分子体系中，额外水分子的存在会促进解离，且水分子间的氢键作用逐渐增强。作为氢键供体的水分子与 $UO_2(111)$ 表面的相互作用更强。此外，在 $UO_2(111)$ 表面的混合吸附中，氢键对体系稳定性具有显著影响。通过解离能垒与吸附能分析表明，当分子水与解离水比例为 1:1 时，表面吸附具有明显优势。在 1 ML 覆盖度下，随着水分子完全解离，表面吸附物间的排斥作用显著增强，导致解离吸附能降至 -0.32 eV。热力学计算表明，0.5 ML 覆盖度为最优构型；随着温度升高，水分子逐渐脱附，最终形成清洁表面。

关键词: 吸附；水团簇；$UO_2(111)$ 表面；解离；密度泛函理论

Abstract: This study examines the behavior of water molecules on the UO2(111) surface, focusing on adsorption and dissociation, using density functional theory (DFT+U). We determined the adsorption configuration of a single water molecule and observed that it exhibits a tendency toward dissociative adsorption, characterized by a low energy barrier for dissociation.In the case of multiple water molecules, the presence of additional water molecules promotes dissociation, and the hydrogen bond interactions between water molecules gradually strengthen. Water molecules that act as hydrogen bond donors interact more strongly with the UO_2(111) surface. Furthermore, in the mixed adsorption on the UO_2(111) surface, the system's stability is significantly influenced by hydrogen bonds. Based on the analysis of dissociation energy barriers and adsorption energies, the surface adsorption shows a clear preference when the ratio of molecular water to dissociated water is 1:1. At a 1 ML coverage, as the water molecules fully dissociate, the repulsive interactions between the surface adsorbates significantly increase, leading to a decrease in the dissociative adsorption energy to -0.32 eV. In the thermodynamic calculations, 0.5 ML coverage is the optimal configuration, and as the temperature increases, water molecules gradually desorb, eventually leading to a clean surface.

Keywords: Adsorption; Water cluster; UO2(111); Dissociation; DFT

Chapter 4

近代物理

Chapter 5

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细水雾抑制钠离子电池单体热失控的实验探究

Author: 陶瑞卿[1]

[1] *中国科学技术大学*

Corresponding Author: ruiqing077@mail.ustc.edu.cn

摘要: 钠离子电池正作为锂离子电池的一种极具潜力的替代品崭露头角，但由于其热稳定性较低且热失控（TR）发生较早，面临着更高的火灾和爆炸风险。因此，高效的抑制策略显得至关重要。水雾（WM）作为一种公认的清洁且高效的灭火介质，本文对其在钠离子电池（SIB）单体中的适用性进行了探究。本研究在受控的热滥用条件下，考察了不同荷电状态（SOC）下的 18650 型 SIB 单体的热失控行为，并对比了有无水雾介入时的差异。结果表明，在达到或未达到临界温度（Tc）时施用水雾，能够有效抑制热失控；其中，临界温度 Tc 随 SOC 的升高而降低，从 0% SOC 时的 182.5 ℃ 降至 100% SOC 时的 155.4 ℃。即使抑制效果未能完全消除热失控，水雾仍能将热失控的峰值温度降低 40%，并减弱气体喷发及火焰的强度。定量分析显示，水雾能够延长热失控的诱导期；对于处于 50% 至 100% SOC 的电池单体，即使在持续加热的条件下，水雾也能将二次热失控的爆发时间延后 6 分钟以上。这一延时显著增加了人员疏散和应急响应的可用时间。这些研究发现不仅为理解 SIB 单体的热失控抑制机制提供了新的视角，也为优化安全防护策略中水雾的应用提供了切实可行的指导。

关键词: 钠离子电池、细水雾、热失控、冷却机理、临界抑制温度

Abstract: Sodium-ion batteries are emerging as promising alternatives to lithium-ion batteries but face heightened fire and explosion risks due to their low thermal stability and early onset of thermal runaway (TR). Efficient suppression strategies are therefore essential. Water mist (WM), widely recognized as a clean and effective extinguishing medium, is investigated here for its applicability to SIB cells. This study examines TR behavior of 18650 SIB cells at different states of charge (SOC) under controlled thermal abuse, with and without WM intervention. Results show that WM application at or before the critical temperature (Tc) can suppress TR, where Tc decreases from 182.5 ◦C at 0% SOC to 155.4 ◦C at 100% SOC. When suppression is incomplete, WM still lowers the TR peak temperature by 40% and reduces gas–flame intensity. Quantitative analysis indicates that WM prolongs the induction period of TR, delaying secondary onset by over 6 min for cells at 50–100% SOC even under sustained heating. This delay substantially enhances the available time for evacuation and emergency response. These findings provide new insights into the TR suppression mechanisms of SIB cells and offer practical guidance for optimizing WM application in safety protection strategies.

Keywords: Sodium-ion battery, Water mist, Thermal runaway, Cooling mechanism, Critical suppression temperature

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隧道内阻塞物对流淌火火焰形态和流场分布的影响

Author: 胡学靖[1]

Co-author: 张培红

[1] *东北大学*

Corresponding Author: 2467853149@qq.com

摘要: 在高速公路隧道内，石化产品在运输过程中发生的各种紧急情况可能导致液体持续泄漏流淌火灾。本文旨在通过实验和模拟方法，探讨滞留车辆导致的堵塞对隧道火灾中流淌火灾燃烧和火焰行为的影响。在阻塞比为 12%/20%/30% 的隧道内进行了一系列流淌火灾实验。改变了泄漏点与阻塞物之间的距离 (d=0m，流淌火在阻塞物下方蔓延，火焰接触阻塞物；d=0.3m，流淌火火焰未接触阻塞物)，并采用了五种泄漏速率：100/150/200/250/300 mL/min。测量了火焰高度、燃烧面积和天花板温度。使用 FDS 模拟进一步揭示了典型的速度、温度、涡度场和涡旋结构。结果显示，d=0m 时火焰高度比 d=0.3m 时更高。当阻塞比从 12% 增加到 30% 时，d=0m 处的最大火焰高度约上升 10%。相比之下，火焰振荡频率在 d=0.3m 时更高，且随着阻塞率从 12% 增加到 30%，其最大值在该位置会增加约 6%。通过分析流淌火的扩散燃烧过程，提出了一种计算瞬时燃烧速率的方法。此外，与火焰接触的阻塞物会显著改变火焰周围的流场和空气的卷吸。基于阻塞物对火焰表面和上层火焰卷吸的限制，修正了卷吸边界和燃烧速率，引入了卷吸修正系数，并建立了不同燃烧阶段流淌火的火焰高度和振荡频率预测模型。

关键词: 流淌火；阻塞物；涡旋动力学；火焰高度；振荡频率

Abstract: Within highway tunnels, various emergencies during the transportation of petrochemical products may lead to liquid spills and fires, forming spill fires in the tunnel. This paper aims to investigate the effects of blockage caused by stranded vehicles on the combustion and flame behavior of spill fires during tunnel fires through experimental and simulation methods. A series of spill fire experiments were conducted in a tunnel with blockage ratios of 12%/20%/30%. The tests varied the distance between the leak location and the blockage (spill fire spreads beneath the blockage and the flame contacting the blockage d=0m; spill fire does not contact the blockage d=0.3m) and employed five discharge rates: 100/150/200/250/300mL/min. Flame height, burning area, and ceiling temperature were measured. FDS simulations further revealed typical velocity, temperature, vorticity fields, and vortex structures. The results indicate that the flame height is greater at d=0 m than at d=0.3 m. When the blockage ratio increases from 12% to 30%, the maximum flame height at d=0 m rises by approximately 10%. In contrast, the flame oscillation frequency is higher at d=0.3 m; similarly, its maximum value at this position increases by around 6% as the blockage ratio increases from 12% to 30%. Blockage in contact with the flame significantly changes the flow field around the flame and air entrainment. By analyzing the spreading combustion process of spill fires, this study proposes a method for calculating the instantaneous combustion rate. Based on the limitations imposed by blockage on both flame surface and upper flame entrainment, this study revised the entrainment boundary and combustion rate, introduced an entrainment limitation coefficient, and established predictive models for the flame height and oscillation frequency of spill fires during different combustion stages.

Keywords: Spill fire, Blockage, Vortex dynamics,Flame height, Oscillation frequency

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双碳目标下生物质-煤耦合燃烧的腐蚀悖论：气-固多组分协同侵袭机理

Author: 赵泽熙[1]

[1] *东北大学*

Corresponding Author: chn_zexi_zhao@163.com

摘要: 在“双碳”目标驱动下，燃煤机组掺烧生物质是实现存量煤电低碳化转型的关键路径。然而，生物质引入的氯、碱金属与煤中硫分共存，导致高温受热面面临复杂的气-固多相协同腐蚀，成为制约掺烧比例与机组安全运行的技术瓶颈。本研究针对此关键科学问题，以锅炉典型用钢 12Cr1MoV 为对象，构建了多组分协同腐蚀模拟实验系统，系统探究了 450-600℃ 范围内 HCl、SO_2、H_2O 及模拟灰分的耦合腐蚀行为与机理。研究揭示了 HCl 主导的“活性氧化”与 SO_2 的竞争吸附抑制之间的动态平衡机制：HCl 通过破坏 Cr_2O_3 保护膜引发剧烈腐蚀，而 SO_2 因较低的反应临界分压可优先占据表面活性位点，部分抑制 Cl^- 的侵蚀。首次发现水蒸气（10 vol%）在混合气氛中的“双向调节”作用：其通过促进更致密 Cr_2O_3 膜的形成并改变 Cl/S 迁移路径，在所有测试工况下均表现出显著的腐蚀抑制效果。在模拟 20% 能量掺比的固-气耦合工况下，混合灰与酸性气体协同作用导致腐蚀速率高达 42.60 mm/a，量化了多相耦合的极值风险。本研究阐明了灰-气多相协同腐蚀机理，相关成果为燃煤掺烧生物质锅炉的材料选型、运行优化与腐蚀防控提供了直接的理论依据与技术支撑。

关键词: 煤电低碳化改造；气-固耦合腐蚀；HCl/SO_2 协同机制；安全控制；保护层失效

Abstract: Driven by the “dual carbon” goals, co-firing biomass in coal-fired power units is a critical pathway for the low-carbon transformation of existing coal power capacity. However, the coexistence of chlorine and alkali metals introduced by biomass with the sulfur inherent in coal leads to complex multiphase gas-solid synergistic corrosion on high-temperature heating surfaces, posing a significant technical bottleneck that limits co-firing ratios and compromises unit safety. To address this key scientific challenge, this study focuses on the typical boiler steel 12Cr1MoV and establishes a multi-component synergistic corrosion simulation experimental system. The coupling corrosion behavior and mechanisms involving HCl, SO_2, H_2O, and simulated ash deposits were systematically investigated within the temperature range of 450–600℃. The study reveals a dynamic equilibrium mechanism between the HCl-dominated “active oxidation” and the competitive adsorption inhibition by SO_2: HCl triggers severe corrosion by destroying the protective Cr_2O_3 scale, whereas SO_2 preferentially occupies active surface sites due to its lower critical reaction partial pressure, thereby partially mitigating Cl^- ingress. For the first time, the “dual regulatory” role of water vapor (10 vol%) in mixed atmospheres was identified: it exhibits a significant corrosion inhibition effect under all tested conditions by promoting the formation of a denser, more stable Cr_2O_3-rich scale and altering the migration pathways of Cl/S species. Under simulated 20% energy-input co-firing conditions with combined ash and gas exposure, the synergistic effect of mixed ash and acid gases results in an extreme corrosion rate of 42.60 mm/a, quantifying the peak risk of multi-phase coupling. This work elucidates the mechanisms of multi-phase ash-gas synergistic corrosion, and the findings provide a direct theoretical basis and technical support for material selection, operational optimization, and corrosion mitigation strategies in coal-biomass co-firing boilers.

Keywords: Coal power low-carbon retrofit; Gas-solid coupling corrosion; HCl/SO_2 synergistic mechanism; Safety control; Protective layer failure

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人工智能驱动的烟气控制系统生成式设计方法

Author: 张晓锦[1]

[1] *重庆大学*

Corresponding Author: zxjin119@outlook.com

摘要: 烟气控制系统是保障基础设施防火安全的关键组成部分。传统烟气控制系统设计主要依赖逐案分析的范式，决策基于有限设计方案之间的比较，缺乏针对多样化基础设施构型与火灾场景的数据驱动优化方法。为克服这些挑战，本研究提出了一种融合扩散模型与 NSGA-II 的 AI 驱动生成式设计框架，用于优化烟气控制系统的方案设计。考虑基础设施构型的多样性与火灾场景的不确定性，构建了扩散模型以高效预测烟气控制性能。同时，基于扩散模型构建了融入火灾风险评估指标的 NSGA-II 框架，通过对设计空间的全局探索，能够自动生成面向随机场景的风险-成本最优方案。以隧道火灾场景为例，该方法对训练数据集内烟气场的预测准确率达到 95%，对训练分布之外的隧道几何构型及火灾场景的预测准确率仍保持在 80% 以上。针对纵向通风、集中排

烟及其组合这三种主导烟气控制模式，优化方案可在数分钟内自动生成，与传统方法相比，通风量分别降低 52%、15% 和 23%，火灾风险分别降低 10%、6% 和 12%。本研究提出了一种稳健、可泛化且面向风险最小化的决策工具，为消防工程中智能化烟气控制系统的研发提供了支持。

关键词: AI 驱动生成式设计，烟气控制系统，扩散模型，NSGA-II，数据驱动优化，隧道火灾

Abstract: Smoke control systems are a critical component for ensuring the fire safety of infrastructure. Traditional smoke control system design predominantly relies on a case-by-case paradigm, with decision-making based on comparisons among a limited set of design schemes, lacking data-driven optimization methods that can accommodate diverse infrastructure configurations and fire scenarios. To overcome these challenges, this study proposes an AI-driven generative design framework that integrates a diffusion model with NSGA-II to optimize smoke control system schemes. Considering the diversity of infrastructure configurations and the uncertainty of fire scenarios, a diffusion model is developed to efficiently predict smoke control performance. Meanwhile, a diffusion model-based NSGA-II framework is constructed by incorporating fire risk assessment indicators, enabling automatic generation of risk-cost optimal solutions for random scenarios through global exploration of the design space. Taking tunnel fire scenarios as a case study, the method achieves 95% prediction accuracy of smoke fields for the training dataset and maintains over 80% accuracy for tunnel geometries and fire scenarios outside the training distribution. For the three dominant smoke control modes—longitudinal ventilation, centralized smoke exhaust, and their combination—optimized schemes can be automatically generated within minutes, reducing ventilation rates by 52%, 15%, and 23%, and fire risk by 10%, 6%, and 12%, respectively, compared with traditional methods. This study presents a robust, generalizable, and risk-minimization-oriented decision-making tool, supporting the development of intelligent smoke control systems in fire protection engineering.

Keywords: AI-driven generative design, smoke control system, diffusion model, NSGA-II, data-driven optimization, tunnel fire

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泄爆压力对氨-氢-空气爆炸动力学的影响

Author: 余佳灵[1]

Co-authors: 赵江月 [1]; 程凯歌 [1]; 潘传鱼 [2]; 朱龙小 [1]; 王喜世 [1]

[1] *中国科学技术大学*

[2] *中国工程物理研究院*

Corresponding Authors: wxs@ustc.edu.cn, yjialing@mail.ustc.edu.cn

摘要: 掺氢是改善氨燃烧性能的有效途径之一，但同时也提高了爆炸危险性。泄爆能够有效降低腔体内部压力，进而减轻爆炸损害。然而，泄爆压力（Pstat）对氨-氢-空气爆炸动力学的影响仍然不清晰。为此，本文通过实验与数值模拟，研究了不同泄爆压力下氨-氢-空气混合物爆炸过程中的超压发展与火焰形态演化。结果表明，提高 Pstat 增强了火焰-压力波相互作用的强度，促使火焰裙边接触管道侧壁的时刻由泄爆后提前至泄爆前，进而影响火焰表面积的增长过程。因此，泄爆膜破裂导致的超压峰值 P1 由线性增长转变为非线性增长。此外，当 Pstat 较低时，火焰形态仅表现为球形和指尖形，表明火焰裙边接触管道侧壁产生的稀疏波不足以诱发郁金香火焰。当 Pstat 增加至 60.14 kPa 时，观察到典型的郁金香火焰。数值模拟结果表明，随着 Pstat 增加，火焰与从泄爆膜反射的压缩波之间的碰撞增强，在火焰前锋前方诱导出郁金香形轴向速度分布。这种轴向速度分布最终导致郁金香火焰的形成。

关键词: 泄爆压力；氨-氢混合物；郁金香火焰；火焰-压力波相互作用；泄爆

Abstract: Blending ammonia with hydrogen is an effective way to improve the combustion performance of ammonia, but it also increases the explosion risk. Venting can effectively reduce the internal overpressure of the enclosure, thereby mitigating explosion damage. However, the influence of vent burst pressure (Pstat) on the explosion dynamics of ammonia–hydrogen–air mixtures remains unclear. To address this problem, the present study experimentally and numerically investigates the overpressure

development and flame morphology evolution during the explosion of ammonia–hydrogen–air mixtures under different vent burst pressures. The results show that increasing Pstat enhances the intensity of flame–pressure wave interaction, advancing the timing of flame skirt contact with the duct sidewall from post-venting to pre-venting, thereby affecting the growth of flame surface area. Consequently, the peak overpressure P1 generated by vent cover rupture transitions from a linear to a nonlinear increase. Furthermore, at low Pstat, only spherical and fingertip flames are observed, indicating that the rarefaction wave generated by flame–wall contact is too weak to induce a tulip flame. When Pstat increases to 60.14 kPa, a typical tulip flame is observed.Numerical simulation results show that with increasing Pstat, the collision between the flame and the compression wave reflected from the vent cover intensifies, inducing a tulip-shaped axial velocity profile ahead of the flame front. This axial velocity distribution ultimately leads to the formation of the tulip flame.

Keywords: Venr burst pressure; Ammonia-hydrogen; Tulip flame; Flame-pressure wave interaction; Vented explosions

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The investigation of free radicals in flaming and smoldering smoke particle

Authors: 章翔[1]; 袁宏永[1]; 潘睿[1]; 孙占辉[1]; 陈涛[1]; 仪洋[1]

[1] *清华大学安全科学学院*

Corresponding Author: 13260393066@163.com

摘要: 火灾烟雾颗粒中的环境持久性自由基可诱导氧化应激并增强颗粒毒性，但明火与阴燃烟雾颗粒的自由基状态差异仍不明晰。本研究采集 7 种典型样品，结合 EPR、Raman 光谱和 OC/EC 分析，比较其自由基特性、碳结构及组成。结果表明，明火颗粒具有更高自由基浓度、更低 g 值、更宽 FWHM 和更高 $P_1/_2$，呈现自由基富集、碳中心和芳香缩合特征。Raman 和 OC/EC 结果显示，明火颗粒富含 D1 型芳香边缘/纳米石墨化碳和 EC/soot-EC，有利于碳中心自由基稳定；阴燃颗粒富含 D3/D4 型无定形碳和 OC/char-EC，对应低自由基负载和强氧相关电子扰动。燃烧模式主导自由基丰度与电子特征，碳结构和组成调控自由基宿主环境。

关键词: 明火烟雾，阴燃烟雾，自由基，EPR 光谱，碳烟颗粒

Abstract: Environmentally persistent free radicals in fire smoke particles can induce oxidative stress and enhance particle toxicity, yet the radical-state differences between flaming and smoldering smoke particles remain unclear. In this study, seven representative smoke particle samples were analyzed using electron paramagnetic resonance spectroscopy, Raman spectroscopy, and OC/EC analysis to link radical properties with carbon structure and carbonaceous composition. The results showed that flaming smoke particles had markedly higher radical concentrations, lower g values, broader FWHM, and higher $P_1/_2$ than smoldering smoke particles, indicating a radical-rich, carbon-centered, and aromatically condensed radical state. Raman and OC/EC results further showed that flaming particles were enriched in D1-type aromatic-edge/nanographitic carbon and EC/soot-EC, which favored the stabilization of carbon-centered radicals. In contrast, smoldering particles were characterized by D3/D4-rich amorphous carbon and OC/char-EC, corresponding to lower radical loading and stronger oxygen-related electronic perturbation. These findings demonstrate that combustion mode governs radical abundance and electronic character, while carbon structure and composition regulate the radical-hosting environment.

Keywords: Flaming smoke, Smoldering smoke, Free radical, EPR spectroscopy, Soot particles

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含水量对镁粉最小点火能量的影响：实验和理论模型

Author: 杜振国[1]

[1] *东北大学*

Corresponding Author: 2439826868@qq.com

摘要: 金属燃料作为可再生清洁能源载体，为化石燃料提供了成熟可行的可持续替代方案。然而近年来，潮湿作业工况下的金属粉尘爆炸事故时有发生。为探明潮湿环境中金属粉尘的潜在爆炸风险，本研究选取三种粒径的球形镁粉，制备了含水量 0%~10% 的含湿样品，利用哈特曼管开展了 500~1500 g/m³ 粉尘浓度下的最小点火能量（MIE）实验，同步测定了含湿镁粉的最小点火温度与 120 ms 点火延迟时刻的实时粉尘浓度；基于斯托克斯沉降理论构建了粉尘实时浓度预测模型，并以电火花点火热理论为基础，引入浓度偏离、颗粒团聚、能量损失三项修正，建立了含湿镁粉 MIE 的预测模型。结果表明：镁粉 MIE 随含水量升高呈单调上升趋势，0%~6% 低中含水量区间 MIE 增长相对平缓，8%~10% 高含水量区间出现跃升。含水量主要通过液膜和氧化层隔绝、湿团聚沉降、气化吸热、水蒸气稀释的多重协同机制抑制镁粉点火敏感性；所建立的 MIE 理论模型与实验数据契合度良好。本研究揭示了含水量对镁粉点火敏感性的多尺度影响机理，量化了粒径、浓度与含水量的耦合作用规律，可为工业含湿镁粉的燃爆风险评估与防控提供关键实验支撑和理论依据。

关键词: 镁粉；含水量；最小点火能；粉尘爆炸

Abstract: As renewable and clean energy carriers, metal fuels offer a mature and feasible sustainable alternative to fossil fuels. However, metal dust explosion accidents under humid operating conditions have occurred frequently in recent years. To clarify the potential explosion risk of metal dust in humid environments, spherical Mg dust with three particle sizes was selected to prepare moisture-containing samples with moisture contents ranging from 0% to 10% in this study. Minimum ignition energy (MIE) tests were conducted in a Hartmann tube at dust concentrations of 500~1500 g/m³. Meanwhile, the minimum ignition temperature of the moisture-containing Mg dust and the real-time dust concentration at the ignition delay time of 120 ms were synchronously measured. A prediction model for real-time dust concentration was established based on Stokes' settling theory. Furthermore, on the basis of the thermal theory of spark ignition, a prediction model for the MIE of moisture-containing Mg dust was developed by introducing three correction terms, namely concentration deviation, particle agglomeration and energy loss. The results show that the MIE of Mg dust exhibits a monotonically increasing trend with the rise of moisture content. The increase of MIE is relatively gentle in the low and medium moisture content range of 0%~6%, while an abrupt jump occurs in the high moisture content range of 8%~10%. Moisture content inhibits the ignition sensitivity of Mg dust mainly through multiple synergistic mechanisms, including the isolation effect of liquid film and oxide layer, wet agglomeration and settling, gasification heat absorption, and water vapor dilution. The established MIE theoretical model is in good agreement with the experimental data. This study reveals the multi-scale influence mechanism of moisture content on the ignition sensitivity of Mg dust, and quantifies the coupling law of particle size, concentration and moisture content. It can provide critical experimental support and theoretical basis for the combustion and explosion risk assessment, prevention and control of industrial moisture-containing Mg dust.

Keywords: Mg dust; moisture content; minimum ignition energy; dust explosion

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Evaluating the Performance of AI in Crisis Detection: A Multi-Scenario Hindcast of Extreme Precipitation Forecasts

Author: 黄冯[1]

[1] *清华大学*

Corresponding Author: huangf23@outlook.com

摘要: 人工智能天气预报（AIWP）模型在全球平均误差指标上表现出色，但其在检测低概率、高影响极端事件（对应急响应至关重要）方面的有效性仍缺乏检验。本研究将三个领先模型

（GraphCast、FuXi 和人工智能预测系统（AIFS））与卫星观测和数值基准在四个不同的历史危机中进行评估。使用以危机为中心的评估框架，包括峰值振幅比（PAR）、空间相关性（SC）、均方根误差（RMSE）、体积偏差和对称极端依赖指数（SEDI），初步结果表明 AIWP 模型存在系统性的强度缺陷。虽然 GFS 在大多数情况下保持 PAR 高于 0.65，但 AI 模型低估峰值降雨量超过 90%，并表现出显著的空间位移。这些发现表明，固有的统计平滑将灾难性信号转化为良性预测。因此，过度依赖当前的 AIWP 模型进行危机检测可能会产生虚假的安全感，反而可能加剧而不是减轻应急脆弱性。

关键词: 危机检测，极端降雨，气象大模型，回溯评估

Abstract: Artificial Intelligence Weather Prediction (AIWP) models excel in global mean-error metrics, yet their efficacy in detecting low-probability, high-impact extreme events–critical for emergency response–remains under-examined. This study evaluates three leading models (GraphCast, FuXi, and Artificial Intelligence Forecasting System (AIFS)) against satellite observations and a numerical baseline across four diverse historical crises. Using a crisis-centric evaluation framework comprising Peak Amplitude Ratio (PAR), Spatial Correlation (SC), Root Mean Square Error (RMSE), volumetric Bias, and the Symmetric Extremal Dependence Index (SEDI), preliminary results reveal a systemic intensity deficit in AIWP models. While GFS maintains a PAR above 0.65 across most scenarios, AI models underestimate peak rainfall by over 90% and exhibit significant spatial displacement. These findings suggest that inherent statistical smoothing transforms catastrophic signals into benign forecasts. Consequently, over-reliance on current AIWP models for crisis detection may yield a false sense of security, potentially exacerbating rather than mitigating emergency vulnerabilities.

Keywords: Crisis Detection, Extreme Precipitation, AI Weather Prediction, Hindcast Evaluation.

Chapter 6

人工智能

Hybrid physics-data driven model for real-time risk assessment of wind-induced disasters

Author: 顾寅[1]

Co-author: 刘奕 [1]

[1] *清华大学安全科学学院*

Corresponding Author: guyin2017@163.com

摘要: 针对典型灾害事故场景（火灾、极端大风天气等）实时、精细化风场模拟的迫切需求，提出了一种物理启发-数据驱动的两阶段深度学习方法框架，用于对具有高维输入不确定性的复杂风场进行快速重构。具体地，基于深度学习直接建立端到端预测模型，在网络架构设计、网络输入特征与输出量选取时充分考虑了流体物理机理以捕获 CFD 建模的显著特征，而数据驱动的误差修正技术可以填补实测数据和预测模型预测之间的剩余空白，捕获真实物理条件下存在的不确定因素。进一步地，提出了一种基于本体技术和知识库构建的事故智能推演仿真框架，具体地，基于公共安全三角形模型构建涉及承灾载体、突发事件、应急管理及后果的多层级安全信息本体模型；基于事件链、预案链理论构建耦合事故演化过程知识库，从而实现相应事故的仿真推演系统开发。以此为基础，结合风场重构研究成果，研发了用于行人、树木等承灾载体的物理-数据混合驱动实时风险评估系统。

关键词: 深度学习；风场重构；风险评估；系统开发

Abstract: In response to the urgent demand for real-time, high-resolution wind field simulations in typical disaster scenarios, this study proposes a physics-inspired, data-driven two-stage deep learning framework for the rapid reconstruction of complex wind fields. Specifically, an end-to-end deep learning model is developed for direct prediction. The network architecture design, along with the selection of input features and output variables, explicitly incorporates fluid dynamics principles to capture the key characteristics of CFD modeling. Meanwhile, data-driven error correction techniques are employed to bridge the gap between measured data and model predictions, enabling the model to better account for uncertainties under real-world physical conditions. Furthermore, an intelligent accident simulation framework based on ontology technology and knowledge bases is proposed. A multi-level safety information ontology model is constructed, covering disaster-prone entities, emergency events, emergency management processes, and consequences, based on the public safety triangle model. In addition, a knowledge base for the coupled evolution of accidents is developed using event chain and contingency plan chain theories, thereby supporting the construction of a simulation and scenario-based system for accident analysis. Building upon this foundation, and integrating the results of is developed for disaster-affected entities such as pedestrians and trees.

Keywords: Deep learning; wind field reconstruction; risk assessment; system development

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基于 L-D 对抗神经网络框架的热工系统开放集事故诊断研究

Authors: 胡少纯[1]; 徐顺浩[1]; 王博[1]; 谭思超[1]; 田瑞峰[1]

[1] *哈尔滨工程大学*

Corresponding Author: 1270134394@qq.com

摘要: 随着社会经济的高速发展，工业生产对能源的需求日益增长。由于常规化石能源对环境存在着严重的污染，亟需加大新型能源的研发投入。随着核反应堆系统安全性和可靠性的不断提高，核能有望在安全性、经济性和环境友好性上达到新的高度，成为全球能源体系脱碳进程中不可或缺的支柱。为了提升反应堆的安全性，快速且精准的系统级故障诊断技术在核电厂中的应用显得尤为重要。现有的故障诊断研究大多基于封闭空间假设，即依靠有监督的方法学习人工标记好的数据进行故障分析。但上述方法模型参数固定，对于未知故障的识别并不敏感。事实上，反应堆系统的故障诊断是一个开集识别问题，系统无法获取所有信息，可能存在未知的变量或状态。基于上述限制，本文创新性地提出了一种基于对抗生成理论的 L-D 对抗神经网络的核电厂故障诊断新型框架。它通过逐步学习并标记未知故障的特征，实现识别未知故障的同时，可有效提高模型可靠性，并具备自我优化功能。通过高维度、非线性的复杂的 AP1000 核电厂软件 PCTran 的事故数据集和基于“华龙一号”后续核电机型智能化开发做设计搭建的 PHM 系统级热工实验台架故障实验数据集开展上述新型框架的可行性及泛化性验证。结果表明，L-D 对抗神经网络模型可以很好的提高未知故障的识别精度。与传统的 openmax、ocsvm 等开集识别算法相比，其对于未知故障识别的准确率提升了 5%-15%。通过 L 网络与 D 网络的不断对抗训练，不断的分离出未知故障特征，从而大幅提高了 L 网络识别未知故障的能力，为压水堆核电厂热工系统故障诊断及辅助决策提供技术支撑。

关键词: 热力系统；系统故障诊断；核反应堆系统；开基识别 L-D 对抗神经网络

Abstract: With the rapid development of the social economy, the demand for energy in industrial production continues to grow. Due to the severe environmental pollution caused by conventional fossil energy, there is an urgent need to increase investment in the research and development of new energy sources. As the safety and reliability of nuclear reactor systems continue to improve, nuclear energy is expected to reach new heights in safety, economic efficiency, and environmental friendliness, becoming an indispensable pillar in the global energy system’s decarbonization process. To further enhance reactor safety, fast and accurate system-level fault diagnosis technologies are particularly important for application in nuclear power plants. Most existing fault diagnosis studies are based on a closed-set assumption, relying on supervised methods trained on manually labeled data for fault analysis; however, such models have fixed parameters and are not sensitive to unknown faults. In fact, fault diagnosis in reactor systems is an open-set recognition problem, where the system cannot access all information and unknown variables or states may exist. To address these limitations, this paper innovatively proposes a novel fault diagnosis framework for nuclear power plants based on an L-D adversarial neural network derived from generative adversarial theory. The framework progressively learns and labels features of unknown faults, enabling their identification while effectively improving model reliability and incorporating self-optimization capability. The feasibility and generalization of the proposed framework are validated using the high-dimensional and nonlinear accident dataset generated by the AP1000 nuclear power plant simulation software PCTran, as well as fault experimental data from a PHM system-level thermal-hydraulic test platform designed and constructed for the intelligent development of the “Hualong One”nuclear reactor. The results show that the L-D adversarial neural network model significantly improves the accuracy of unknown fault identification. Compared with traditional open-set recognition algorithms such as OpenMax and OCSVM, the accuracy for unknown fault recognition is improved by 5%–15%. Through continuous adversarial training between the L network and the D network, unknown fault features are progressively separated, greatly enhancing the L network’s capability to recognize unknown faults, thereby providing technical support for fault diagnosis and auxiliary decision-making in the thermal-hydraulic systems of pressurized water reactor nuclear power plants.

Keywords: Thermal systems; System-level fault diagnosis; Nuclear reactor systems; Open-set recognition; L-D adversarial neural network

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高通量堆系统可靠性与可用性智能建模及动态分析研究

Author: 伍怡[1]

Co-authors: 刘涛 [1]; 童节娟 [1]

[1] *清华大学*

Corresponding Authors: liu-tao@tsinghua.edu.cn, tongjj@tsinghua.edu.cn, wuyi23@mails.tsinghua.edu.cn

摘要: 面向高通量堆安全关键可修复系统在复杂工况下的在线动态可靠性与可用性评估需求，针对现有方法中环境感知失效率更新与系统级评估脱节、连续时间马尔可夫链（CTMC）模型构建依赖人工、状态空间增大后重复瞬态评估代价高等问题，本文提出一种高通量堆系统可靠性与可用性动态智能建模与分析方法。该方法构建了融合物理信息神经网络（PINN）与大语言模型辅助自动建模的 PEARL 框架，实现了环境感知失效率处理、CTMC 自动生成、状态空间约简以及物理约束瞬态求解的一体化流程。其中，MarkovOps 模块可根据结构化输入或工程文本描述，自动生成显式带速率标注的马尔可夫状态转移图，并支持失效、维修、备用切换、启动失效和共因失效等复杂机制建模；PINN 模块用于学习系统状态概率随时间演化的规律，从而实现可靠性与可用性的快速在线查询。以宽能谱超高通量试验堆（简称高通量堆）的反应堆冷却剂系统和设备冷却水系统为案例开展验证，结果表明，所提方法在保证评估精度的同时，能够实现 CTMC 的快速自动生成以及一次训练后的多时刻快速推理，为研究堆系统在线动态可靠性与可用性评估提供了一种可行方法。

关键词: 在线动态可靠性与可用性；环境感知失效率；连续时间马尔可夫链自动生成；物理信息神经网络；宽能谱超高通量试验堆

Abstract: For the online dynamic assessment of reliability and availability of safety-critical repairable systems in the Tsinghua High Flux Reactor (THFR) under complex operating conditions, existing methods still face several challenges. Environment-aware failure-rate updating is often disconnected from system-level assessment. The construction of Continuous-Time Markov Chain (CTMC) models still relies heavily on manual work. Repeated transient evaluation also becomes increasingly expensive as the state space grows. To address these problems, this study proposes a dynamic intelligent modeling and analysis method for the reliability and availability of THFR systems. A PEARL framework is developed by integrating Physics-Informed Neural Networks (PINNs) with large language model (LLM)-assisted automated modeling. The framework establishes a unified workflow for environment-aware failure-rate processing, automated CTMC generation, state-space reduction, and physics-constrained transient solving. Within this framework, the MarkovOps module can automatically generate explicit, rate-labeled Markov state transition diagrams from structured inputs or engineering textual descriptions. It also supports the modeling of complex mechanisms, including failures, repairs, standby switching, start-up failures, and common-cause failures (CCF). The PINN module is used to learn the temporal evolution of system state probabilities. It further enables rapid online querying of reliability and availability. The proposed method is validated using the Reactor Coolant System (RCS) and the Component Cooling Water System (CCWS) of THFR. The results show that the method can achieve rapid automated CTMC generation while maintaining assessment accuracy. It also supports fast multi-time inference after a single round of training. This study therefore provides a feasible approach for the online dynamic assessment of reliability and availability of research reactor systems.

Keywords: online dynamic reliability and availability; environment-aware failure rate; automated continuous-time Markov chain (CTMC) generation; Physics-Informed Neural Network (PINN); Tsinghua High Flux Reactor (THFR)

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基于残差驱动的自适应深度有限元方法在压力容器应力集中分析中的应用

Author: 张雨辰[1]

Co-author: 肖扬怀 [2]

[1] *中国原子能科学研究院*

[2] *中国原子能科学研究院反应堆工程技术研究所*

Corresponding Authors: 3266369374@qq.com, 499665019@qq.com

摘要: 在带孔结构、圆柱壳体及压力容器接管等典型工程问题中，几何不连续性易引发显著的局部应力集中，对计算精度与效率提出了较高要求。传统有限元方法通常通过网格加密刻画该类区域，但依赖人工调整且计算成本较高；现有基于深度学习的方法虽具有一定灵活性，但在自适应能力及物理一致性方面仍存在不足。本文提出一种基于残差驱动的自适应深度有限元方法（ADFEM），用于应力集中结构的多尺度分析。通过构造残差指标识别高误差区域，并在局部引入修正子网络，实现全局近似与局部增强的层级耦合。该方法基于总势能框架构建，在避免显式网格重构的同时保持物理一致性。通过带孔平板、受拉圆柱壳体以及带接管压力容器三个算例，验证了该方法在不同结构中的适用性。结果表明，该方法能够有效定位应力集中区域，并在关键区域降低近似误差。所提出的框架为应力敏感结构的自适应分析提供了一种新的实现路径。

关键词: 自适应深度有限元；残差驱动；应力集中；多尺度分析；压力容器

Abstract: Stress concentration commonly arises in structures with geometric discontinuities, such as plates with holes, cylindrical shells, and pressure vessels with nozzle connections, posing challenges for accurate and efficient analysis. Conventional finite element methods address this issue through mesh refinement, which increases computational cost and relies on manual intervention. Existing deep learning-based approaches provide flexible representations but often lack adaptive resolution and consistency with physical formulations.This study proposes a residual-driven adaptive deep finite element method (ADFEM) for multi-scale analysis of stress-concentrated structures. A residual-based indicator is employed to identify high-error regions, where local correction networks are introduced through a hierarchical refinement strategy. The global approximation is progressively enhanced by coupling with localized corrections within a total potential energy framework, ensuring physical consistency while avoiding explicit mesh reconstruction.Numerical examples, including a plate with a circular hole, a cylindrical shell under tensile loading, and a pressure vessel with nozzle connection, demonstrate the applicability of the proposed method. The results show that the method effectively captures stress concentration and reduces approximation error in critical regions. The proposed framework provides an alternative approach for adaptive analysis of stress-sensitive structures.

Keywords: adaptive deep finite element method; residual-driven refinement; stress concentration; multi-scale analysis; pressure vessel

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Study on real-time prediction framework for heat release rate and ceiling heat flux profile in a tunnel fire with lateral smoke extraction using deep learning

Author: 宋恪斌[1]

Co-authors: 胡鹏; 邓磊; Fukumoto Kazui ; 张晓磊; 唐飞; 胡隆华

[1] *中国科学技术大学火灾安全全国重点实验室*

Corresponding Author: songkebin@mail.ustc.edu.cn

摘要: 由于隧道属于密闭空间且通风条件复杂，隧道火灾构成了严重的能源安全风险。一个典型场景是列车因受电弓故障引发车顶火灾，不仅释放大量热能，还可能导致车载电能与燃料能源的浪费。本研究主要关注纵向通风与横向排气相结合的耦合排烟系统在列车火灾中对能量释放和流场演变的影响，同时探索基于人工智能的列车火灾能量释放预测方法。与传统隧道地面火灾相比，区间隧道列车顶板火灾的燃烧速率呈非单调变化，其流场演变特征也显示出复杂的能量传递模式，对隧道能源管理与安全控制提出了新的要求。同时为了揭示隧道火灾全周期随时间变化的预测过程，克服传统火灾物理模型的时间限制，本文提出了一种基于深度学习的隧道火灾热释放率（HRR）和天花板热通量分布的全周期实时预测框架。该框架集成了 ResNet-18 和 ViT Small 用

于火焰图像特征提取，同时嵌入物理先验信息作为约束，在隧道纵向通风和横向提取的耦合条件下，实现了对 HRR 和隧道天花板下热通量分布的快速准确的全周期预测。

关键词: 隧道火灾、深度学习、质量损失速率、热释放速率、顶棚热流、侧向排烟

Abstract: Tunnel fires pose significant energy safety risks due to the narrow-restricted spaces and complex ventilation conditions. A typical scenario is a train roof fire triggered by a pantograph malfunction, which not only releases substantial thermal energy but also results in the wastage of electrical and fuel energy. This study focuses on the impact of the coupled lateral smoke exhaust system, which combines longitudinal ventilation and lateral exhaust, on fire heat release rate and flow field evolution during train fires, while also exploring an AI-based approach for predicting train fire dynamics. Compared with traditional ground fire in tunnels, the burning rate of train roof fires in interval tunnels shows non-monotonic changes, the evolution characteristics of the flow field also differ significantly. To reveal the prediction process of the full-period changes of tunnel fires over time and overcome the temporal limitations of traditional fire physical models, this paper proposes a full-period, real-time prediction framework for heat release rate (HRR) and ceiling heat flux profile of tunnel fires using deep learning. The framework integrates ResNet-18 and ViT-Small for flame image feature extraction, with physical prior information incorporated as auxiliary input features to enhance the model's predictive performance and physical interpretability. This enables rapid and accurate full-period prediction of the HRR and the heat flux profile beneath the tunnel ceiling under the coupled conditions of longitudinal ventilation and lateral extraction in a tunnel.

Keywords: Tunnel fire; Deep learning; Mass burning rate; Heat release rate; Ceiling heat flux; Lateral smoke extraction

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基于独立注意力演化轨迹的复合故障热工机理溯源

Authors: 李俊良[1]; 王博[1]

[1] *哈尔滨工程大学核科学与技术学院*

Corresponding Authors: 3126278883@qq.com, bowang@hrbeu.edu.cn

摘要: 针对 AP1000 核电厂在严重复合瞬态下由于强非线性关联导致的显著特征覆盖问题，提出了一种基于独立注意力度量的动态诊断架构。基于 AP1000 模拟程序 PCTRAN，对同源强关联与跨系统弱关联复合工况下的注意力动态演化行为进行了对比分析。研究表明，该架构通过引入拓扑空间度量与独立激活机制，有效解除了传统判别模型的互斥性约束，精准分离了重叠的失水特征并切断了跨系统的间接热工干扰。研究结果可为 72 小时非能动观察窗口内的操纵员辅助决策提供透明、量化的物理依据。

关键词: 核电厂；深度学习；复合故障；独立注意力

Abstract: Significant feature masking occurs in AP1000 nuclear power plants due to strong nonlinear correlations during severe composite transients. To address this, this study proposes a dynamic diagnostic architecture based on independent attention metrics. The architecture was evaluated using the AP1000 simulation system PCTRAN. A comparative analysis was conducted on the dynamic evolution of attention behaviors under composite conditions involving homologous strong correlations and cross-system weak correlations. While traditional discriminative models are restricted by mutual exclusivity constraints, the proposed architecture eliminates these barriers by incorporating topological space metrics and independent activation mechanisms. This approach enables the precise isolation of overlapping loss-of-coolant features and severs indirect cross-system thermal-hydraulic interference. These findings provide a transparent, quantified physical basis for operator decision support within the 72-hour passive observation window.

Keywords: Nuclear power plant; Deep learning; Composite faults; Independent attention.

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融合自注意力机制和 CONV-LSTM 的核电厂跨工况时序预测方法研究

Authors: 谭奥星[1]; 王博[1]

[1] *哈尔滨工程大学核科学与技术学院*

Corresponding Authors: bowang@hrbeu.edu.cn, tax3081883660@outlook.com

摘要: 随着全球能源需求的不断增长和环保要求的日益提高，核电作为一种绿色、清洁的能源形式，日益受到关注，核电厂在全球能源结构中的地位逐渐重要。然而，核电厂的复杂性及其对安全性的高度要求，使得其运行面临着诸多挑战，尤其是在时序数据的预测和监控方面。针对这一问题，本文提出了一种基于深度学习的核电厂跨工况时序预测方法。该方法结合了卷积神经网络（CNN）、长短期记忆网络（LSTM）和自注意力机制（Attention），能够有效处理核电厂不同工况下的时序数据。数据来源于 AP1000 核电厂的 PCTRAN 仿真数据。通过数据预处理和特征提取技术，本文构建了一个高效的时序预测模型，能够在核电厂运行过程中对多种工况下的时序数据进行高精度预测，从而为核电厂的安全运行提供重要支持。实验结果表明，该方法在处理复杂的时序数据时具有较高的预测精度，并能够应对核电厂运行过程中多变的非线性和时变特性。

关键词: 跨工况时序预测；核电厂；深度学习；集成学习；长期预测

Abstract: As global energy demand continues to grow and environmental requirements become increasingly stringent, nuclear energy, as a green and clean energy source, has gained significant attention, with nuclear power plants playing an increasingly important role in the global energy structure. However, the complexity of nuclear power plants and their high safety requirements pose numerous challenges in their operation, particularly in the prediction and monitoring of time-series data. To address this issue, this paper proposes a deep learning-based method for cross-condition time-series prediction in nuclear power plants. This method integrates Convolutional Neural Networks (CNN), Long Short-Term Memory Networks (LSTM), and Attention mechanisms, enabling effective processing of time-series data under various operating conditions of nuclear power plants. The data used in this study comes from the PCTRAN simulation data of the AP1000 nuclear power plant. Through data preprocessing and feature extraction techniques, an efficient time-series prediction model is constructed, capable of providing high-precision predictions for time-series data under multiple conditions during the operation of nuclear power plants, thereby offering important support for their safe operation. Experimental results demonstrate that this method achieves high prediction accuracy when handling complex time-series data and is capable of addressing the nonlinear and time-varying characteristics encountered in nuclear plant operations.

Keywords: Cross-condition time-series prediction; nuclear power plant; deep learning; ensemble learning; long-term prediction

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面向结构性网络退化的解耦式大语言模型推理系统可靠性调度方法

Author: 黄冯[1]

[1] *清华大学*

Corresponding Author: huangf23@outlook.com

摘要: 随着大语言模型推理服务从单体式架构转向 Prefill-Decode 解耦架构，跨节点 KV Cache 传输逐渐成为影响系统可靠性的关键因素。长上下文请求会产生大规模状态迁移，使推理服务的成功完成不仅依赖 GPU 计算能力和显存容量，也依赖数据中心网络路径的可用性。现有调度方法多依赖本地队列长度、连接数或显存余量进行逐请求路由，能够较好处理局部计算扰动，但在结

构性网络退化下可能产生误判。当核心链路带宽下降时，请求可能在 KV Cache 传输阶段阻塞并最终超时，而该过程并不一定及时反映到目标节点的本地队列指标中，从而诱发持续的超时级联失效。

本文提出 OTF-R，一种面向解耦式大语言模型推理系统的双环可靠性调度方法。该方法通过慢环聚合全局拓扑与资源状态，将网络退化和资源拥塞转换为 pod 级风险价格信号；快环在逐请求尺度融合本地队列、显存状态与全局风险价格，实现故障感知路由。基于 SimPy 离散事件仿真，本文在 64 节点 Fat-Tree 推理集群中注入计算退化和核心链路退化故障，并采用失败率、退化可用性、韧性指数、超时失败数和失败构成等指标进行评估。结果表明，局部计算退化主要可由本地队列感知调度处理，而结构性网络退化需要全局风险价格抑制超时级联。在最严重网络退化场景下，OTF-R 将平均失败率由 20.1% 降低至 5.9%，将退化可用性由 0.32 提升至 0.99，显著提升了系统在退化工况下的可靠性与韧性。

关键词: 大语言模型推理；解耦式服务；可靠性调度；结构性网络退化；级联失效；韧性控制

Abstract: As large language model (LLM) inference systems move from monolithic serving architectures to prefill-decode disaggregation, cross-node key-value (KV) cache transfer becomes a critical factor affecting system reliability. Long-context requests generate large state transfers, making successful inference dependent not only on GPU compute capacity and memory availability, but also on the availability of data-center network paths. Existing schedulers usually rely on local queue length, active connections, or memory availability for per-request routing. While such local policies are effective for component-level compute perturbations, they may be misleading under structural network degradation. When core-link bandwidth is reduced, requests can stall during KV-cache transfer and eventually time out, without being promptly reflected in the target node's local queue indicators. This can lead to timeout-driven cascading failures.

This paper proposes OTF-R, a dual-loop reliability-aware scheduling method for disaggregated LLM inference systems. The slow loop aggregates global topology and resource states and converts network degradation and resource congestion into a pod-level risk price. The fast loop then combines local queue information, memory state, and the global risk price to perform fault-aware request routing. Using a SimPy-based discrete-event simulator, we evaluate OTF-R on a 64-node Fat-Tree inference cluster with injected compute degradation and core-link network degradation. Reliability is assessed using failure rate, degraded availability, resilience index, timeout failures, and failure composition. The results show that local queue-aware scheduling is sufficient for component-level compute degradation, whereas structural network degradation requires global risk pricing to suppress timeout cascades. Under the most severe network degradation scenario, OTF-R reduces the mean failure rate from 20.1% to 5.9% and improves degraded availability from 0.32 to 0.99, significantly enhancing system reliability and resilience under degraded operation.

Keywords: large language model inference; disaggregated serving; reliability-aware scheduling; structural network degradation; cascading failure; resilience control

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A High-fidelity Compression Method for Optical Sensor Satellite Images Based on Detail Information Enhancement

Author: 项媛媛[1]

[1] *浙江工业大学*

Corresponding Author: xiangyuanyuan@zjut.edu.cn

摘要: 针对光学遥感卫星图像数据量激增与星上计算资源受限、高压缩比下细节失真严重的问题，本文提出一种基于细节增强的光学卫星图像高保真压缩方法。该方法引入间隔采样模块降低输入图像分辨率，显著减少模型计算复杂度，适配星上轻量化部署需求；同时设计细节信息增强模块，补偿压缩过程中的纹理与边缘损失，提升重建图像保真度。基于变分自编码器构建端到端可训练压缩框架，在多光谱与全色卫星图像数据集上开展对比实验。结果表明，所提方法在率失真

性能、细节重建效果与推理速度上均优于传统星上编解码器与现有深度学习压缩模型，可在高压缩比下实现卫星图像的高效、高保真传输，为星载光学图像实时压缩提供有效技术方案。

关键词: 光学传感器；卫星图像；图像压缩；细节增强；深度学习；星上压缩

Abstract: Aiming at the problems of explosive growth of optical remote sensing satellite image data, limited on-board computing resources, and severe detail distortion at high compression ratios, this paper proposes a high-fidelity compression method for optical satellite images based on detail enhancement. The method introduces an interval sampling module to reduce the input image resolution, which significantly decreases the model computational complexity and meets the requirements of lightweight on-board deployment. Meanwhile, a detail information enhancement module is designed to compensate for the loss of texture and edge during compression and improve the fidelity of reconstructed images. An end-to-end trainable compression framework is constructed based on variational autoencoder, and comparative experiments are carried out on multispectral and panchromatic satellite image datasets. The results show that the proposed method outperforms traditional on-board codecs and existing deep learning compression models in rate-distortion performance, detail reconstruction effect and inference speed. It can realize efficient and high-fidelity transmission of satellite images at high compression ratios, providing an effective technical solution for real-time compression of on-board optical images.

Keywords: Optical Sensor; Satellite Image; Image Compression; Detail Enhancement; Deep Learning; On-board Compression

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Interpretable Ensemble Learning for CO2-Water-Coal Wettability Prediction and In-Situ Core Validation

Authors: 余晨颖[1]; 贾云中[1]; 刘怡帆[1]; 林煜垚[1]; 易嘉奇[1]

[1] *重庆大学资源与安全学院*

Corresponding Authors: liuyifan202305@163.com, 2529530554@qq.com, yuchenying2021@163.com, yunzhong.jia@cqu.edu.cn

摘要: 深部煤层兼具 CO2 地质封存潜力与 CO2 强化煤层气开采价值，其 CO2-水-煤三相体系润湿性直接影响 CO2 吸附、甲烷置换、毛管行为及封存安全性。然而，受煤岩非均质性、实验条件差异及模型泛化能力不足等因素制约，煤润湿性的快速准确预测仍具有挑战。本文构建了包含 531 组 CO2-水-煤接触角数据的跨区域、多来源数据库，选取灰分含量、温度、压力和最大镜质体反射率作为输入变量，以接触角作为预测目标，建立并比较了随机森林、XGBoost、LightGBM、CatBoost 和 GBDT 等五类集成机器学习模型。各模型采用贝叶斯优化进行超参数寻优，并利用独立测试集评价预测性能。结果表明，CatBoost 模型表现最优，测试集决定系数 R2 达 0.881，RMSE 为 9.089°，MAE 为 6.641°。进一步采用 SHAP 方法揭示模型决策机制，发现压力是影响接触角的主控因素，其次为最大镜质体反射率、灰分含量和温度。当压力超过 7.38 MPa 后，CO2 吸附状态和密度变化促使接触角显著增大；煤阶升高会增强煤表面疏水性，而灰分中的亲水性矿物组分则总体降低接触角。最后，利用准噶尔煤田 0-1100 m 深度梯度原位岩芯样品开展外部验证，模型取得 R2 = 0.7206、MAE = 6.904° 的预测效果。研究表明，融合集成学习与可解释性分析的方法可有效连接实验室数据与实际储层润湿性评价，为 CO2 地质封存储层筛选、参数优化和工程设计提供数据驱动支撑。

关键词: CO2 地质封存；煤润湿性；接触角预测；集成机器学习；SHAP 可解释性；原位岩芯验证

Abstract: Deep coal seams are promising targets for geological CO2 storage and CO2-enhanced coalbed methane recovery, where the wettability of the CO2-water-coal system plays a key role in CO2 adsorption, methane displacement, capillary behavior, and storage security. Nevertheless, reliable wettability prediction remains difficult because coal properties are highly heterogeneous and existing models often show limited transferability. In this study, a cross-regional and multi-source database containing 531 CO2-water-coal contact-angle records was compiled. Four accessible variables, namely ash content, temperature, pressure, and maximum vitrinite reflectance, were used as model inputs, while contact

angle was taken as the prediction target. Five ensemble learning algorithms, including random forest, XGBoost, LightGBM, CatBoost, and gradient boosting decision tree, were developed and optimized through Bayesian hyperparameter tuning. Their predictive capability was then evaluated on an independent test set. Among the tested models, CatBoost achieved the best overall performance, with an R2 of 0.881, RMSE of 9.089°, and MAE of 6.641° on the test dataset. SHAP analysis was further introduced to interpret the model behavior and quantify the contribution of each variable. The results indicate that pressure is the dominant factor controlling contact angle, followed by maximum vitrinite reflectance, ash content, and temperature. A pressure threshold near 7.38 MPa marks a transition in CO2 adsorption behavior, above which the contact angle increases sharply. Higher coal rank enhances hydrophobicity, whereas ash-related hydrophilic minerals tend to reduce the contact angle. External validation using in-situ core samples from the Junggar Coalfield along a 0-1100 m depth profile yielded an R2 of 0.7206 and an MAE of 6.904°, demonstrating encouraging transferability under field-relevant conditions. This work provides an interpretable data-driven framework for assessing coal wettability and supports reservoir screening and engineering design for CO2 geological sequestration.

Keywords: CO2 geological storage; coal wettability; contact angle estimation; ensemble machine learning; SHAP interpretation; in-situ core validation

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Shared-Feature Branched Mixed PINN for Heterogeneous Neutron Diffusion Eigenvalue Problems

Author: 康耀中[1]

[1] *中国科学院上海应用物理研究所*

Corresponding Author: kangyaozhong@sinap.ac.cn

摘要: 在非均匀多材料中子扩散特征值问题中，不同材料区域通量场分布特征差异显著，传统物理信息神经网络（PINN）难以同时兼顾全局共享特征与局部介质细节。为此提出了一种共享特征分支式 PINN 方法，该方法通过共享特征提取与材料专属分支相结合的网络结构，在保持全局特征信息的同时增强了对局部介质差异的表达。进一步地，基于混合形式中子扩散方程，联合预测两群中子通量与中子流，将原始二阶扩散方程重构为通量-中子流耦合的一阶残差系统，并采用基于梯度范数反馈的自适应平衡策略，以缓解各损失项间的梯度失衡。针对特征值问题，构建源项迭代框架，实现 keff 与通量场的协同求解。在二维两群 BIBLIS 基准题上的数值结果表明，该方法在 keff 预测精度、通量分布误差以及训练速度上均优于普通 PINN，keff 误差为 1.9 pcm，两群中子通量 L2 误差为 0.815% 和 0.837%，训练提速 274%，表明该方法在复杂非均匀多材料中子扩散特征值问题的 PINN 求解中具有较好的应用潜力。

关键词: 物理信息神经网络；中子扩散特征值问题；源项迭代框架

Abstract: In heterogeneous neutron diffusion eigenvalue problems, the flux-field characteristics differ significantly among material regions, making it difficult for conventional physics-informed neural networks (PINN) to simultaneously capture globally shared features and local material-specific details. To address this issue, a shared-feature branched Mixed PINN is proposed. By combining shared feature extraction with material-specific branches, the proposed network preserves global feature information while enhancing the representation of local material heterogeneity.Furthermore, based on the mixed formulation of the neutron diffusion equation, the two-group neutron fluxes and neutron currents are jointly predicted. The original second-order diffusion equations are reformulated into a first-order residual system coupling neutron fluxes and currents. A gradient-norm-feedback-based adaptive balancing strategy is introduced to alleviate gradient imbalance among different loss terms. For the eigenvalue problem, a source-iteration framework is constructed to achieve the coupled solution of keff and the neutron flux field.Numerical results on the two-dimensional two-group BIBLIS benchmark show that the proposed method outperforms conventional PINN in keff prediction accuracy, flux-distribution error, and training efficiency. The keff error is reduced to 1.9 pcm, the relative L2 errors of the two-group neutron fluxes are 0.815% and 0.837%, respectively, and the training speed is improved by 274%. These results indicate that the proposed method has good potential for PINN-based solutions of complex heterogeneous neutron diffusion eigenvalue problems.

Keywords: Physics-informed neural networks; Neutron diffusion eigenvalue problem; Source-iteration framework

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基于显著性引导的双向复制粘贴半监督医学图像分割方法

Author: 刘毅[1]

Co-authors: 杨强 [1]; 刘首鹏 [1]

[1] *成都理工大学*

Corresponding Authors: yangqiang07@cdut.edu.cn, bmelsp@163.com, junjian59@163.com

摘要: 半监督医学图像分割（SSMIS）在减少对稀缺标注医学数据依赖方面展现出良好前景。然而，该领域仍面临诸多挑战，例如标注数据与无标注数据之间存在分布不匹配、现有图像混合策略（如随机裁剪）极易破坏医学解剖结构的连贯性，以及混合过程中引入大量无关背景噪声等问题。为解决这些难题，本文提出了一种显著性引导的半监督医学图像分割框架（SC-BCP）。该框架利用模型自身的梯度反馈，设计了一种显著性引导掩码（Saliency-Guided Mask, SGM）生成机制。具体而言，该机制首先提取置信度加权的前景梯度响应，随后通过形态学提纯与焦点区域评估，动态锁定最具信息量的解剖结构；最后提取其宏观特征生成可控的几何混合掩码。这一策略替代了传统的随机矩形掩码，在图像混合中有效保护了器官边界的完整性并抑制了背景干扰。在 ACDC 和 PROMISE12 数据集上的实验验证了该框架的有效性。相对于基线 BCP 方法，SC-BCP 取得了显著的性能提升，在 ACDC 数据集，仅使用 10% 标注数据下，Dice 系数提升了 1.35%，95HD 下降了 2.4mm；在 PROMISE12 数据集，使用 20% 标注数据下 Dice 系数提升了 15.71%，95HD 下降了 9.63mm。

关键词: 医学图像分割；半监督学习；一致性正则化；显著图

Abstract: Semi-supervised medical image segmentation (SSMIS) has shown great promise in reducing reliance on scarce annotated medical data. However, it still faces several challenges, including the distribution mismatch between labeled and unlabeled data, the disruption of anatomical structure caused by conventional image mixing strategies such as random cropping, and the introduction of excessive irrelevant background noise during the mixing process. To address these issues, we propose a saliency-guided semi-supervised medical image segmentation framework, termed SC-BCP. The proposed framework leverages the model's own gradient feedback to develop a Saliency-Guided Mask (SGM) generation mechanism. Specifically, it first extracts confidence-weighted foreground gradient responses, then dynamically identifies the most informative anatomical structures through morphological refinement and focal-region assessment, and finally derives controllable geometric mixing masks from their macroscopic features. Compared with conventional random rectangular masks, the proposed strategy better preserves organ boundary integrity and suppresses background interference during image mixing. Experiments on the ACDC and PROMISE12 datasets demonstrate the effectiveness of SC-BCP. Compared with the baseline BCP method, SC-BCP achieves significant performance improvements. On ACDC, using only 10% labeled data, it improves the Dice coefficient by 1.35% and reduces the 95% Hausdorff Distance (95HD) by 2.4 mm. On PROMISE12, with 20% labeled data, it improves the Dice coefficient by 15.71% and reduces the 95HD by 9.63 mm.

Keywords: Medical image segmentation；Semi-supervised learning；Consistency regularizationy；Saliency maps

Chapter 7

工程博士论坛

水体放射性核素在线监测系统研发及现场应用

Author: 郭生良[1]

[1] *清华大学工程物理系*

Corresponding Author: 13831779@qq.com

摘要: 为提高环境水体放射性监测能力并实现核事故的快速预警，研发了一套可适配多种工况的在线水体放射性测量系统。该系统基于大体积低本底铅室屏蔽结构设计，可根据监测需求配置高纯锗（HPGe）或溴化铈（$CeBr_3$）探测器。通过数值模拟方法，确定了系统对不同能量伽马射线的探测效率及典型核素的最小可探测活度浓度。结果表明，对于常见人工放射性核素 131I、60Co 及 137Cs，系统在正常工况下最小可探测活度浓度均低于 0.02 Bq/L。利用核素衰变纲图与天然衰变链关系，计算了水中天然放射性核素贡献的总 α 与总 β 活度。采用低本底气式正比计数器对在线测量结果进行验证，两者在总 α 与总 β 测量中的平均相对误差分别为 12.6% 与 4.5%，结果一致性良好。该监测系统提供站房与车载两种安装方案，已实际应用于饮用水源、长江流域及核设施排放口等关键点位，并纳入四川省核应急体系，解决了复杂环境下快速测量与稳定运行的工程问题。

关键词: 水体 γ 核素在线监测，溴化铈探测器，总 α 与总 β

Abstract: To enhance the monitoring capability of environmental water radioactivity and enable rapid warning of nuclear accidents, an online water radioactivity measurement system adaptable to various working conditions has been developed. The system is designed based on a large-volume, low-background lead-shielded structure and can be configured with either a high-purity germanium (HPGe) or cerium bromide (CeBr3) detector flexibly according to monitoring requirements. Through numerical simulation, the detection efficiency for gamma rays of different energies and the minimum detectable activity concentration for typical radionuclides were determined. The results show that for common artificial radionuclides such as 131I, 60Co, and 137Cs, the minimum detectable activity concentration of the system is below 0.02 Bq/L under normal operating conditions. Using the decay schemes of radionuclides and the natural decay chains, the total α and total β activities contributed by natural radionuclides in water were further calculated. The online measurement results were validated using a low-background gas-flow proportional counter, and the average relative errors were 12.6% and 4.5% for total α and total β measurements respectively, indicating good consistency. The monitoring system offers two installation options: station-based and vehicle-mounted. It has been practically deployed at key locations such as drinking water sources, the Yangtze River basin, and nuclear facility discharge outlets, and has been incorporated into the nuclear emergency system of Sichuan Province, addressing engineering challenges related to rapid measurement and stable operation in complex environments.

Keywords: online monitoring γ nuclides in water, cerium bromide detector，total α and tota β

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一体化供热堆工程模拟机关键技术研究

Authors: 孙俊[1]; 何雷元[2]; 杨淑涵[2]; 王煦嘉[2]; 周韦[2]

[1] *清华大学*

[2] *上海核工程研究设计院股份有限公司*

Corresponding Author: hly917@126.com

摘要: 一体化供热堆主要是用于满足工业供汽、核能供暖、海水淡化等需求的全新堆型，为解决一体化供热堆研发过程中的控制运行方案论证，工艺、控制和人机操作界面系统闭环设计验证，以及操作规程研发验证等综合性问题，需要研发一套适用于一体化供热堆的工程模拟机。本文基于一体化供热堆型号特点，开展了一体化供热堆工程模拟机关键技术的深入分析和研发工作，建立了一体化供热堆工程模拟机，并利用所研发的工程模拟机对供热堆运行控制方案进行了验证和优化。研究发现了一体化全自然循环反应堆降功率特有的惯性延迟特性，采用经过优化的控制系统可以有效缓解一体化供热反应堆功率线性变化瞬态工况下反应堆功率、一回路平均温度、二回路蒸汽压力等关键参数的周期性震荡。所研发的一体化供热堆工程模拟机为供热堆控制方案论证提供了有利的研究工具，为后续工艺、仪控闭环验证、操作规程研发验证提供了有利工具。

关键词: 一体化供热反应堆；工程模拟机；实时仿真；DCS

Abstract: The integrated heating reactor is a novel design intended to meet diverse energy demands, including industrial steam supply, district heating, and seawater desalination. To address key challenges in its development—such as verifying control strategies, conducting closed-loop validation of processes, instrumentation and control (I&C), and human–machine interface systems, and ensuring the correctness and practicality of operating procedures—a dedicated engineering simulator is essential. Building on the reactor's specific design features, this study analyzes key enabling technologies, develops an engineering simulator, and uses it to verify and optimize operational control schemes. The investigation reveals an inherent inertia-induced delay in power ramping unique to fully natural-circulation reactors. By applying optimized control systemtrategies, oscillations in reactor power, primary loop average temperature, and secondary loop steam pressure during ramp power change transients are effectively suppressed. The developed engineering simulator therefore serves as a powerful platform for evaluating control strategies, providing crucial support for closed-loop verification of processes and instrumentation, and refining operational procedures.

Keywords: integrated heating reactor; engineering simulator; real-time simulation; distributed control system

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镧蛋白工程化细菌外膜囊泡用于协同靶向放射免疫治疗

Author: 张菲菲[1]

[1] *兰州大学*

Corresponding Author: 2558578812@qq.com

摘要: 靶向放射性核素治疗（TRT）与免疫治疗的联合为增强抗肿瘤免疫提供了强有力的策略，然而适应性递送平台的开发仍面临挑战。本研究报道了一种可编程的” 即插即用” 纳米平台——TRT@LnOMVs，通过将镧蛋白（LanM）展示于减毒鼠伤寒沙门氏菌来源的外膜囊泡（OMVs）表面，实现了多种治疗性放射性核素（如 177Lu、90Y、225Ac）在温和条件下的高效、稳定标记，克服了传统螯合剂方法的局限性。该平台具有模块化特性，可通过脂质插入策略便捷地偶联靶向配体（如 PSMA、FAP）。在前列腺癌模型中，与临床批准的 ^177^Lu-PSMA-617（PluvictoTM）进行头对头比较，PSMA 靶向 TRT@LnOMVs 实现了 90% 的生存率，远超 PluvictoTM 的 25%。单细胞

RNA 测序和转录组分析揭示，TRT@LnOMVs 通过激活先天免疫并重编程免疫抑制性髓系细胞群，从根本上重塑肿瘤免疫微环境，触发强大的抗肿瘤免疫应答。该研究为下一代放射免疫治疗提供了强有力的范式。

关键词: 细菌外膜囊泡；放射免疫治疗；镧蛋白；靶向放射性核素治疗；肿瘤免疫微环境

Abstract: The combination of targeted radionuclide therapy (TRT) with immunotherapy offers a potent strategy to amplify anti-tumor immunity, yet the development of adaptable delivery platforms remains challenging. Herein, we report a programmable, “plug-and-play” nanoplatform, termed TRT@LnOMVs, engineered for synergistic radio-immunotherapy. By displaying lanmodulin (LanM) on the surface of outer membrane vesicles (OMVs) derived from attenuated Salmonella typhimurium, this platform enables versatile and high-efficiency radiolabeling of diverse therapeutic radioisotopes (177Lu, 90Y, 225Ac) under mild conditions, circumventing the limitations of conventional chelator-based methods. The platform’s modularity is further demonstrated by the facile incorporation of lipid-conjugated ligands for precision targeting. In a head-to-head comparison with clinically approved 177Lu-PSMA-617 (PluvictoTM), PSMA-targeted TRT@LnOMVs achieved a 90% survival rate in a prostate cancer model, far surpassing the 25% survival rate of PluvictoTM. Single-cell RNA sequencing and transcriptomic analysis revealed that TRT@LnOMVs fundamentally remodel the tumor immune microenvironment by activating innate immunity and reprogramming immunosuppressive myeloid compartments to trigger robust anti-tumor immunity. Collectively, TRT@LnOMVs represent a versatile class of bio-hybrid therapeutics, offering a robust paradigm for next-generation radio-immunotherapy.

Keywords: Outer membrane vesicles; Radio-immunotherapy; Lanmodulin; Targeted radionuclide therapy; Tumor immune microenvironment

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加速器质子辐照镓镍合金靶与铌-镓胶囊封装靶制备 ^{68}Ge 研究

Author: 李勇[1]

Co-authors: 王宇 [1]; 赵鹏飞 [1]; 官国英 [1]; 安世忠 [1]; 赵龙云 [1]; 陈靖 [2]; 张利峰 [1]

[1] *中国原子能科学研究院*

[2] *清华大学*

Corresponding Author: liyong24@mails.tsinghua.edu.cn

摘要: 本研究对比了通过质子辐照两种靶件制备生产 68Ge 的方法：镓镍合金靶件和铌-镓胶囊封装靶件。基于回旋加速器同位素辐照靶站要求，镓镍合金靶件通过优化电沉积工艺，在铜靶托上电镀得到镓镍合金层。而铌-镓胶囊封装靶件采用耐液态金属镓腐蚀的铌作为封装外壳，内部填充天然金属镓而制得。两种靶件经回旋加速器上质子束进行辐照，生成的 68Ge 随后使用树脂柱进行分离纯化。结果表明，镓镍合金靶件表面光滑、牢固性良好，但其较低的靶材载量和易受热损伤的特性限制了其大规模应用。铌-镓胶囊封装靶件具有更高的靶材载量，在辐照条件下的稳定性和安全性更优，但由于镓的熔点低，其对铌外壳焊接和整体密封性能要求较高。在 68Ge 的分离纯化方面，电镀靶的溶解过程为开放式操作，会引入大量杂质，需要结合螯合树脂和凝胶树脂进行分离纯化。而铌-镓胶囊封装靶件可实现封闭操作，杂质水平更低，分离纯化更具优势。

关键词: 锗-68；镓镍合金靶件；铌-镓胶囊封装靶件；分离纯化

Abstract: This study compares the production of 68Ge using proton irradiation on two types of targets: an electroplated gallium-nickel alloy solid target and a niobium-encapsulated capsule with natural gallium. The alloy target was prepared on copper via electroplating, while the capsule was designed and fabricated to be irradiated in a cyclotron. The generated 68Ge was then separated and purified using resin columns. Results show the electroplated target had a smooth surface and good adhesion, but its low loading capacity and vulnerability to thermal damage limit its use for large-scale production. The niobium-encapsulated target, with its higher loading capacity, improved stability and safety under irradiation, though it requires precise welding and sealing due to gallium’s low melting point. For the

separation and purification of 68Ge, the dissolution of the electroplated target is an open operation that introduces significant impurities, necessitating a combined purification process using both chelating and gel resins. In contrast, the niobium-encapsulated target allows for a closed operation, resulting in lower impurity levels and offering distinct advantages for subsequent purification.

Keywords: germanium-68; gallium-nickel alloy target; Niobium-encapsulated gallium capsule target; separation and purification

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燃料棒包壳与定位格架微动磨损行为的数值模拟研究

Author: 陈俊宇[1]

Co-authors: 崔文栋 [2]; 于莅洋 [2]; 聂君锋 [2]

[1] *清华大学*

[2] *清华大学核能与新能源技术研究院*

Corresponding Author: chenjuny24@mails.tsinghua.edu.cn

摘要: 压水堆燃料组件在服役过程中受冷却剂流致振动影响，会导致燃料棒包壳与定位格架之间发生微幅往复的相对滑移，即格架-燃料棒微动（Grid-to-Rod Fretting, GTRF）。长期的微动累积会引发包壳表面磨损及疲劳损伤，进而导致燃料棒破损失效，成为当前核电机组燃料棒失效的主要原因。因此，研究包壳的微动磨损演化机制和进行磨损预测，对提升燃料组件可靠性及保障反应堆安全运行具有重要意义。本文基于燃料棒包壳与定位格架的实际几何特征，建立了包壳-刚凸接触的微动磨损有限元分析模型，结合 Archard 磨损理论，利用 ABAQUS 中的 UMESHMOTION 子程序与 ALE 自适应网格技术，实现了微动磨损过程的动态模拟。重点研究了法向载荷和切向位移等微动参数对包壳磨损特性的影响，并深入分析了微动磨损过程中的接触压力和应力分布规律，得到磨损形貌和磨损量曲线，为 GTRF 磨损行为的预测与评估提供了有效的数值计算方法。

关键词: 微动磨损；燃料组件；有限元分析

Abstract: Pressurized water reactor (PWR) fuel assemblies are subjected to coolant flow-induced vibration (FIV), which causes small-amplitude reciprocating relative sliding between the fuel rod cladding and the spacer grids, known as Grid-to-Rod Fretting (GTRF). Long-term fretting accumulation induces surface wear and fatigue damage on the cladding, eventually leading to the rupture and failure of the fuel rods. As GTRF is currently one of the primary causes of fuel rod failure in nuclear power plants, investigating the fretting wear evolution mechanism of the cladding and predicting the wear volume is of great significance for improving the reliability of fuel assemblies and ensuring the safe operation of reactors. Based on the actual geometric characteristics of the fuel rod cladding and spacer grids, a finite element analysis (FEA) model for the cladding-to-rigid dimple contact was established in this paper. Incorporating the Archard wear equation, the dynamic simulation of the fretting wear process was achieved by utilizing the UMESHMOTION subroutine and the Arbitrary Lagrangian-Eulerian (ALE) adaptive meshing technique in ABAQUS. The effects of fretting parameters, such as normal load and tangential displacement, on the wear characteristics of the cladding were systematically investigated. Furthermore, the contact pressure and stress distribution patterns during the fretting wear process were analyzed to obtain the wear profiles and wear volume curves. This study provides an effective numerical calculation method for the prediction and evaluation of GTRF wear behavior.

Keywords: Fretting wear；Fuel assembly；Finite element analysis

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高效阻氚涂层的研究进展与新型设计思路

Author: 李鑫[1]

Co-authors: 吴孟涵[2]; 廖斌[3]; 邢继[2]; 陈靖[4]

[1] *清华大学中国核电工程有限公司*

[2] *中国核电工程有限公司*

[3] *北京师范大学*

[4] *清华大学*

Corresponding Authors: liaobingz@bnu.edu.cn, jingxia@tsinghua.edu.cn, wumha@cnpe.cc, 625593929@qq.com, xingji@cnpe.cc

摘要: 在迈向聚变能商业化的进程中，聚变堆氚安全包容已成为制约百万千瓦级聚变发电站发展的关键瓶颈之一。对于百万千瓦功率的聚变堆，系统内每日在线循环的氚总量达十几公斤。然而，基于极其严格的辐射防护标准，聚变设施向环境的允许氚排放量被限制在极低的水平（数十 Ci 级别）。海量的氚滞留量与近乎零排放的安全要求之间形成了巨大矛盾，亟需开发高效、长寿命的阻氚屏障，以彻底阻断氚通过结构材料（如第一壁、管道等）的渗透与扩散。
目前，针对氚阻挡层的研究多采用物理气相沉积（PVD）、化学气相沉积（CVD）等常规制备技术。然而，现有涂层普遍存在致密度不足、界面结合力弱、内应力大易开裂以及高温辐照下阻氚性能迅速退化等致命缺陷，难以满足聚变堆苛刻的服役环境。针对上述痛点，本项目拟提出一种基于先进载能离子束技术制备高效阻氚涂层的全新解决方案，其核心创新点主要体现在制备技术的升级与涂层结构的仿生设计两方面。
首先，在制备技术上，本项目摒弃传统沉积方法，引入先进的磁过滤阴极弧（FCVA）载能离子束技术。该技术通过磁过滤装置彻底滤除了大颗粒中性杂质，可获得高纯度、高离化率的金属/非金属离子。利用载能离子在基体表面的亚注入效应，不仅实现了涂层与基体之间的稳定结合，还能在较低温度下原位生长出无孔洞、无柱状晶缺陷的极高致密涂层，从物理路径上直接切断了氚的快速扩散通道。
其次，在结构设计上，本项目突破传统单层阻挡的局限，提出构建“类皮肤”多功能梯度涂层结构。涂层被精巧地设计为“阻氚层-储氚层”复合体系。外层阻氚层依托高致密、低氚溶解度的陶瓷或金属间化合物，发挥“物理屏蔽”功能，将氚渗透率降至最低；内层储氚层则利用特定材料与氚的可逆 trapping 效应，构建“化学捕获”缓冲区。当微量氚突破阻氚层时，会被储氚层定点吸附固定，形成动态平衡，有效缓解了氚在涂层/基体界面的富集与侧向扩散，实现“阻-储”协同增效。
综上，本项目通过“高能束流精密调控 + 仿生类皮肤结构设计”的双轮驱动，可为解决聚变堆海量氚的安全包容难题提供革命性的材料方案，不仅具有重要的科学价值，更为我国聚变工程的实质性推进提供坚实的安全技术保障。

关键词: 聚变堆；氚安全包容；磁过滤载能离子束；类皮肤涂层；阻氚层；储氚层

Abstract: Safe tritium containment is a critical bottleneck for gigawatt-level fusion power plants. The massive daily tritium circulation (up to tens of kilograms) to sustain plasma burnup strictly contradicts the near-zero environmental emission limits (on the order of tens of Curies). Conventional barrier coatings prepared by traditional methods suffer from poor density, weak adhesion, and rapid performance degradation under harsh fusion environments.
To address this, we propose a novel approach utilizing advanced filtered energetic ion beam technology to prepare highly efficient tritium barrier coatings. This technique thoroughly eliminates macroparticle impurities, enabling the *in-situ* growth of ultra-dense, columnar-free coatings with robust pseudo-diffusion interfacial bonding. This fundamentally eliminates micro-defects and physically blocks tritium fast diffusion pathways.
Furthermore, we pioneer a biomimetic “skin-like”gradient structure comprising a “tritium-blocking layer”and an inner “tritium-storage layer.”The outer dense ceramic or intermetallic layer provides primary physical shielding to minimize permeation, while the inner layer acts as a chemical capture buffer. It immobilizes any trace permeated tritium via reversible trapping effects, establishing a dynamic equilibrium that effectively prevents interfacial enrichment and lateral diffusion.
By combining precision energetic beam control with this synergistic “blocking-storage”structural design, this project develops a revolutionary barrier coating. It provides a crucial material solution for the safe containment of massive tritium inventories in future fusion engineering.

Keywords: Fusion reactor; Tritium containment; Energetic ion beam; Skin-like coating; Tritium barrier

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后处理厂设计数据管理示范系统开发研究

Author: 陈勇[1]

Co-authors: 秦永泉 [2]; 牟勇胜

[1] *清华大学核能与新能源技术研究院*

[2] *中国核电工程有限公司*

Corresponding Author: chenyoucn@sohu.com

摘要: 多源异构数据模式下以业务数据标准为基础，构建动态可扩展数据模型、实现多维度数据交互联动是建立综合性信息化平台的基础。通过后处理厂设计流程梳理确定了数据标准化的范围、内容、数据类型以及数据流转过程；基于后处理厂设计流程开展了数据标准化与规范化研究，形成了标准化数据清册，为多源异构数据的识别和内在关联关系的建立提供基本准则和核心依据；以数据标准的对象类为基础建立了核燃料后处理厂 PBS（Plant Breakdown Structure）画布；利用数据库动态建模技术、联机事务处理（OLTP-Online Transaction Processing）和联机分析处理（OLAP-Online Analytical Processing）技术建立了数据存储模型，设计了数据处理主流程图；结合多板块对设计数据的需求和多层级微服务理念设计了系统的总体架构，开发了后处理厂设计数据管理示范系统，并在后处理示范工程建安中应用，为多板块数据深度应用提供了技术支撑。

关键词: 后处理厂，设计数据管理，示范系统

Abstract: Building a dynamic and scalable data model based on business data standards under a multi-source and heterogeneous data environment, and achieving multi-dimensional data interaction is the foundation for establishing a comprehensive information platform. By analyzing the design processes of the reprocessing plant, the scope, content, data types, and data flow processes for data standardization have been determined. Based on the design processes of the reprocessing plant, research on data standardization and normalization has been conducted, resulting in a standardized data catalog, which provides basic guidelines and core references for identifying multi-source heterogeneous data and establishing their intrinsic relationships. Based on the object classes of the data standards, the Plant Breakdown Structure (PBS) canvas for the nuclear fuel reprocessing plant has been established. Using dynamic database modeling technology, as well as Online Transaction Processing (OLTP) and Online Analytical Processing (OLAP) technologies, a data storage model has been developed, and the main data processing workflow has been designed. By integrating the design data requirements of multiple sectors and the concept of multi-level micro services, the overall system architecture has been designed, and a demonstration data management system for the reprocessing plant has been developed. This system has been applied in the construction of the reprocessing demonstration project, providing technical support for in-depth data applications across multiple sectors.

Keywords: Reprocessing Plant, Design Data Management, Demonstration System

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铁腐蚀产物对铁白铜传热管腐蚀影响试验研究

Author: 孔夏明[1]

[1] *中船 719 所*

Corresponding Author: kongkean2008@163.com

摘要: 铁白铜以其出色的耐腐蚀性和热交换效率，广泛应用于核动力装置的海水换热系统，但近年来在使用中也发生了多起铁白铜传热管腐蚀泄漏问题。通过传热管失效分析，发现热管表面附着了大量铁腐蚀产物，可能是导致传热管腐蚀泄漏的原因。本文通过实验室内合成铁腐蚀产物，模拟核动力装置水质环境，开展了铁腐蚀产物对铁白铜传热管腐蚀影响实验研究。实验结果证明

在海水中，当致密铁腐蚀产物层吸附于铁白铜表面时，其在边界处对铁白铜具有一定的腐蚀促进作用；当多孔铁腐蚀产物层吸附于铁白铜表面时，其对铁白铜表面产生垢下腐蚀作用，经过 30 天浸泡后，腐蚀坑深度达到 102μm，以此推算深度腐蚀速率为 1.24mm/a。

关键词: 铁白铜；铁腐蚀产物；垢下腐蚀

Abstract: Iron white copper (often referred to as cupronickel) is extensively utilized in the seawater heat exchange systems of nuclear power installations owing to its superior corrosion resistance and thermal efficiency. However, in recent years, numerous cases of corrosion-induced leakage in these heat transfer tubes have been reported during operation.Failure analysis revealed that a significant accumulation of iron corrosion products adhered to the tube surfaces, suggesting these deposits as the probable cause of the leaks. This study investigates the impact of these products on the corrosion behavior of iron white copper tubes by synthesizing iron corrosion products in the laboratory and simulating the water chemistry environment of nuclear power facilities.
Experimental results demonstrate that in a seawater environment:When a dense layer of iron corrosion products adheres to the surface, it promotes corrosion at the boundaries.
When a porous layer adheres, it induces under-deposit corrosion.After 30 days of immersion, the corrosion pit depth reached 102 μm, which extrapolates to a deep penetration corrosion rate of 1.24 mm/a.

Keywords: Iron white copper (BFe) ；Iron corrosion products；Under-deposit corrosion

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超高精度 X 射线光学元件加工技术

Author: 樊非[1]

Co-authors: 侯晶 [1]; 王铭 [1]; 钟波 [1]; 黄文会 [2]

[1] *中国工程物理研究院激光聚变研究中心*

[2] *清华大学工程物理系*

Corresponding Author: fanfei65790299@163.com

摘要: 高精度 X 射线单晶硅反射镜是同步辐射光源和自由电子激光装置中的关键光学元件，其面形精度、斜率误差和表面粗糙度直接影响衍射极限聚焦、光束亮度和空间分辨率等核心性能。长期以来，高品质 X 射线单晶硅反射镜主要依赖国外供应，发展自主可控的超高精度 X 射线光学元件加工技术具有重要意义。然而，受单晶硅材料难加工特性、复杂曲面误差确定性控制难度以及近零缺陷表面创成能力不足等因素制约，国内元件在纳米级面形、纳弧度斜率和原子级超光滑表面等全空间频段指标方面仍存在差距。
针对上述问题，本文提出了“超精密磨削成形—气囊快速抛光—磁流变精密修形”组合加工工艺路线，突破了单晶硅 X 射线光学元件亚纳米级低损伤表面加工关键技术。通过研究单晶硅材料表面力学特征，揭示了磁场、流量、浸入深度等工艺参数对磁流变抛光力的影响规律，建立了基于磨料优化配比的低应力磁流变抛光方法，实现了单晶硅元件低损伤表面创成。同时，建立了宽范围磁流变去除函数调控方法，发展了不同空间尺度去除函数与元件频谱误差相匹配的确定性修正算法，可根据表面误差分布特征选择兼顾修形精度与加工效率的去除函数组合，实现元件全空间频段纳米级误差修正。
基于上述技术，完成了 600 mm 单晶硅反射镜和 X 射线柱面 KB 镜研制。其中，600 mm 单晶硅反射镜面形误差 PV 值达到 7.1 nm，表面粗糙度 RMS 达到 0.18 nm；柱面 KB 镜面形误差 PV 值达到 6.38 nm，表面粗糙度 RMS 达到 0.23 nm。经 X 射线显微成像应用验证，所研制元件成像效果达到 J-Tec 同类元件水平。该研究为同步辐射光源和自由电子激光装置中高性能 X 射线光学元件的自主研制奠定了技术基础。

关键词: 同步辐射光源；自由电子激光；X 射线光学；单晶硅反射镜；超精密加工

Abstract: Single-crystal silicon mirrors are enabling optical components in synchrotron radiation sources and X-ray free-electron laser facilities, where residual figure error, slope error, and surface microroughness directly limit diffraction-limited focusing, brilliance preservation, and imaging resolution. The

fabrication of high-quality X-ray mirrors remains technically demanding because single-crystal silicon is brittle and damage-sensitive, while X-ray optics require deterministic control of surface errors over a broad spatial-frequency range together with near defect-free, atomically smooth surfaces.
Here, we report an integrated fabrication process combining ultra-precision grinding, rapid bonnet polishing, and magnetorheological finishing for high-precision X-ray optical components. The surface mechanical response of single-crystal silicon was investigated, and the influence of magnetic field strength, slurry flow rate, and immersion depth on the magnetorheological finishing force was clarified. Based on optimized abrasive formulations, a low-stress magnetorheological finishing strategy was developed to suppress surface and subsurface damage during material removal.
To enable deterministic correction over multiple spatial scales, a tunable removal-function control method was established, and a frequency-domain matching algorithm was developed to correlate removal functions with measured surface-error spectra. This approach allows suitable removal-function combinations to be selected according to the spatial distribution of surface errors, thereby improving both correction accuracy and processing efficiency. As a result, nanometer-level error correction across the relevant spatial-frequency range was achieved.
Using the developed process, a 600 mm single-crystal silicon mirror and a cylindrical Kirkpatrick–Baez mirror were fabricated. The 600 mm mirror achieved a peak-to-valley figure error of 7.1 nm and a root-mean-square surface roughness of 0.18 nm, while the cylindrical KB mirror achieved a peak-to-valley figure error of 6.38 nm and a root-mean-square roughness of 0.23 nm. X-ray microscopic imaging tests further confirmed that the fabricated optics delivered imaging performance comparable to that of similar J-Tec components. These results demonstrate a viable process route for the domestic fabrication of high-performance X-ray optics for synchrotron radiation and X-ray free-electron laser applications.

Keywords: Synchrotron radiation sources; X-ray free-electron lasers; X-ray optics; single-crystal silicon mirrors; ultra-precision fabrication

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机器学习增强 LIBS 法用于熔盐中高浓度铀的定量分析

Author: 卿琪[1]

[1] *清华大学*

Corresponding Author: qq22@mails.tsinghua.edu.cn

摘要: 激光诱导击穿光谱（LIBS）作为一种定量检测手段，可应用于乏燃料电解精炼过程中熔盐内铀（U）离子浓度的快速检测，但受限于数据分析方法的不足，其定量准确性偏低，在高浓度离子检测场景中该问题尤为突出。为此，本研究以固体 LiCl-KCl-UO2Cl2 熔盐中的 U 离子 (含量 0-20 wt.%) 为研究对象，提出了一种机器学习（ML）增强的 LIBS 建模流程，采用偏最小二乘回归（PLSR）算法建立定量模型，全面评估数据预处理算法、特征提取算法及建模算法对模型性能的提升效果。结果表明，采用通道基线校正（CBC）-通道内标（CIS）-竞争性自适应重加权采样（CARS）特征提取-偏最小二乘回归（PLSR）的建模流程为最佳建模方案，模型的预测集决定系数（R2p）> 0.99，实现了对熔盐中高浓度 U 的准确定量，与未进行预处理的传统 ULR 模型相比，预测性能提升了 82.32%。本研究提出的机器学习增强型 LIBS 建模流程，有望攻克液态熔盐体系中高浓度铀及其他离子精准定量分析的技术难题.

关键词: 激光诱导击穿光谱，高浓度铀，机器学习，熔盐，定量分析

Abstract: Laser-Induced Breakdown Spectroscopy (LIBS) can serve as a rapid detection method for quantifying uranium (U) concentration in molten salt during the electrorefining of spent nuclear fuel. However, its quantification accuracy is low due to limitations in data analysis methods, a problem that becomes particularly pronounced in the detection of high-concentration ions. Herein, this study focuses on solid LiCl-KCl-UO2Cl2 molten salt with a U content of 0-20 wt% as the research object. By integrating machine learning, the modeling approach of the LIBS quantitative analysis model is gradually optimized, with a comprehensive evaluation of the performance enhancement effects of data preprocessing algorithms, feature extraction algorithms, and modeling algorithms. The results indicate that the optimal modeling scheme is Channel Baseline Correction (CBC)-Channel Internal Standard (CIS)-Competitive Adaptive Reweighted Sampling (CARS) feature extraction-Partial Least Squares Regression

(PLSR), which achieves a prediction set coefficient of determination (R2p) > 0.99 and enables the accurate quantification of high-concentration U in molten salt. The optimized modeling flow improved the prediction performance (evaluated by CV-RMSEp) by 82.32% relative to the baseline ULR model without preprocessing. The machine learning-enhanced LIBS modeling scheme proposed in this study is expected to overcome the technical challenges of precise quantitative analysis for high-concentration uranium and other ions in liquid molten salt systems.

Keywords: LIBS, High concentration uranium, Machine learning, Molten salt, Quantitative analysis

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一种用于三维辐射场精细重建的深度学习框架

Author: 胡豪[1]

[1] *清华大学*

Corresponding Author: huhao22@mails.tsinghua.edu.cn

摘要: 核能是全球清洁能源组合的关键组成部分。在核设施的设计、运行、退役及后处理等全生命周期中，准确表征三维空间剂量率分布对于保障作业人员辐射安全及优化屏蔽方案至关重要。然而，受限于探测成本与环境限制，实际工程中的测点通常极度稀疏，使得获取高分辨率辐射场数据面临巨大挑战。本研究提出了一种通用的深度学习框架 PatchUNet3D，旨在通过极少量测点实现高精度三维辐射场重建。该框架的核心创新在于 Patchify Stem 模块。该模块采用单步大步长（stride=5）三维卷积，替代了标准 UNet3D 前两级的全分辨率编码操作，将极稀疏输入的有效信息密度提升了约 125 倍，从根本上解决了标准架构在处理海量零值体素时参数更新效率低下的瓶颈。在参数量相近（约 5.8M）的条件下，本研究建立了 PatchUNet3D 与标准 UNet3D 的严格消融对比。以核电站放射性废物桶暂存库为典型验证场景，在复杂度递增的蒙特卡洛仿真数据集上进行的系统评估结果表明，所提框架在重建精度、高剂量区域保真度及鲁棒性方面均显著优于基准模型。实验证实，PatchUNet3D 在仅有 1 到 10 个测点的条件下仍能保持优异的性能，大幅降低了对密集传感器网络的依赖。本研究为核设施低成本、实时辐射监测提供了新的技术范式，在提升核安全保障与运维效率方面具有显著的应用价值

关键词: 三维辐射场重建；深度学习；核废物处置；稀疏数据；U-Net

Abstract: Nuclear energy is a critical component of the global clean energy portfolio. The safety and efficiency of its lifecycle, particularly during radioactive waste disposal, rely on the accurate characterization of the three-dimensional (3D) radiation field. However, the sparse distribution of measurements often makes it difficult to obtain high-resolution radiation field data. This study addresses this challenge by developing an innovative PatchUNet3D deep learning framework for high-accuracy 3D radiation field reconstruction from sparse measurements. The core innovation of the proposed method is the Patchify Stem module —a single large-stride (stride=5) 3D convolution that replaces the first two full-resolution encoding stages of the standard UNet3D, boosting the effective information density of the sparse input by a factor of ~125×. The effectiveness of the proposed method is evaluated by comparing its performance against a conventional single-step UNet3D architecture designed for the same end-to-end prediction task. Our results demonstrate that, with nearly identical parameter counts, PatchUNet3D significantly outperforms the UNet3D baseline. Moreover, this method significantly reduces the reliance on dense sensor networks, enabling more cost-effective monitoring systems. The framework's performance was rigorously evaluated on a simulated dataset representing diverse scenarios within a nuclear waste disposal facility. The results confirm the model's high accuracy and robustness, demonstrating its substantial application value in advancing the safety and efficiency of nuclear waste disposal operations.

Keywords: 3D Radiation Field; Deep Learning; Nuclear Waste Disposal; Sparse Data; UNet3D; PatchUNet3D; Patchify Stem.

Chapter 8

英文论坛

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高温气冷堆主氦风机无变压器逆变器仿真设计

Author: 金俞熹[1]

Co-authors: hong wang ; kui wang ; yinan geng

[1] *清华大学核能与新能源技术研究院*

Corresponding Author: yx-jin24@mails.tsinghua.edu.cn

摘要: 摘要：针对高温气冷堆主氦风机传统 H 桥级联驱动方案依赖移相变压器、体积大成本高，以及三电平拓扑在 6kV 中压工况下存在超压击穿风险的问题，本文将 5L-ANPC 无变压器拓扑应用于 4.5MW 主氦风机驱动系统，完成调制策略适配与电容电压平衡控制参数整定，搭建仿真模型开展全工况验证。结果表明，系统输出线电压 THD 低至 0.39%，直流侧中点电压稳态波动收窄至 ±200V，负载阶跃下具备优异的动稳态性能。本文结合安全裕量给出 IGBT 选型参考，为该驱动高温气冷堆主氦风机系统无变压器化升级提供了工程可行方案。

关键词: 高温气冷堆；主氦风机；5L-ANPC；零序电压；IGBT 选型

Abstract: To address the defects of the traditional H-bridge cascaded drive scheme for the main helium blower of High Temperature Gas-cooled Reactor (HTGR), including dependence on phase-shifting transformers, large volume and high cost, as well as the over-voltage breakdown risk of three-level topology under 6kV medium-voltage conditions, this paper applies the transformer-less five-level active neutral-point-clamped (5L-ANPC) topology to the 4.5MW main helium blower drive system. The modulation strategy adaptation and parameter tuning of capacitor voltage balance control are completed, and a simulation model is established for full-operating-condition verification. The results show that the THD of system output line voltage is as low as 0.39%, the steady-state fluctuation of DC-side neutral-point voltage is narrowed to ±200V, and the system presents excellent dynamic and steady-state performance under load steps. Combined with safety margin requirements, this paper provides IGBT selection reference, and offers an engineering feasible scheme for the transformer-less upgrade of the HTGR main helium blower drive system.

Keywords: HIGH TEMPERATURE GAS-COOLED REACTOR (HTGR); MAIN HELIUM BLOWER; FIVE-LEVEL ACTIVE NEUTRAL-POINT-CLAMPED (5L-ANPC); ZERO-SEQUENCE VOLTAGE; IGBT SELECTION

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基于粒子尺度固液二元响应的过冷液体流动行为研究

Author: 于东旭[1]

[1] *清华大学工程物理系*

Corresponding Author: ydx22@mails.tsinghua.edu.cn

摘要: 过冷液体展现出丰富的物理现象和非线性流变响应，理解其流动行为是液体物理学中的一项重大挑战。为此，我们引入了局域构形松弛时间 τ_{LC} 的概念。τ_{LC} 在空间上呈不均匀分布；通过比较其所表征的局部松弛速率与外加剪切速率，我们发现局部区域的剪切响应可呈现类固或类液两种形式——在此意义下，τ_{LC} 与麦克斯韦时间相类似。基于这种微观固液二元响应，我们系统考察了不同剪切速率下的流动行为，不仅能描述宏观剪切变稀的起源，还成功预测了启动剪切过程中瞬态应力演化的主要特征。进一步，我们从局部构形中提取出结构序参量，为 τ_{LC} 及相关的固液二元响应建立了微观结构基础，从而构建起一个贯通过冷液体微观结构、局域动力学、局域力学响应与宏观流动行为的框架。最后，我们基于势垒激发模型对该框架进行了建模，阐明了局部结构、流动与热激发如何共同调控 τ_{LC}；该模型可预测出两类不同响应的粒子，与实际观察到的微观固液二元响应相吻合。

关键词: 过冷液体；流变；动态不均匀；黏弹性；

Abstract: Understanding the flow behaviors of supercooled liquids presents a major challenge in liquid-state physics due to the strong nonlinearity and rich phenomena. To unravel this complexity, we introduce the concept of local configurational relaxation time τ_{LC}, which allows us to embody the solid-liquid duality, proposed by Maxwell for phenomenologically describing materials'response to external load, at the particle level. The spatial distribution of τ_{LC} in flow is heterogeneous. Depending on the comparison between the local mobility measured by τ_{LC} and the external shear rate, the shear response of local regions is either solidlike or liquidlike. In this way, τ_{LC} plays a role similar to the Maxwell time. By applying this microscopic solid-liquid duality to different conditions of shear flow with a wide range of shear rates, we describe the emergence of shear thinning in steady shear and predict the major characteristics of the transient response to start-up shear. Furthermore, we reveal a clear structural foundation for τ_{LC} and the solid-liquid duality associated with it by introducing an order parameter extracted from local configuration. Thus, we establish a framework that connects microscopic structure, dynamics, local mechanical response, and flow behaviors for supercooled liquids. Finally, we rationalize our framework in terms of activations from energy basins that are facilitated by shear. This model illustrates how local structure, convection, and thermal activation collectively determine τ_{LC}. Notably, it predicts two distinct response groups, which well correspond to the microscopic solid-liquid duality.

Keywords: supercooled liquids; rheology; dynamic heterogeneity; viscoelasticity;

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Joint Self-Collimation Compton Imaging: A High-Resolution and High-SNR Solution for Wide-Energy SPECT

Author: 李沛泽[1]

[1] *清华大学*

Corresponding Author: lipeizeamm@163.com

摘要: 传统的高能伽马光子 SPECT 成像技术从根本上受限于机械准直固有的分辨率-灵敏度权衡。虽然探测器自准直（SC）提供了一种高效的替代方案，但其在 511 keV 能量下的性能会因多路复用歧义和晶间散射而严重下降。我们提出了一种联合自准直康普顿（JSCC）成像方法，该方法巧妙地将多层间隔 MATRICES 架构的几何路径与康普顿散射运动学的物理约束相结合。通过提取康普顿锥信息来“筛选”和消除重叠的投影轨迹，JSCC 显著提高了信噪比（SNR），同时保持了 SC 设计固有的高空间分辨率。基于克拉默-拉奥下界（CRLB）驱动的系统参数优化，我们开发了一种统一的列表模式 MLEM 重建框架，适用于单光子和散射事件。全面的蒙特卡罗模拟表明，即使在超短的 10 秒动态采集条件下，JSCC 也能实现比独立 SC 更优异的对比度恢复、更快的收敛速度和更高的几何保真度。所发现的与尺度相关的性能提升凸显了 JSCC 在大视野临床高能 SPECT 和诊疗一体化应用中的巨大潜力。

关键词: 单光子断层成像，高能成像，自准直，康普顿成像，诊疗一体化

Abstract: Conventional SPECT for high-energy gamma photons is fundamentally bottlenecked by the resolution-sensitivity trade-off inherent to mechanical collimation. While detector self-collimation (SC) offers a high-efficiency alternative, its performance at 511 keV is severely degraded by multiplexing ambiguities and inter-crystal scattering. We propose Joint Self-Collimation Compton (JSCC) imaging, a novel methodology that synergistically integrates the geometric pathways of a multi-layer interspaced MATRICES architecture with the physical constraints of Compton scattering kinematics. By extracting Compton cone information to “screen” and disambiguate overlapped projection trajectories, JSCC significantly enhances the signal-to-noise ratio (SNR) while preserving the intrinsic high spatial resolution of the SC design. Following a Cramer-Rao Lower Bound (CRLB)-driven system parameter optimization, we developed a unified list-mode MLEM reconstruction framework for both single-photon and scattering events. Comprehensive Monte Carlo simulations demonstrate that JSCC achieves superior contrast recovery, faster convergence, and higher geometric fidelity than standalone SC, even under ultra-short 10-second dynamic acquisitions. The identified scale-dependent performance gain underscores the immense potential of JSCC for large-field-of-view clinical high-energy SPECT and theranostic applications.

Keywords: SPECT, High energy imaging, Self-collimation, Compton imaging, Theranostics

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A statistical analysis of early-stage Ni-Si clusters in irradiated 316L stainless steel

Author: 郭逸飞[1]

Co-authors: Kenji Nishida [2]; Kenta Murakami [3]; Naoto Sekimura [3]; 陈东钺 [1]; 古玛叶丽 [4]; 李正操 [1]; 吕沙沙 [5]

[1] *清华大学*

[2] *日本电力中央研究所*

[3] *东京大学*

[4] *清华大学核能与新能源技术研究院*

[5] *北京师范大学*

Corresponding Author: gyf23@mails.tsinghua.edu.cn

摘要: 辐射诱发的溶质团簇化在核反应堆用不锈钢的性能退化过程中起着关键作用。然而，Ni-Si 团簇的早期形核机制仍未完全明确。本研究利用原子探针断层扫描技术，对离子辐照的 316L 不锈钢中 Ni 和 Si 的初始团簇化行为进行了研究。将无硅（NS）和高硅（HS）含量的高纯模型合金在 290℃ 下用 3 MeV 的 Ni^{2+} 离子辐照至 0.8 dpa。采用 IPM 法发现，在高硅样品中存在 Ni 团簇和 Si 团簇，而在无硅样品中也存在镍团簇。此外，无硅样品中 Ni 团簇的数量密度较低且半径较小。采用改进的局部浓度法分析溶质偏聚情况，结果显示，添加 Si 显著增强了 Ni 和 Cr 的偏聚，其中 S 的偏聚最为明显。此外，对通过 IPM 识别出的团簇应用最近邻距离（NND）法，对不同类型团簇间的空间分布进行了分析。结果表明，Ni-Si 存在共团簇化趋势，同时有证据表明镍团簇存在均匀形核现象，暗示可能存在双重形核机制。这种多方法研究途径为辐照下的早期团簇过程提供了新的见解。

关键词: 不锈钢；离子辐照；三维原子探针；溶质团聚

Abstract: Radiation-induced solute clustering plays a critical role in the degradation of stainless steels used in nuclear reactors. However, the early-stage nucleation mechanisms of Ni-Si clusters remain incompletely understood. This study investigates the initial clustering behavior of Ni and Si in ion-irradiated 316L stainless steel using atom probe tomography. High-purity model alloys with no Si (NS) and high Si (HS) content were irradiated with 3 MeV Ni2+ at 290 ℃ to 0.8 dpa. Ni clusters and Si clusters were found in the HS samples, while Ni clusters were found in the NS samples, using the iso-position method (IPM). Moreover, the number density of Ni clusters in the NS samples was low and the radius

was small. A modified local concentration method was used to analyze solute segregation, revealing significant Ni and Cr segregation enhanced by Si addition, with Si exhibiting the most pronounced segregation. Complementarily, the nearest neighbor distance (NND) method, applied to clusters identified via the IPM, provided spatial distribution analysis between different types of clusters. The results indicate a tendency for Ni–Si co-clustering, alongside evidence of homogeneous nucleation of Ni clustering, suggesting a dual nucleation mechanism. This multi-method approach offers new insight into early-stage precipitation under irradiation.

Keywords: Stainless steel; Ion irradiation; Atom probe tomography; Solute clustering

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InSight-R: 界面数据驱动的动态人因可靠性分析框架

Authors: 萧星宇[1]; 王海涛[1]; 童节娟[1]; 梁金刚[1]

[1] *清华大学*

Corresponding Authors: tongjj@tsinghua.edu.cn, xxy23@mails.tsinghua.edu.cn, jingang@tsinghua.edu.cn, wanght@tsinghua.edu.c

摘要: 在人机交互密集的安全关键系统中，人机界面（HMI）失效仍是导致人为错误的重要来源。然而，传统的人类可靠性分析（HRA）方法在很大程度上依赖定性判断，难以刻画界面设计因素对人为失误的定量影响。尽管近年来基于认知建模的方法引入了一定的量化机制，但其通常未能在动态运行情境中，将客观界面设计属性与人为错误概率建立直接关联。针对这一关键问题，本文提出了一种结构化的界面数据驱动概率建模框架——InSight-R，用于定量刻画界面设计属性与界面诱发人为错误之间的关联机制。

该框架融合了客观界面特征分析、实证行为数据以及层次化概率推断方法，实现了对界面诱发风险的路径级诊断。模型基于理论驱动的方向性关系，刻画了界面指标与操作者认知—行为状态之间的耦合机制，其中目标显著性、语义干扰和交互跨度等关键因素共同影响执行类错误与时间偏差类错误的发生概率。通过在高保真核电仿真平台上开展典型面板巡检任务实验，并结合持证操纵员与学生被试数据对模型进行验证，结果表明：视觉复杂性与语义复杂性的提升显著增加了执行错误和时间偏差的发生概率。

通过建立界面设计属性与人为错误概率之间的定量映射关系，InSight-R 为人机界面相关绩效塑形因子的建模提供了数据驱动的细化路径，并为动态可解释的人类可靠性分析提供了重要支撑。

关键词: 人类可靠性分析，人机界面，界面诱发的人因错误，层次化概率建模，动态风险分析

Abstract: Human–machine interface (HMI) failures remain a major contributor to human errors in safety-critical systems, yet conventional human reliability analysis (HRA) largely relies on qualitative judgment. Although recent cognitive modeling approaches introduce quantitative mechanisms, they rarely link objective interface design attributes directly to human error probabilities in dynamic operational contexts. To address this gap, we propose InSight-R, a structured interface data-driven probabilistic framework that quantitatively models the association between interface design attributes and interface-induced human errors. By integrating objective interface analytics, empirical behavioral data, and hierarchical probabilistic inference, the framework enables pathlevel diagnosis of interface-induced risks. The model captures theoretically motivated directional relationships between interface metrics and operator cognitive–behavioral states, where target salience, semantic interference, and interaction span jointly predict execution-related and time-deviation errors. The framework was evaluated on a highfidelity nuclear simulator using representative panel-inspection tasks with licensed operators and student participants. Results show that increased visual and semantic complexity is associated with higher probabilities of execution errors and temporal deviations. By establishing a quantitative link between interface design attributes and human error probabilities, InSight-R provides a data-driven refinement of HMI-related

performance shaping factors and supports dynamically interpretable human reliability analysis.

Keywords: Human reliability analysis, Human–machine interface, Interface-induced human error, Hierarchical probabilistic modeling, Dynamic risk analysis

Chapter 9

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亚太赫兹过模同轴切伦科夫发生器模式控制研究

Author: 王俊清[1]

Co-authors: 肖仁珍; 陈坤

[1] *清华大学工程物理系*

Corresponding Author: wangjunq21@mails.tsinghua.edu.cn

摘要: 在本文中，我们提出了一种亚太赫兹同轴过模切伦科夫产生器，其工作频率在 340 GHz 左右，器件过模比（直径与波长比值）约为 6.74。该器件设计的工作模式为准 TEM 模，由于较大的过模比，工作模式与相邻的角向非对称模式谐振特性接近，因而极易可能激励出角向非对称模式从而造成模式竞争，这会使得器件工作状态不够稳定。简要分析了模式竞争的产生原因，利用刻槽慢波结构显著改变了不同模式的谐振特性，并通过三维仿真验证了这种方法抑制模式竞争的有效性。在磁场约 6 T，二极管电压约 300 kV，二极管电流约 1.4 kA 的仿真条件下，器件最终产生了频率约 337 GHz，功率约 62 MW 的太赫兹波。

关键词: 切伦科夫产生器、模式竞争、太赫兹

Abstract: This paper presents a sub-terahertz coaxial overmoded Cherenkov generator operating at approximately 340 GHz, with an overmoded ratio (diameter-to-wavelength ratio, D/λ) of about 6.74. The designed operating mode of the device is the quasi-TEM mode. Due to the large overmoded ratio, the resonant characteristics of the operating mode are close to those of the asymmetric modes, making it highly likely to excite the angular asymmetric modes and induces significant mode competition, which can lead to operational instability. By implementing a slotted slow-wave structure (SWS), the resonant characteristics of different modes are substantially altered. The effectiveness of this approach in suppressing mode competition is verified through 3D PIC simulations.Under the simulation conditions of a magnetic field of approximately 6 T, a diode voltage of about 300 kV, and a diode current of approximately 1.4 kA, the device ultimately generated terahertz waves with a frequency of about 337 GHz and a power of approximately 62 MW.

Keywords: Cherenkov generator, mode competition, terahertz

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AM-MCMC 与 RPF 耦合的概率断裂力学方法及 CRDM 飞射物风险量化研究

Authors: 张贺[1]; 孔德岩

[1] *哈尔滨工程大学*

Corresponding Author: zh15764600118@qq.com

摘要: 依据 HAD102/04-2019 核安全导则，核电厂控制棒驱动机构（CRDM）全寿期失效概率低于 10^{-7} 方可判定为不可信飞射物。针对传统静态概率断裂力学（PFM）方法过度保守、无法同化在役数据的缺陷，本文以华龙一号 ML-B+ 型 CRDM 为对象，聚焦应力腐蚀开裂（SCC）失效模式开展评估。构建含热老化效应与非线性残余应力的半椭圆缺陷模型，剔除裂纹萌生阶段，搭建高阶 SCC 扩展模型与误差 ≤5% 的代理模型；提出自适应马尔可夫链蒙特卡洛（AM-MCMC）与正则化粒子滤波（RPF）耦合的贝叶斯准动态框架，实现参数无偏识别与失效概率动态更新。蒙特卡洛仿真表明，关键截面与焊缝失效概率均稳定处于 10^{-8} 量级，远低于安全阈值；全寿期演化平稳，初始缺陷深度为核心主控因素。OSSE 含噪测试验证算法跟踪精度与收敛性满足工程要求。本方法突破传统 PFM 局限，验证了 CRDM 的不可信飞射物合规性，为核电关键部件全寿期安全评估提供支撑。

关键词: 控制棒驱动机构；应力腐蚀开裂；概率断裂力学；贝叶斯动态评估；自适应马尔可夫链蒙特卡洛；不可信飞射物评定

Abstract: In accordance with the HAD102/04-2019 Nuclear Safety Guideline, a full-life failure probability below 10−7 is required for a nuclear power plant Control Rod Drive Mechanism (CRDM) to qualify as an incredible projectile. Conventional static Probabilistic Fracture Mechanics (PFM) methods are inherently overly conservative and incapable of assimilating in-service inspection data. Taking the HPR1000 ML-B+ type CRDM as the research object, this paper assesses the dominant failure mode of Stress Corrosion Cracking (SCC). A semi-elliptical crack defect model incorporating thermal aging effects and nonlinear residual stresses is constructed, excluding the crack initiation phase. A high-order SCC growth model and a surrogate model with relative error ≤ 5% are developed. A quasi-dynamic Bayesian framework coupling Adaptive Markov Chain Monte Carlo (AM-MCMC) and Regularized Particle Filter (RPF) is proposed to enable unbiased parameter identification and dynamic failure probability updating. Monte Carlo simulations show that the failure probabilities of all critical sections and welds are consistently on the order of 10−8, well below the safety threshold. The full-life evolution of failure probabilities is stable without abrupt increases, and initial defect depth is identified as the dominant controlling factor via sensitivity analysis. Noisy Observing System Simulation Experiment (OSSE) tests verify that the tracking accuracy and convergence performance of the algorithm meet engineering requirements. The proposed method overcomes the limitations of conventional PFM approaches, validates the incredible projectile compliance of the CRDM, and provides a quantitative basis for full-life safety assessment of key nuclear power components.

Keywords: Control Rod Drive Mechanism (CRDM); Stress Corrosion Cracking (SCC); Probabilistic Fracture Mechanics (PFM); Bayesian Dynamic Assessment; Adaptive Markov Chain Monte Carlo (AM-MCMC); Incredible Projectile Qualification

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辐照-高温耦合作用下核电堆坑混凝土劣化机制与结构长期性能评价方法

Author: 荣华[1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Author: ronghua_mcc@163.com

摘要: 核电延寿是国际核电发展的重要战略，超设计期后核电结构服役性能评价与提升是确保安全延寿的重要保障。核电堆坑结构长期处于高温辐照环境，其辐照作用下的劣化检测及评价是决定能否延寿的关键因素。针对辐照作用下堆坑结构长期性能精准评价难题，开展了大量高剂量辐照试验并创建国内首个辐照混凝土性能数据库，基于试验数据开展理论分析，系统揭示了高剂量辐照作用下混凝土宏观性能退化机理，建立了基于微观力学的辐照混凝土多尺度性能演化模型，构建了辐照-热-力耦合机制作用下堆坑结构性能评价与寿命预测方法，实现了辐照混凝土结构性能的精准预测。研究成果成功应用于秦山二期和田湾核电延寿中期评估项目中，精准挖掘了机组的安全裕度。

关键词: 辐照，混凝土，核电，堆坑，性能评价

Abstract: Nuclear power plant (NPP) life extension is a critical strategy for the global development of nuclear energy. The evaluation and enhancement of the in-service performance of nuclear power structures beyond their design service life serve as an essential safeguard for safe life extension. Nuclear reactor pit structures are chronically exposed to high-temperature and irradiation environments, and the detection and evaluation of their irradiation-induced deterioration constitute a decisive factor for life extension feasibility.To address the challenge of accurately evaluating the long-term performance of reactor pit structures under irradiation, extensive high-dose irradiation tests were conducted and the first domestic performance database for irradiated concrete was established. Based on experimental data, theoretical analyses were performed to systematically reveal the macroscopic performance degradation mechanism of concrete under high-dose irradiation. A micromechanics-based multi-scale performance evolution model for irradiated concrete was developed, and a performance evaluation and life prediction method for reactor pit structures under the irradiation-thermal-mechanical coupling mechanism was constructed, enabling precise prediction of the performance of irradiated concrete structures.The research findings have been successfully applied to the mid-term life extension evaluation projects of Qinshan Phase II and Tianwan Nuclear Power Plants, accurately identifying the safety margins of the units.

Keywords: Concrete; Nuclear Power; Reactor Pit; Performance Evaluation

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基于 SRIM 和 TCAD 的 GaN 中子探测器瞬态电流响应研究

Author: 相传峰[1]

[1] *核生化灾害防护化学全国重点实验室*

Corresponding Author: xiangchf@163.com

摘要: 本研究利用计算机辅助设计（Technology Computer Aided Design，TCAD）软件，确定了 p-i-n 氮化镓（Gallium Nitride，GaN）二极管中本征氮化镓（i-GaN）层的最佳厚度和掺杂浓度，以提高探测效率和器件可靠性。该研究了 α 和 3H 粒子在 GaN p-i-n 二极管内引起的能量损失和瞬态电流响应。此外，研究了由电子-空穴对收集引起的瞬态电流行为，结果表明，瞬态电流响应中的拖尾效应源于辐射诱导的空穴积累。增大探测器的反向偏压会导致瞬态电流脉冲幅度增大，这归因于耗尽区展宽增强了载流子的收集。这些结果有望推动基于 GaN 的中子探测器技术的发展，这对于下一代核科学和空间科学应用至关重要。

关键词: 中子探测器；氮化镓；TCAD；SRIM；瞬态电流

Abstract: This study employed Technology Computer-Aided Design (TCAD) simulations to determine the optimal thickness and doping concentration of the intrinsic gallium nitride (i-GaN) layer in p-i-n GaN diodes, aiming to improve detection efficiency and device reliability. The energy loss and transient current responses induced by α particles and tritium (3H) particles in GaN p-i-n diodes were investigated. In addition, the transient current behavior associated with electron–hole pair collection was analyzed. The results indicate that the tailing effect observed in the transient current response originates from radiation-induced hole accumulation. Increasing the reverse bias voltage of the detector leads to a higher transient current pulse amplitude, which is attributed to the widening of the depletion region and the resulting enhancement of carrier collection. These findings are expected to contribute to the development of GaN-based neutron detector technologies, which are of critical importance for next-generation applications in nuclear science and space science.

Keywords: Neutron detector; GaN; Technology Computer Aided Design; SRIM, transient current

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基于 cosSUBC 子通道程序的三维弹棒事故改进研究

Author: 章林艺[1]

Co-authors: 孟召灿 [1]; 李剑 [1]; 王幸 [1]

[1] *国家电力投资集团科学技术研究院有限公司*

Corresponding Author: yyhistory@163.com

摘要: 在弹棒事故的计算中，与传统的一维分析方法相比，三维分析方法避免了一维分析方法中的部分保守假设，可以获得更为现实但依然保守的分析结果。随着计算机硬件的快速发展以及分析方法的改进，具备了采用更精确的方法进行分析的条件，可以合理地获得安全分析裕量。因此有必要采用三维方法进行弹棒事故分析，在保证安全分析具有足够裕量的前提下合理地释放部分保守性。本研究通过改进子通道程序的临界后换热模块、与中子动力学耦合模块，实现三维弹棒的事故分析功能，然后通过抽取耦合程序热棒文件的三维弹棒结果的热工参数，开展后续的 DNBR 分析与焓分析。

关键词: cosSUBC；三维弹棒；DNBR 分析；焓分析

Abstract: In the calculation of rod ejection accidents, compared with the traditional one-dimensional analysis method, the three-dimensional analysis method avoids some conservative assumptions and can obtain more realistic but still conservative analysis results. With the rapid development of computer hardware and the improvement of analysis methods, the conditions for more accurate analysis methods are available, which can reasonably obtain safety analysis margins. Therefore, it is necessary to use the three-dimensional method for rod ejection accident analysis to reasonably release some conservatism on the premise of ensuring that the safety analysis has sufficient margin. In this study, by coupling the core subchannel software and the neutron kinetics software in COSINE software package, and then extracting the thermal parameters of the three-dimensional rod ejection result of the hot rod file, the subsequent DNBR analysis and enthalpy analysis are carried out to realize the research on the accident analysis function of three-dimensional rod ejection.

Keywords: cosSUBC; Three-dimensional rod ejection; DNBR analysis; Enthalpyanalysis

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Analysis of 3D-printed vaginal cylinder template-guided interstitial adaptive brachytherapy for cervical cancer

Author: 曹鸿斌[1]

[1] *上海交通大学医学院附属仁济医院*

Corresponding Author: rj_hongbin_cao@126.com

摘要: 探索个体化 3D 打印阴道柱插植近距离治疗（individualized 3D-printed vaginal cylinder template-guided interstitial brachytherapy , 3D-p-VC-ISBT）用于局部晚期子宫颈癌近距离治疗的优势，为临床自适应近距离放疗提供参考。分析中晚期宫颈癌患者的临床资料，个体化 3D 打印阴道柱插植治疗。采用 Mann-Whitney 检验，Kruskal-Wallis 检验进行三种计划（腔内计划、插植计划、插植组预计划）数据的比较。个体化 3D 打印阴道柱插植近距离治疗的靶区剂量更优，能根据肿瘤体积和位置变化自适应调整插植计划，操作更安全、高效。

关键词: 组织间插植近距离治疗，自适应近距离治疗，个体化 3D 打印阴道柱，宫颈癌

Abstract: To explore the advantages of individualized 3D-printed vaginal cylinder template-guided interstitial brachytherapy (3D-p-VC-ISBT) in locally advanced cervical cancer, and to provide reference for clinical adaptive brachytherapy.
Clinical data of patients with advanced cervical cancer were analyzed, and individualized 3D-printed vaginal cylinder interstitial implantation therapy was adopted.

Mann-Whitney test and Kruskal-Wallis test were used to compare the data of three types of plans, including intracavitary plan, interstitial implantation plan, and pre-plan of the interstitial implantation group.
Individualized 3D-printed vaginal cylinder template-guided interstitial brachytherapy delivers superior target volume dose coverage. It enables adaptive adjustment of the interstitial implantation plan according to changes in tumor volume and location, with safer and more efficient clinical operation.

Keywords: interstitial brachytherapy, IGABT, 3D-printed individualized vaginal cylinder template, Cervical cancer

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某气体收料仿真与实验研究

Author: 张权权[1]

[1] *四川红华实业有限公司*

Corresponding Author: zhangqq814@126.com

摘要: 在铀浓缩工程，容器收料是生产的关键环节，制约着生产效率。本研究从实际生产需求出发，采用 VOF、LEE 模型，建立了一套能够精准分析收料容器内部物料相变过程的数值仿真模型，并用真实物料进行了验证，为后续容器设计优化和制冷设备设计优化提供了基础。

关键词: 铀浓缩；容器；相变；仿真；

Abstract: In the field of uranium enrichment engineering, material collection in vessels is a critical production link that restricts production efficiency. Based on actual production requirements, this study adopts the VOF and Lee models to establish a numerical simulation model capable of accurately analyzing the material phase transition process inside the receiving vessel. The material collection process is simulated and verified with real materials, which provides a foundation for the subsequent design and optimization of vessels and refrigeration equipment.

Keywords: Uranium enrichment；vessel；phase change；simulation

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基于 MRI/CT 双分支形变向量场影像组学的自适应放疗决策预测方法

Author: 戴相昆[1]

Co-authors: 传滨解 [2]; 李君利 [1]; 王海洋 [2]; 石张磊 [2]; 金王媛 [2]

[1] *清华大学工程物理系*

[2] *解放军总医院第一医学中心放射治疗科*

Corresponding Author: dxk_301@163.com

摘要: 目的：针对磁共振引导在线自适应放疗中决策高度依赖临床经验、缺乏客观量化评估的问题，提出一种基于 MRI/CT 双分支形变向量场影像组学的自适应放疗决策预测方法，旨在为临床提供可靠的辅助决策依据。方法：构建端到端的智能辅助分析架构，深度挖掘形变放射组学特征，结合多模态影像特征库与机器学习算法，建立 MRI 与 CT 双分支分类预测模型。采用 StratifiedGroupKFold 和留一法交叉验证进行患者级评估，通过特征融合（Delta 一阶统计特征、形变场特征、PTV 边缘特征）提升预测性能。结果：多模态特征融合将 AUC 从基准 0.7059 提升至

0.9698（提升 37%）。MRI 分支在外部感兴趣区域结合 156 维特征集时 AUC 接近 0.97；CT 分支在 Dose_50 区域结合 122 维特征集时达到全局最优性能，AUC 为 0.9848，敏感性达 1.0。双分支 AUC 均超过 0.96。结论：所提方法可在分次治疗期间为自适应放疗决策提供量化支持，有望减少不必要的计划修改，提升治疗精度与效率，具有良好的临床转化潜力。

关键词: 自适应放疗；形变向量场；影像组学；多模态融合；机器学习

Abstract: Objective: To address the lack of objective and quantitative evaluation methods for decision-making in MRI-guided online adaptive radiotherapy (ART), which currently relies heavily on clinical experience, this study proposes a prediction method for ART decision-making based on MRI/CT dual-branch deformation vector field radiomics, aiming to provide reliable decision support for clinicians. Methods: An end-to-end intelligent analysis framework was constructed to deeply mine deformation radiomics features. A dual-branch (MRI/CT) classification prediction model was developed by integrating a multimodal radiomics feature library with machine learning algorithms. Patient-level evaluation was performed using StratifiedGroupKFold and leave-one-out cross-validation. Feature fusion (Delta first-order statistics, deformation field features, and PTV edge features) was employed to enhance predictive performance. Results: Multimodal feature fusion improved the AUC from a baseline of 0.7059 to 0.9698 (a 37% increase). The MRI branch achieved an AUC close to 0.97 using a 156-dimensional feature set in the external region of interest. The CT branch reached the global optimal performance with an AUC of 0.9848 and a sensitivity of 1.0 using a 122-dimensional feature set in the Dose_50 region. Both branches achieved AUC values exceeding 0.96. Conclusion: The proposed method provides quantitative support for ART decisions during fractionated treatment, potentially reducing unnecessary plan modifications and improving treatment accuracy and efficiency, demonstrating strong potential for clinical translation.

Keywords: Adaptive radiotherapy; Deformation vector field; Radiomics; Multimodal fusion; Machine learning

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空间闭式布雷顿循环氦氙工质泄漏对离心压气机性能的影响机制研究

Author: 许日升[1]

[1] *清华大学*

Corresponding Author: xrs23@mails.tsinghua.edu.cn

摘要: 针对空间闭式布雷顿循环中 He-Xe 二元混合工质长期非等比例泄漏问题，本文建立了“泄漏演化—物性漂移—压气机性能变化—系统匹配迁移”的耦合分析框架，研究 He 优先泄漏对离心压气机全寿期性能和运行裕度的影响。首先，通过等效泄漏模型获得系统压力、工质组成和平均摩尔质量随服役时间的变化规律；随后，结合变组分真实气体物性模型和三维 CFD 计算，分析不同服役阶段下压气机性能图的演化特征；最后，引入压气机—涡轮系统匹配模型，揭示运行线和实际工作点的迁移机制。结果表明，长期 He 优先泄漏会导致系统总压非线性下降、混合工质平均摩尔质量升高和气体常数降低，进而推动压气机工作点向大折合流量侧迁移并逐渐偏离高效区。寿期末叶轮通道内高相对马赫数区域扩大，局部阻塞趋势和吸力面—轮盖角区分离增强，是效率下降和阻塞裕度收缩的重要原因。研究表明，长寿命 He-Xe 闭式布雷顿循环压气机设计应考虑工质泄漏引起的全寿期边界漂移和运行裕度变化。

关键词: 闭式布雷顿循环；He-Xe 混合工质；离心压气机；非等比例泄漏；真实气体物性；系统匹配；运行裕度

Abstract: This study investigates the influence of long-term non-proportional leakage of He-Xe binary working fluid on the lifetime performance and operating margin of a centrifugal compressor in a space closed Brayton cycle. A coupled analysis framework of “leakage evolution–property drift–compressor performance variation–system matching migration”is established. First, an equivalent leakage model is developed to predict the temporal evolution of system pressure, mixture composition, and mean molar mass. Then, a variable-composition real-gas property model is coupled with three-dimensional CFD

simulations to obtain compressor performance maps at different service stages. Finally, a compressor–turbine system matching model is introduced to determine the migration of the operating line and actual operating point. The results show that preferential helium leakage leads to a nonlinear decrease in system pressure, an increase in mean molar mass, and a reduction in the gas constant. These variations drive the compressor operating point toward the high corrected-flow-rate region and gradually away from the initial high-efficiency zone. At the end of service life, the high relative Mach number region expands inside the impeller passage, accompanied by local choking tendency and enhanced separation near the suction-surface/shroud corner. These flow mechanisms contribute to efficiency degradation and choking-margin reduction. The results indicate that the design of long-life He-Xe centrifugal compressors should account for lifetime boundary drift and operating-margin redistribution induced by working-fluid leakage.

Keywords: closed Brayton cycle; He-Xe working fluid; centrifugal compressor; non-proportional leakage; real-gas properties; system matching; operating margin

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Nuclear Accident Evacuation Path Planning Based on Transformer fused with physical information

Author: 马悦翔[1]

[1] *中国辐射防护研究院*

Corresponding Author: 1952312773@qq.com

摘要: 核事故引发的动态放射性烟羽给场外应急撤离带来了极大的不确定性。针对传统算法易导致高辐射暴露、以及全局时空感知能力不足的局限，本文提出了一种融合物理先验与深度学习的核应急时空路径规划模型（Phy-TransA）。*该模型采用分层决策架构：基于 A* 算法结合路网拓扑生成候选路径集，利用 Transformer 网络分析多维时空物理特征向量，预测不同时空下决策节点分支的风险概率。基于 URBAN 2000 IOP #10 现场示踪实验数据与拉格朗日粒子追踪模型的进行辐射场仿真，结果表明：在释放源存在空间偏移与间歇性释放的未知异构场景下，Phy-TransA *展现出良好的泛化能力。相较于传统 A* 算法，本模型在仅增加 38.28% 通行时间的条件下，将撤离路径的累积剂量中位数降低了 95.40%，有效规避了局部高浓度烟羽。

关键词: 核应急，路径规划，Transformer，辐射防护，A*

Abstract: The dynamic radioactive plumes induced by nuclear accidents introduce significant uncertainties into off-site emergency evacuations. To address the vulnerability to radiation exposure and the lack of global spatiotemporal perception inherent in traditional algorithms,
this paper proposes a spatiotemporal path planning model for nuclear emergencies, termed Phy-TransA, *which integrates physical priors with deep learning. The model employs a hierarchical decision-making architecture: it generates a set of candidate paths based on the A* algorithm and road network topology, and utilizes a Transformer network to analyze multidimensional spatiotemporal physical feature vectors, predicting the risk probabilities of decision node branches across different spatiotemporal contexts. Radiation field simulations were conducted using the URBAN 2000 IOP #10 field tracer experiment data and a Lagrangian particle tracking model. The results indicate that in unknown heterogeneous
scenarios characterized by source spatial offsets and intermittent releases, Phy-TransA*exhibits algorithmic validity and scenario adaptability. Compared with the traditional A* algorithm, the proposed model reduces the median cumulative dose of evacuation paths by 95.40%, accompanied by a 38.28% increase in travel time, effectively bypassing local high-concentration plumes.

Keywords: Nuclear emergency, Path planning, Transformer, Radiation protection, A*

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低真空气体分离系统管道内颗粒团聚和沉积仿真研究

Author: 魏永春[1]

[1] *清华大学、中核第七研究设计院有限公司*

Corresponding Author: 1031018702@qq.com

摘要: 针对低真空气体分离系统中的粉末影响运行设备运行问题，在欧拉-拉格朗日框架下构建了用于描述气固两相流中颗粒团聚和沉积的动力学模型，模拟计算了不同气体流量下直管、弯管和三通管中的颗粒团聚和沉积特性，以探索使粉末直接沉积或团聚形成大颗粒后重力沉降于管道中，减少进入设备粉末而延长设备元件使用寿命的方法。结果表明，直管内颗粒曳力是颗粒的主要沉积机制，而弯管和三通管内颗粒曳力和惯性力竞争是颗粒沉积的主导机制。可通过增大管道直径等措施促进颗粒团聚增大粒径和延长重力沉降时间，以增大颗粒沉积比例，也可在关键设备前通过优化三通管路设计促进颗粒沉积，但需注意流速值的变化。

关键词: 低真空；团聚；沉积；管道；流速

Abstract: To address the operational issues caused by powder particles in low-vacuum gas separation systems, a kinetic model describing particle agglomeration and deposition in gas-solid two-phase flow was constructed within the Eulerian-Lagrangian framework. Simulations were conducted to evaluate the particle agglomeration and deposition characteristics in straight pipes, elbow pipes, and tee pipes under varying gas flow rates to explore methods for extending equipment component lifespan. This involves promoting direct particle deposition or agglomeration into larger particles that subsequently settle gravitationally within the pipeline. Results indicate that drag force dominates particle deposition in straight pipes, while drag force and inertial force compete as the primary deposition mechanisms in elbows and tees. Measures such as increasing pipe diameter can promote particle agglomeration to enlarge particle size and extend gravitational settling time, thereby increasing the proportion of particle deposition. Alternatively, optimizing tee pipe configurationsdesigning bends before critical equipment or can facilitate particle depositionelocity changes must be carefully monitored.

Keywords: low vacuum; agglomeration; deposition; pipe; particle

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快堆绕丝定位燃料组件辐照变形分析技术及行为研究

Authors: 王浩煜[1];

[1] *清华大学*

Corresponding Author: whyah666@163.com

摘要: 快堆是我国核能“热堆-快堆-聚变堆”三步走发展战略的重要组成部分，燃料组件作为其核心技术之一，其辐照变形行为直接影响堆芯安全运行。快堆采用绕丝定位的三角形紧密栅格燃料组件，辐照后产生的燃料棒直径增大、椭圆化及冷却剂通道变形等问题可能引发局部传热恶化和结构完整性风险。本研究围绕绕丝定位燃料组件辐照变形分析技术开展两方面工作：在精细模拟方面，首次建立了耦合辐照效应、精细结构及预紧力的全生命周期分析方法，完整模拟了从预张紧制造到堆芯运行的变形及应力演化过程。结果表明，运行前期燃料棒全长呈螺旋形变形且包壳周向应力呈“葫芦形”分布，随着辐照进行，活性区外螺旋变形逐渐消退、应力趋于均匀，该演化规律与辐照后热室检查结果吻合。在燃料组件高效计算方面，开发了基于壳-梁单元的三维辐照变形高效分析模型，通过耦合约束、轴向连接单元和一般接触技术简化复杂机械相互作用，并采用用户子程序引入材料辐照行为及非均匀堆内条件。验证表明，该模型在节点数增加 6 倍的条件下可达到与精细模型相当的精度，求解速度提升 10 倍以上，兼具高保真度与高效性。后续将进一步深化燃料组件辐照变形机制研究。

关键词: 快堆，燃料组件，辐照变形，数值模拟

Abstract: Fast reactors are an important part of China’s three-step nuclear energy development strategy of “thermal reactor - fast reactor - fusion reactor”. As one of the core technologies, the irradiation deformation behavior of fuel assemblies directly affects the safe operation of the reactor core. Fast reactors use wire-wrapped triangular tight lattice fuel assemblies. Problems such as increased fuel rod diameter, elliptical deformation, and coolant channel deformation after irradiation may cause local heat transfer deterioration and structural integrity risks. This study focuses on the irradiation deformation analysis technology of wire-wrapped fuel assemblies and conducts two aspects of work: in the aspect of fine simulation, a full life cycle analysis method coupling irradiation effects, fine structures, and pre-tightening forces is established for the first time, which fully simulates the deformation and stress evolution process from pre-tightening manufacturing to reactor core operation. The results show that in the early stage of operation, the fuel rods deform in a helical shape throughout their length and the circumferential stress of the cladding shows a “gourd-shaped” distribution. As irradiation proceeds, the helical deformation outside the active zone gradually disappears and the stress tends to be uniform. This evolution law is consistent with the results of post-irradiation hot cell inspection. In the aspect of efficient calculation of fuel assemblies, a three-dimensional irradiation deformation efficient analysis model based on shell-beam elements is developed. By coupling constraints, axial connection elements, and general contact technology, complex mechanical interactions are simplified, and user subroutines are used to introduce material irradiation behavior and non-uniform in-core conditions. Verification shows that this model can achieve the same accuracy as the fine model with a sixfold increase in the number of nodes and a tenfold increase in the solution speed, combining high fidelity and efficiency. Further research will be conducted to deepen the study of the irradiation deformation mechanism of fuel assemblies.

Keywords: Fast reactor, fuel assembly, irradiation deformation, numerical simulation

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Uncertainty and Sensitivity Analysis of Radioactive Source Terms from Intact Containment Category for Nuclear Power Plants Based on BEPU Method

Author: 孙婧[1]

Co-authors: Shengsheng Lin [2]; Xuhao Zhang [2]

[1] *清华大学核能与新能源技术研究院*

[2] *CNPE*

Corresponding Author: sunj25@mails.tsinghua.edu.cn

摘要: 本研究提出了一套利用最佳估算加不确定性方法对核电厂严重事故源项进行不确定性与敏感性分析的综合流程。该流程纳入了严重事故管理指南行动，并探讨了其对放射性释放份额的影响。分析应用于中国某双环路压水堆安全壳完整释放类别（源自二级概率安全评估）。通过 MAAP 程序运行 200 个案例，识别并量化了影响源项的关键参数（包括低压安注和安全壳喷淋启动时机）的不确定性。结果表明，低压安注注入时机对惰性气体和碘化铯释放份额的影响最大，通过斯皮尔曼等级相关系数分析证实二者存在强相关性。安全壳喷淋启动对惰性气体具有中等程度影响，但对碘化铯的作用较小。研究还强调了气溶胶行为和严重事故进程参数的重要性，这些参数虽有一定影响，但与严重事故管理指南行动相比相关性较弱。这些发现表明，在选择释放类别的代表性事故序列时，需特别关注源项计算中严重事故管理指南行动的不确定性。该研究有助于提高二级概率安全评估中源项预测的准确性和可靠性，并为未来在严重事故分析中应用最佳估算加不确定性方法的研究提供了参考。

关键词: 不确定性分析，敏感性分析，源项，SAMG，BEPU

Abstract: This study presents a comprehensive procedure for uncertainty and sensitivity analysis of source terms in severe accidents of nuclear power plant, utilizing the Best Estimate Plus Uncertainty (BEPU) methodology. The procedure incorporates Severe Accident Management Guidelines (SAMG) actions and explores their impact on radioactive release fractions. The analysis is applied to the containment intact release category for a two-loop pressurized water reactor (PWR) in China, derived from Level 2 Probabilistic Safety Assessment (PSA). Key parameters influencing the source term, including

the timing of Low-Pressure Safety Injection (LPSI) and containment spray activation, are identified and their uncertainties quantified following running of 200 cases by MAAP code. The results demonstrate that the LPSI injection timing is the most influential factor on both noble gases and Cesium Iodide (CsI) release fractions, with a strong correlation identified through Spearman's rank correlation coefficient analysis. The containment spray activation has a moderate influence on noble gases while it plays a less significant role for CsI. The study also highlights the importance of aerosol behavior and severe accident progression parameters, which, although influential, exhibit weaker correlations than SAMG actions. These findings indicate the importance of selecting representative accident sequences for release categories with particular attention to SAMG action uncertainties during source term calculation. The research contributes to enhancing the accuracy and reliability of source term predictions in Level 2 PSA and provides an insight for future investigations into the application of BEPU in severe accident analysis.

Keywords: Uncertainty Analysis, Sensitivity Analysis, Source Term, SAMG, BEPU

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FLASH 闪疗关键技术及原理样机研制

Authors: 张亮; 刘佛诚; 嘉儒施; 陈怀璧; 皓查

Corresponding Author: zhangliangthu@foxmail.com

摘要: FLASH 放疗以超高剂量率（≥40 Gy/s）在百毫秒内完成照射，可在杀灭肿瘤的同时显著保护正常组织，但现有 X 射线设备剂量率低、多角度切换慢，制约其临床转化。本研究针对上述瓶颈，研制一套静态多角度 FLASH-X 射线装置：通过紧凑型大流强（≥400 mA）驻波加速管与高转速韧致辐射旋转靶，实现单管剂量率 ≥40 Gy/s（80 cm 源皮距）；采用超级电容储能与固态脉冲调制技术，构建 300 kW 级瞬时大功率电源及 FPGA 多通道同步控制系统；创新设计五源环形集成的静态机架，配合一进五出微波分配网络，规避机械旋转速度限制。预期建成国际先进的原理样机，为 FLASH 放疗临床转化提供核心装备支撑，推动我国高端放疗设备自主创新。

关键词: FLASH 放疗；超高剂量率；多角度 X 射线装置；直线加速器；固态脉冲调制器

Abstract: FLASH radiotherapy delivers ultra-high dose rates (≥40 Gy/s) within hundreds of milliseconds, sparing normal tissues while effectively killing tumors. However, conventional X-ray devices suffer from low dose rates and slow multi-angle switching, hindering clinical translation. This study addresses these bottlenecks by developing a static multi-angle FLASH X-ray apparatus. Key innovations include: a compact high-current (≥400 mA) standing-wave accelerating tube and a high-speed rotating bremsstrahlung target, achieving a single-tube dose rate ≥40 Gy/s at 80 cm SSD; a supercapacitor-based solid-state pulse modulator providing 300 kW instantaneous power and an FPGA-based multi-channel synchronized control system; and a static gantry integrating five fixed X-ray sources with a 1-to-5 microwave power distribution network, eliminating the speed limitation of mechanical rotation. An advanced prototype is expected to be established, providing essential equipment support for clinical translation of FLASH radiotherapy and promoting independent innovation of high-end radiotherapy devices in China.

Keywords: FLASH radiotherapy; ultra-high dose rate; multi-angle X-ray apparatus; linear accelerator; solid-state pulse modulator

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小鼠体内 ^{177}Lu-FAP 临床前吸收剂量评估：基于 SPECT/CT 图像的 GATE 蒙特卡洛全粒子输运与 MIRD 近似模型物理差异

Authors: 庞瑞磊[1]; 王鹤霖[1]; 顾月清[1]; 韩智豪[1]

[1] *中国药科大学*

Corresponding Author: 2093497737@qq.com

摘要: 摘要

背景：成纤维细胞激活蛋白（FAP）是放射性药物治疗（RPT）的重要靶点，在多种实体瘤中高表达。随着 ^{177}Lu 标记 FAP 药物的快速发展，准确评估临床前模型中的吸收剂量对疗效、安全及临床转化至关重要。目前，基于 MIRD 的器官水平剂量估算与基于蒙特卡罗（MC）的体素水平剂量计算在物理模型上存在本质差异，其一致性尚需系统比较。本研究旨在比较 GATE 蒙特卡罗模拟与 MIRD 方法在荷瘤小鼠中的剂量计算结果，重点探讨 MC 在粒子输运、次级电子沉积、组织非均匀性及边界效应等物理过程中的优势。

方法：基于 U87 荷瘤 BALB/c 裸鼠模型，尾静脉注射三种 177Lu-FAP 药物。于注射后进行小动物 SPECT/CT 显像，手动勾画主要器官 VOI，获取各时间点器官放射性活度。采用 OLINDA/EXM、Odam 及 PKAD 算法计算 TIAC 并归一化，结合 S 值获得 MIRD 体系器官吸收剂量。同时，将 SPECT/CT 图像导入 3D Slicer 进行格式转换，利用 Python 进行空间坐标变换，作为 GATE 模拟输入。基于 GATE v9.0（Geant4）进行体素级 MC 模拟，以 CT 图像（0.25 mm 体素）构建体素化体模，SPECT 图像定义体素化源。物理过程包含光电效应、康普顿散射、韧致辐射，无能量削减及方差减少。放射源为 177Lu，DoseActor 输出能量沉积与剂量分布。模拟时间为实际采集的 1/10–1/100，统计不确定性 <5%，每只小鼠耗时 3.5 小时。基于 VOI 计算各器官剂量率，积分拟合得总吸收剂量，并分析能量剖面及剂量等高线。

结果：三种放射性药物在肿瘤中均显示出较高的放射性摄取与滞留。在器官吸收剂量方面，基于 MIRD 方法（OLINDA/EXM、Odam、PKAD）计算得到的肾脏和肿瘤吸收剂量分别为 19.78—45.94Gy/GBq 和 670.27—744.43 Gy/GBq，不同计算工具之间结果较为接近/存在一定差异。GATE 蒙特卡罗模拟获得的体素级剂量分布显示，肿瘤内剂量呈现明显异质性，平均吸收剂量为 713.51—840.10Gy/GBq，与 MIRD 方法相比差异为 12%—25%。肾脏剂量在体素水平同样表现出局部热点，最高与平均剂量比值可达 2.5。

结论：MIRD 方法提供器官平均水平剂量，适用于快速评估，但无法反映内部剂量异质性。GATE-MC 通过精确模拟粒子输运、次级电子沉积及边界效应，揭示肿瘤及肾脏内部的剂量异质性，更接近真实物理分布。两者物理本质互补，联合使用可为 RPT 药物临床前剂量学表征及临床转化提供更全面的物理依据。

关键词: 吸收剂量；MIRD；蒙特卡洛；辐射剂量学；医学物理

Abstract: Abstract

Background: Fibroblast activation protein (FAP) is an important target for radionuclide radiotherapies (RPT) and is highly expressed in various solid tumors. With the rapid development of ^{177}Lu-labeled FAP agents, accurate assessment of absorbed dose in preclinical models is essential for efficacy, safety, and clinical translation. Currently, MIRD-based organ-level dosimetry and Monte Carlo (MC)-based voxel-level dose calculations have fundamental differences in physical models, and their consistency requires systematic comparison. This study aims to compare GATE Monte Carlo simulations with MIRD-based methods for dose calculation in tumor-bearing mice, with an emphasis on the advantages of MC in physical processes such as particle transport, secondary electron deposition, tissue heterogeneity, and boundary effects.

Methods: Based on a U87 tumor-bearing BALB/c nude mouse model, three ^{177}Lu-FAP agents were injected via the tail vein. Small-animal SPECT/CT imaging was performed at multiple time points post-injection, and VOIs of major organs were manually delineated to obtain organ radioactivity at each time point. OLINDA/EXM, Odam, and the PKAD algorithm were used to calculate TIACs followed by normalization, and organ absorbed doses were obtained based on the MIRD framework combined with S-values. Meanwhile, SPECT/CT images were imported into 3D Slicer for format conversion, and spatial coordinate transformation was performed using Python to generate input for GATE simulations. Voxel-level MC simulations were performed using GATE v9.0 (Geant4). CT images (0.25 mm voxel size) were used to construct a voxelized phantom, and SPECT images were used to define a voxelized source. The physical processes included photoelectric effect, Compton scattering, and bremsstrahlung, without energy cuts or variance reduction. The radioactive sources were ^{177}Lu. DoseActor was used to output energy deposition and dose distributions. The simulation time was set to 1/10–1/100 of the actual acquisition time, with statistical uncertainty <5%. Each mouse simulation took 3.5 hours on a computing

cluster. Based on the delineated VOIs, dose rates of each organ were calculated, and total absorbed doses were obtained by integral fitting. Energy profiles and dose contour lines were also analyzed.

Results: All three radiopharmaceuticals showed high radioactive uptake and retention in tumors. In terms of organ absorbed doses, the kidney and tumor absorbed doses calculated by the MIRD-based methods (OLINDA/EXM, Odam, PKAD) were 19.78–45.94 Gy/GBq and 670.27–744.43 Gy/GBq, respectively. The results from different calculation tools were relatively close / showed some differences. Voxel-level dose distributions obtained from GATE Monte Carlo simulations revealed significant intratumoral dose heterogeneity, with mean absorbed doses ranging from 713.51 to 840.10 Gy/GBq, showing a difference of 12%–25% compared to the MIRD-based methods. At the voxel level, the kidneys also exhibited local hotspots, with a maximum-to-mean dose ratio reaching 2.5.

Conclusion: The MIRD-based methods provide organ-level mean doses suitable for rapid assessment but fail to reflect internal dose heterogeneity. GATE-MC, by accurately simulating particle transport, secondary electron deposition, and boundary effects, reveals dose heterogeneity within tumors and kidneys, which is closer to the true physical distribution. The two approaches are physically complementary, and their combined use can provide a more comprehensive physical basis for preclinical dosimetry characterization and clinical translation of RPT agents.

Keywords: Absorbed dose; MIRD; Monte Carlo; Radiation dosimetry; Medical physics

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快堆用多群燃耗数据库的制作与验证

Author: 肖越[1]

Co-authors: 吴海成[2]; 吴小飞[2]

[1] *中国原子能科学研究院*

[2] *China Institute of atomic Energy*

Corresponding Author: xiaoyue_0708@163.com

摘要: 为研制高准确度快堆用燃耗数据库并建立精细化、系统化的基准检验方法，本研究开发了 LIB_Convert 程序，结合通用燃耗数据库制作系统 GENDEPLIX，基于 CNAF 3.4 和 ENDF/B-Ⅷ.0 数据库，制作了适用于 CINDER90 程序的燃耗数据库 FRBurn.lib。然后以 TAKAHAMA-3 压水堆为对象，系统开展了燃耗数据库的基准检验方法研究，并将所建立的方法体系应用于 FRBurn.lib 的验证。最后，以日本 JOYO 快堆 MK-1 组件为基准题对 FRBurn.lib 进行验证，计算值与实验值符合良好，验证了该数据库的准确性与可靠性。

关键词: 燃耗数据库；燃耗基准检验；积存量计算；JOYO；CINDER90

Abstract: To develop a high-accuracy burnup database for fast reactors and establish a refined and systematic benchmark validation method, this study developed the LIB_Convert code. Combined with the general burnup database production system GENDEPLIX, a burnup database FRBurn.lib suitable for the CINDER90 code was produced based on the CNAF 3.4 and ENDF/B-VIII.0 libraries. Then, taking the TAKAHAMA-3 pressurized water reactor as the object, systematic research on the benchmark validation method for the burnup database was carried out, and the established methodology was applied to the verification of FRBurn.lib. Finally, the FRBurn.lib database was validated using the Japanese JOYO fast reactor MK-1 assembly as a benchmark problem. The calculated values are in good agreement with the experimental values, verifying the accuracy and reliability of the database.

Keywords: Burnup database; Burnup benchmark validation; Inventory calculation; JOYO; CINDER90

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基于宏观电子密度的质子屏蔽逆向设计

Author: 李振超[1]

[1] *兰州大学*

Corresponding Author: 320220917411@lzu.edu.cn

摘要: 贝特-布洛赫 (Bethe-Bloch) 公式中平均激发能 (I 值) 的准确确定一直是辐射屏蔽优化的难点，迫使工程设计往往依赖耗时的黑箱搜索算法或忽略化学键效应的布拉格加和定则 (BAR)。本文提出了一种受局域等离子体近似 (LPA) 理论启发的半经验模型，揭示了宏观电子密度 (ρe) 与质子最大能量沉积 (Eth) 之间存在的稳定规律。通过对 112 种单质及复合材料的 Geant4 模拟分析，证明了 ρe 作为一个集体参量，能有效捕捉独立原子模型所忽略的凝聚态效应。研究发现，材料的 I 值与 ρe 遵循 1/ρe∝I-2/3 的标度关系，该指数偏离了理想电子气的理论预测值 1/ρe∝I-2，反映了凝聚态物质中的几何约束与费米面效应。针对壳层结构引起的电子云体积异常，本文进一步提出了一种针对离子化合物的等电子修正方法，显著降低了预测误差。基于此，建立了利用单一变量 ρe 直接计算 Eth 的经验模型（R2>0.99989），并实现了屏蔽设计的逆向求解。与多目标遗传算法 (NSGA-II) 相比，该逆向设计在保证平均误差小于 3.7% 的同时，计算效率实现了 5 个数量级以上的提升。此外，本文还基于特征材料的反演策略给出了包含厚度变量的完整 Eth(d,ρe) 解析公式，为受质量与体积双重约束的空间辐射屏蔽设计提供了一种兼具物理解释性与计算高效性的解析方法。

关键词: 平均激发能；阻止本领；壳层效应；电子密度；贝特-布洛赫公式

Abstract: In the optimal design of radiation shielding, the shielding performance of known materials can be accurately calculated using the Bethe–Bloch formula. Nevertheless, practical design still relies on time-consuming black-box search algorithms. The optimal shielding materials obtained in this way not only lack physical justification but are also unconvincing: the algorithmic results are sometimes irreproducible, and outputs from different algorithms can differ substantially. This creates an urgent demand to clearly identify, through rigorous physical formulas, what the optimal shielding material is under given conditions and how to determine it uniquely. In this paper, we propose a semi-empirical model inspired by the Local Plasma Approximation (LPA) theory, revealing a robust scaling correlation between macroscopic electron density (ρe) and full absorption threshold (Eth). Through Geant4 simulation analysis of 112 elemental and composite materials, we demonstrate that ρe, as a collective parameter, effectively captures the condensed matter effects ignored by independent atom models. We observe a strong empirical correlation where the material's I-value and ρe follow a scaling relation of 1/ρe∝I-2/3. This exponent deviates from the theoretical prediction for an ideal electron gas (1/ρe∝I-2). To address volume anomalies caused by shell structures, we further propose an isoelectronic correction method for ionic compounds, which significantly reduces prediction errors. Based on this, we established an empirical model using the single variable ρe to directly calculate Eth (R2>0.99989) and implemented an inverse design solution for shielding. Compared to the Multi-objective Genetic Algorithm (NSGA-II), this inverse design method achieves a calculation efficiency improvement of over five orders of magnitude while maintaining the mean absolute percentage error (MAPE) of less than 4.6%. Furthermore, based on an inversion strategy using characteristic materials, we provide a complete analytical formula for Eth(d, ρe) including thickness variables. This offers an analytical method combining physical interpretability and computational efficiency for space radiation shielding design subject to dual mass and volume constraints.

Keywords: Mean Excitation Energy;Stopping Power;Shell Effect;Electron Density;Bethe-Bloch Formula

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Toward a multipactor-free cavity design for a very-high-frequency continuous-wave electron gun

Authors: 段懿桐[1]; 郑连敏[1]; 杜应超[1]

[1] *清华大学工程物理系*

摘要: 甚高频（VHF）光阴极电子枪可产生高重复频率、高亮度电子束，并工作于连续波模式。二次电子倍增（Multipactor）是制约其应用的关键问题，会导致功率损耗、腔体损伤、束流品质下降及寿命缩短。本文证实腔体内为非谐振二次电子倍增并确定其易发区域，通过系统优化腔体几何结构实现倍增抑制；基于电子轨迹统计分析阐明抑制机理，研究铜材料二次电子产额（SEY）的影响，最终提出一种具有极低二次电子倍增效应与优异射频性能的优化腔体方案，为 VHF 电子枪稳定运行提供支撑。

关键词: 二次电子倍增，二次电子，甚高频电子枪，腔形

Abstract: A VHF photocathode electron gun generates high-repetition-rate, high-brightness electron bunches in continuous-wave mode. Multipactor is a critical issue that causes power loss, cavity damage, beam quality degradation, and shortened lifetime. This work confirms non-resonant multipactor in the cavity, identifies its dominant region, and systematically optimizes cavity geometry to suppress multipactor. The suppression mechanism is clarified via statistical analysis of electron trajectories. The influence of copper secondary electron yield (SEY) is investigated, and an optimized cavity with ultra-low multipactor and excellent RF performance is proposed for stable VHF gun operation.

Keywords: multipactor, secondary electron, VHF electrongun, cavity shape

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用于中子毒物浓度在线测量的光中子源设计

Author: 宗春光[1]

Co-authors: 杨祎罡 [1]; 李元景 [1]; 申金明 [2]; 於民锋 [1]; 刘立兴 [2]; 王东宇 [2]; 刘必成 [2]; 亮张 [2]

[1] *清华大学工程物理系*

[2] *同方威视技术股份有限公司*

Corresponding Author: zongcg21@mails.tsinghua.edu.cn

摘要: 本文针对乏燃料后处理流程中子毒物浓度在线测量的需求，设计了一种基于 7 MeV 小型电子直线加速器的脉冲光中子源技术方案。通过蒙特卡罗模拟，设计了铍中子转换靶的结构（Φ160 mm×40 mm 圆柱体），优化了其与待测溶液的相对位置，使单位流强产生的进入待测溶液的中子数达 1.4×10-5 n/e。模拟结果表明该光中子源的单脉冲中子产额达 9.3×107 个，其中能量在 1 MeV 以下的部分占 89%，在典型浓度的中子毒物溶液中发生辐射俘获的份额达 17.8%；在加速器出束脉冲期间进入待测溶液的中子占比达 94.7%，由于源的展宽引入的中子存活寿命测量偏差不大于 1.12%。光子转换靶和中子转换靶的温度和应力水平均处于安全使用范围内，满足长期稳定运行的要求。本设计为中子毒物浓度在线测量提供可行的中子源，具有良好的应用前景。

关键词: 中子毒物浓度；光中子源；铍靶；中子存活寿命

Abstract: This paper proposes a design scheme for a photoneutron source based on a compact 7 MeV electron linear accelerator, which addresses the need for the online measurement of the neutron poison concentration. The structure of the beryllium neutron conversion target is designed as a Φ160 mm × 40 mm cylinder, and its position relative to the solution to be measured is optimized through Monte Carlo simulations, so that the number of neutrons entering the solution per unit flux reaches 1.4×10-5 n/e. Simulation results show that the photoneutron source achieves a single-pulse neutron yield of 9.3×107 n/s. The proportion of neutrons with the energy below 1 MeV accounting for 89% of the total, of which 17.8% will undergo radiative capture in typical gadolinium solutions. The proportion of neutrons entering the solution to be measured during the accelerator beam pulse period is 94.7%, and the deviation of neutron lifetime measurement caused by the broadening of the source is no more than 1.12%. The temperature and stress levels of the target materials are within the safe range, thereby satisfying the criteria necessary for ensuring long-term stable operation. This design provides a feasible neutron source for the online measurement of the neutron poison concentration, thereby demonstrating its promising application potential.

Keywords: neutron poison concentration; photoneutron source; beryllium target; neutron lifetime

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Building a net-zero power system under future climate conditions with data-driven forecasting and adequacy assessment

Authors: 吕晋宁[1]; 任晋辉; 张枢; 陈文颖

[1] *清华大学工程物理系*

Corresponding Author: lvjn24@mails.tsinghua.edu.cn

摘要: 随着全球能源系统向碳中和转型，可再生能源发电波动性的不断增强以及负荷对气候变化的敏感性上升，正对净零电力系统的充裕性带来重大挑战。然而，现有评估通常缺乏一种能够在未来气候条件下，同时刻画高时空分辨率长期负荷变化以及输电与储能约束的分析框架。为此，本研究构建了一个综合评估框架，通过耦合高分辨率负荷预测与电力系统模拟，对净零电力系统的充裕性进行评估。首先，我们为中国开发了一个基于神经网络的小时电力负荷模型（HELM），用于预测不同社会经济与气候情景下的省级电力负荷。随后，将预测结果嵌入一个覆盖 30 个省份、8760 小时的模拟模型中，在每种碳中和转型情景下，通过超过 300 组跨省输电与储能配置方案评估系统运行表现。结果表明，到 2060 年，全国电力需求将达到 23262.59 TWh，夏季峰值负荷将达到 3234 GW，显示出未来电力系统在负荷波动加剧和峰值负荷攀升方面面临的挑战。在以风电和光伏为主导的电力系统中，显著的时空错配将导致最高达 59.54% 的潜在电力短缺。针对性扩张输电和储能可有效缓解这些缺口，使全国系统充裕性提高 16.25%，并在浙江等受电省份实现超过 50% 的提升。这些发现通过强调跨省基础设施、灵活性资源和市场化支持机制的协同发展，为中国能源转型提供了战略性路线图。

关键词: 净零电力系统，电力负荷预测，机器学习，系统充裕性，跨省电力传输，储能

Abstract: As global energy systems transition toward carbon neutrality, the increasing variability of renewable generation and climate-sensitive load poses significant challenges to net-zero power system adequacy. However, current assessments often lack a framework that captures high-resolution, long-term load dynamics alongside transmission and storage constraints under future climate conditions. This study constructs an integrated assessment framework to evaluate the adequacy of a net-zero power system by coupling high-resolution load forecasting with power system simulations. We first developed a neural network-based Hourly Electricity Load Model (HELM) for China to forecast provincial load under diverse socioeconomic and climate scenarios. These forecasts were then integrated into an 8760-hour simulation model encompassing 30 provinces to assess system performance under more than 300 configurations of interprovincial transmission and energy storage for each carbon-neutral transition scenario. Results show that national electricity demand will reach 23262.59 TWh in 2060, with a summer peak of 3234 GW, revealing the challenges ahead in demand volatility and rising peak loads. In a power system dominated by wind and solar power, substantial spatiotemporal mismatches lead to potential electricity deficits of up to 59.54%. Targeted expansion of transmission and storage can mitigate these gaps, enhancing national system adequacy by 16.25% and exceeding 50% in power-importing provinces such as Zhejiang. These findings provide a strategic roadmap for China’s energy transition by emphasizing the coordinated development of interprovincial infrastructure, flexible resources, and market-based support mechanisms.

Keywords: Net-zero power system, Electricity load forecasting, Machine learning, System adequacy, Interprovincial transmission, Energy storage

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基于 X 射线正交双投影的圆形管材截面参数在线检测系统研究

Author: 孙煜昌[1]

Co-authors: 曾天辰 [1]; 王立强 [1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Author: sunyc23@mails.tsinghua.edu.cn

摘要: 圆形管材（如电缆和胶管）的几何截面参数（内外径、壁厚及偏心）是表征制造质量的关键指标。现有基于 X 射线数字成像的检测方法通常依赖于射线衰减曲线中边界突变点的定位，然而受限于探测器物理像素尺寸及系统噪声，导致定位精度不足并进一步影响参数反演的准确性与稳定性。针对上述问题，本文提出一种结合探测器亚像素微动与闭环差值驱动优化（Closed-loop residual-driven optimization, CRO）的截面参数重建方法。首先，通过引入亚像素级探测器微动采样策略，获取多帧位移采样数据并进行拼接，从而在不改变物理像素尺寸的前提下提高投影信号的等效采样分辨率，实现突变点的亚像素级定位。解析仿真结果表明，相较于无微动情况（探测器像素为 0.2 mm），当微动步长分别缩小至 0.1 mm、0.05 mm 和 0.04 mm 时，内轮廓长轴参数的平均绝对误差（MAE）分别降低了 38.10%，40.01% 和 47.25%。进一步地，针对实际测量中存在的噪声等干扰，本文构建了一种基于突变点处差值符号反馈的闭环迭代优化算法（CRO）。该方法以测量投影与参数化轮廓模型解析投影在突变点处的差值为反馈信号，通过差值的符号驱动更新策略对轮廓参数进行修正，从而提升轮廓参数的精度并增强算法对实际干扰因素的鲁棒性。Monte Carlo（MC）仿真数据表明（以 0.04 mm 微动步长为例），引入 CRO 算法优化后，轮廓参数的 MAE 下降了 69.44%，最大误差为 0.03 mm。综上，本文提出的协同硬件与软件算法的方案在不依赖复杂成像重建的前提下，实现了对圆形管材截面参数的高精度反演，为工业在线检测提供了一种高效且具有工程可行性的解决方案。

关键词: X 射线、在线检测、亚像素微动

Abstract: The geometric cross-sectional parameters of circular tubes including inner and outer diameters, wall thickness, and eccentricity are critical indicators for manufacturing quality evaluation. Existing X-ray digital imaging-based inspection methods typically rely on the localization of edge transition points (ETPs) in attenuation curves. However, their performance is fundamentally limited by the detector's physical pixel size and noise, leading to insufficient localization accuracy and, consequently, degraded precision and stability in parameter inversion. To address these limitations, this paper proposes a novel cross-sectional parameter reconstruction framework that integrates detector sub-pixel motion with a closed-loop residual-driven optimization (CRO) algorithm. First, a sub-pixel detector motion scheme is introduced to enhance the effective sampling resolution of the projection signal. Analytical simulation results demonstrate that, compared with the no-motion case (detector pixel size of 0.2 mm), reducing the motion step size to 0.1 mm, 0.05 mm and 0.04 mm decreases the mean absolute error (MAE) of the inner contour major axis by 38.10%, 40.01%, and 47.25%, respectively. Furthermore, to mitigate the influence of noise and other practical disturbances, a closed-loop iterative optimization algorithm based on residual sign feedback is developed. In the proposed CRO framework, the residual between measured projections and analytically computed projections from a parametric contour model is evaluated at the ETPs to guide parameter updates, enabling iterative refinement of contour parameters. Monte Carlo (MC) simulation results demonstrate that taking a motion step size of 0.04 mm as an example, the introduction of the CRO algorithm reduces the MAEof inner contour major axis by 69.44%, with a maximum MAE of only 0.03 mm. In summary, the proposed approach provides an efficient and paratically feasible solution for high-accuracy industrial online inspection.

Keywords: X-ray, Online inspection, Sub-pixel motion

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基于 LightGBM 的核电站失水事故关键参数预测与相关性分析

Author: 庞勃[1]

Co-authors: 林源峰 [2]; 秦国旭 [2]; 黄善仿 [3]

[1] *中国核动力研究设计院；清华大学工程物理系；核反应堆技术全国重点实验室*

[2] *中国核动力研究设计院；核反应堆全国重点实验室*

[3] *清华大学工程物理系*

Corresponding Author: pang-b24@mails.tsinghua.edu.cn

摘要: 全范围模拟机在核电厂应急演练、人员培训及事故分析环节具有关键作用。传统系统程序在反应堆系统处于复杂事故工况时计算性能无法满足实时性需求。本研究以核电厂小破口失水事故 (SBLOCA) 为对象，通过数字试验生成大规模数据集，经过数据预处理与标准化处理，利用机器学习人工智能算法建立了轻量梯度提升决策树（LightGBM）回归模型，并通过 SHAP 可解释性分析识别出特征贡献因素，该模型可用于预测燃料包壳峰值温度、反应堆一回路冷却剂压力及稳压器水位等关键参数。该模型均方误差（MSE）低于 0.002，决定系数（R^2）超过 0.98，预测速度较系统程序提升约 32500 倍，单个数据点计算耗时不足 0.0004 秒。本研究为核电站全范围模拟机复杂工况计算提供了一种新的解决方法。

关键词: 核电厂仿真; 轻量梯度提升决策树; 参数预测; 相关性分析

Abstract: The full-scope simulator plays a critical role in nuclear power plant emergency drills, personnel training, and accident analysis. Traditional system programs lack sufficient computational performance to meet real-time requirements when simulating complex accident scenarios in reactor systems. This study focuses on the Small Break Loss of Coolant Accident (SBLOCA) in nuclear power plants, generating large-scale datasets through digital simulations. After data preprocessing and standardization, a lightweight Gradient Boosting Decision Tree (LightGBM) regression model was developed using machine learning algorithms. SHAP (Shapiro's Hypothesis Testing and Interpretation) analysis identified the contributing factors, enabling the model to predict key parameters such as fuel peak cladding temperature, primary reactor coolant pressure, and pressurizer water level. The model achieved a mean square error (MSE) below 0.002 and a coefficient of determination (R^2) exceeding 0.98, with a prediction speed approximately 32,500 times faster than traditional system programs—requiring less than 0.0004 seconds per data point. This study provides a novel solution for complex condition simulations in nuclear power plant full-scope simulators.

Keywords: Nuclear Power Plant Simulator; LightGBM; Parameter Prediction; SHAP

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Investigation of ultraviolet spectrum and energy level assignments of Gd I in the 305–325nm region

Author: 李云飞[1]

[1] *核工业理化工程研究院*

Corresponding Author: liyunfei40@163.com

摘要: 本文利用共振电离光谱技术研究了 305–325 nm 范围内钆原子的紫外光谱，共获得了 196 条跃迁谱线，其中包括 66 条强线。通过结合已有文献数据和泵浦-探测技术验证，共标识了 190 条谱线的跃迁上下能级，其中 172 条为首次报道。同时，还首次标识了 17 个偶宇称高激发态能级。本文报道的强线将有助于未来对钆原子类氢态和自电离态的研究，并实现用于共振电离质谱分析的双色、两步光电离路径。

关键词: 钆原子，紫外光谱，共振电离光谱，泵浦-探测技术

Abstract: The ultraviolet spectrum of Gd I in the 305–325 nm range was studied using resonance ionization spectroscopy, revealing 196 transition lines, including 66 strong ones. The lower and upper energy levels were assigned to 190 lines by combining available reference data with pump–probe verification, 172 of which are reported for the first time. Seventeen new even-parity high-lying excited states were also identified. The strong lines reported here will contribute to future studies of Gd I Rydberg and autoionization states and enable two-color, two-step photoionization pathways for and resonance ionization mass spectrometry analysis.

Keywords: Atomic gadolinium, Ultraviolet spectrum, Resonance ionization spectroscopy, Pump-probe technique

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Analysis of gadolinium concentration in solutions based on photoneutrons’lifetime measurement

Author: 於民锋[1]

[1] *清华大学*

Corresponding Author: yumf21@mails.tsinghua.edu.cn

摘要: 在乏核燃料再处理过程中，通常会在乏核燃料溶液中添加中子毒剂，以使溶液保持在亚临界状态。硝酸钆是一种广泛使用的中子毒剂，在乏核燃料再处理过程中必须精确测定其浓度。本研究提出了一种基于电子直线加速器驱动的光中子源的钆浓度监测方法，通过分析钆溶液中光中子的寿命来测定钆浓度。文中呈现并讨论了蒙特卡洛模拟与实验结果。结果表明，该方法在 0.1 g/L 至 1.0 g/L 的浓度范围内对钆浓度的测定效果良好。

关键词: 中子寿命；中子毒物；光中子；浓度分析

Abstract: In spent nuclear fuel reprocessing, neutron poisons are usually added to the spent nuclear fuel solution for maintaining the solution in subcritical state. Gadolinium nitrate is a widely used neutron poison, and its concentration should be exactly known for spent nuclear fuel reprocessing. In this study, an e-LINAC driven photoneutron source based gadolinium concentration monitoring method is proposed to measure the gadolinium concentration by analyzing the lifetime of photoneutrons in gadolinium solutions. Monte Carlo simulation and experimental results are both presented and discussed. The results demonstrate this method works well for measuring gadolinium concentration within the range of 0.1g/L~ 1.0 g/L.

Keywords: Neutron lifetime; neutron poison; Photoneutron; concentration analysis;

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PF3 含量对取料器附近 Ni(PF3)4 热分解影响的数值模拟研究

Author: 吴俊禄[1]

Co-authors: 张子涵 [2]; 姜东君 [1]; 子学郭 [2]

[1] *清华大学*

[2] *核工业理化工程研究院*

Corresponding Author: wujl22@mails.tsinghua.edu.cn

摘要: 气体离心机正常运转时，超高声速气流会在取料器口部形成一道强激波，伴随着高温。这种高温会导致部分热稳定性较差的工质发生热分解，影响机器正常运转，甚至堵塞取料器。为了解决工质在取料器口部的热分解问题，本文提出了一种在离心机中混入辅助气体的方法。本文使用等径圆管的取料器模型、以四 (三氟膦) 镍（Ni(PF3)4）为工质进行了流固热耦合模拟验证。计算结果表明：随着辅助气体 PF3 的比例增加，取料流量增大，流体最高温度降低，相对分解速率也明显降低，但是混入过多 PF3 会使取料器的水力学状态发生改变。因此，应综合考虑取料器的水力学状态和工质热分解程度，严格控制辅助气体的体积分数，能一定程度上缓解取料器口部的工质热分解问题。

关键词: 气体离心机；取料器；工质热分解；四 (三氟膦) 镍；混合气体

Abstract: In order to solve the problem of thermal decomposition of part of the processing gas at the mouth of the scoop, a method of mixing the gas of the decomposition product of the processing gas into the centrifuge is proposed. By mixing the decomposition product gas, the Mach number of the gas stream can be reduced, the temperature can be lowered, and the thermal decomposition rate can be reduced. In this paper, the axisymmetric equal-diameter scoop model is used to simulate and verify the separation of tetra(trifluorophosphine)nickel (Ni(PF3)4). By mixing PF3 with different volume fractions in Ni(PF3)4, the following results are obtained: with the increase of mixed PF3 volume fraction, the reclaiming flow rate increases, the maximum temperature of the fluid gradually decreases, and the relative decomposition rate also decreases significantly, but when the volume fraction reaches 50%, the hydraulic state of the scoop also changes. Therefore, the hydraulic state of the scoop and the degree of thermal decomposition of the working substance should be comprehensively considered, and the volume fraction of the auxiliary gas should be strictly controlled, which can alleviate the problem of thermal decomposition of the working substance at the mouth of the scoop to a certain extent.

Keywords: Gas Centrifuges; Scoops; Thermal Decomposition of Processing Gas; Tetrakis(trifluorophosphane)nickel; Gas Mixtures

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Research on hydrogen risk prediction in probability safety analysis for severe accidents of nuclear power plants

Author: 孙婧[1]

Co-authors: Lin Shengsheng [2]; Shi Xueyao [2]; Wang Hui [2]

[1] *清华大学核能与新能源技术研究院*

[2] *CNPE*

Corresponding Author: sunj25@mails.tsinghua.edu.cn

摘要: 福岛核事故后氢气燃烧风险始终是核电行业关注的重点问题。在核电厂概率安全分析的氢气风险评估中，传统方法采用集总参数程序计算，计算速度快但可能存在较大不确定性，而新近发展的 CFD 分析方法更为精确，但由于多种因素尚未广泛应用于 PSA 的氢气风险分析。本文首先针对中国某第三代大型压水堆核电厂华龙一号，采用集总参数分析程序 MAAP 分析小 LOCA 严重事故下的氢气参数，进而分析氢气爆燃向爆轰转变的概率及其不确定性。其次，采用 CFD 程序 GASFLOW 对同一事故序列进行分析，以获得更准确的氢气分布及其他参数，同时获取氢气的 DDT 概率值。CFD 计算获得的氢气分布可用于指导集总参数程序的不确定值，从而获得更准确的氢气 DDT 值。分析结果表明，采用集总参数程序方法进行氢气风险评估存在一定的不确定性，可结合 CFD 软件给出的气体分布分析结果进行修正，以获得更准确、可靠的概率值。

关键词: 氢气风险，DDT，MAAP，Sherman-Berman，GASFLOW，华龙一号

Abstract: The risk of hydrogen combustion after the Fukushima nuclear accident has always been a topic of concern for the nuclear power industry. In the hydrogen risk assessment of probability safety analysis (PSA) in nuclear power plants, the traditional methods by using lumped parameter program method is fast but may have large uncertainties,
while the newly developed CFD analysis method is more accurate but has not yet been widely applied to the hydrogen risk analysis of PSA due to a variety of factors. The lumped parameter analysis program MAAP is used firstly to obtain the hydrogen parameters under the severe accident of small LOCA in this paper, based on China's third-generation large-scale pressurized water reactor (PWR) nuclear power plant HPR1000, and then the probability of deflagaration to detonation (DDT) for hydrogen risk is analyzed with uncertainty. Secondly, the CFD software GASFLOW program is used to analyze the same accident sequence to obtain more accurate hydrogen distribution and other parameters, and at the same time to obtain the DDT probability value of hydrogen risk. The hydrogen distribution obtained by CFD calculation can be used to guide the uncertainty value
of the lumped parameter program to produce more accurate DDT value of hydrogen risk. The analysis results show that there is a certain uncertainty in hydrogen risk assessment when using lumped parameter program method, which can be corrected by combining the gas distribution analysis results given by CFD software, to obtain a more accurate and reliable probability value, so as to provide

Keywords: Hydrogen risk, DDT, MAAP, Sherman-Berman, GASFLOW, HPR1000

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氦氙混合气体在平行槽道中的直接数值模拟与湍流普朗特数模型

Authors: 王舜琦[1]; 吉宇[1]; 孙俊[1]; 孙玉良[1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Author: wangsq22@mails.tsinghua.edu.cn

摘要: 氦氙混合气体被广泛应用于多种微型气冷核反应堆的设计中。然而，由于其普朗特数显著不同（约为 0.2），氦氙混合气体的湍流流动与换热特性尚不完全明确。由于以往大多数湍流普朗特数模型的研究对象均为更低普朗特数流体（如液态金属，Pr<0.03）或更高普朗特数流体（如水，Pr»1），因此在为氦氙混合气体选择合适的湍流普朗特数模型方面仍存在挑战。直接数值模拟方法是湍流建模的基础，有助于湍流模型的构建。本文对平面通道内氦氙混合气体的流动与换热进行了直接数值模拟，雷诺数范围为 5600 至 13700，普朗特数范围为 0.2~0.3。同时，结合 SST k-ω 湍流模型，对几种湍流普朗特数模型进行 RANS 计算，并与直接数值模拟结果进行了对比。综合考虑雷诺数、普朗特数及壁面法向距离的影响，提出了一种三参数湍流普朗特数模型，以表征近壁面区域的变化规律。该模型还对特定湍流模型下湍流黏度的偏差进行了补偿，并给出了新模型在有修正与无修正情况下的对比结果。通过分析，提出了新模型的使用建议。

关键词: 氦氙混合气体, 直接数值模拟, 普朗特数，槽道, 湍流普朗特数模型

Abstract: The helium-xenon gas mixture is used in various designs of micro gas-cooled nuclear reactors. The turbulent flow and heat transfer of helium-xenon is not well understood due to its distinct Prandtl number (~0.2). There is still challenge in choosing proper turbulent Prandtl number model for helium-xenon, since most previous turbulent Prandtl number models were investigated for lower Prandtl number fluids (liquid metals, <0.03) or larger Prandtl number fluids (water, »1). The direct numerical simulation method is fundamental in turbulence modeling and is helpful in formulating turbulence models. The flow and heat transfer of helium-xenon in a planar channel was simulated with the Reynolds numbers ranging from 5,600 to 13,700 and the Prandtl numbers of 0.2~0.3. Several turbulent Prandtl number models along with the SST k-ω turbulence model were also used and compared with direct numerical simulation method. By considering the effects of Reynolds number, Prandtl number and wall-normal distance, a three-parameter turbulent Prandtl number model was proposed to depict the near wall variations. It also compensated the deviation of turbulent viscosity from the specific turbulence model and show the comparison results between the new model with and without correction. Through analysis, usage suggestions for the new model were given.

Keywords: helium-xenon gas mixture, direct numerical simulation, Prandtl number, planar channel, turbulent Prandtl number model

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基于伴随可微物理的闭式布雷顿气冷堆数字孪生在线参数反演方法

Authors: 李承远[2]; 邓坚[1]; 黄善仿[2]; 邱方志[1]; 严章蕊[1]

[1] *中国核动力研究设计院*

[2] *清华大学工程物理系*

Corresponding Authors: qzf_npic@163.com, lichengyuan98@gmail.com, dengjian_npic@163.com, 956200219@qq.com

摘要: 先进反应堆数字孪生需要在传感器稀疏、工况非定常的条件下完成在线参数反演。现有方法多依赖卡尔曼类滤波器或四维变分方案，在部分观测和瞬态激励下精度明显下降。本文提出一种基于伴随的可微物理反演框架：通过反向模式自动微分穿透隐式微分代数（DAE）求解器获得解析参数灵敏度，结合 Tikhonov 正则化的 L-BFGS 优化求解反问题。框架围绕一个 14 状态闭式布雷顿气冷堆数字孪生构建，保留了含三种反应性反馈的六群点堆动力学、回热器与辐射器热容、管道摩擦以及含功率管理与分配（PMAD）控制器的轴系动力学。在全观测稳态、全观测瞬态、部分观测噪声扫描三类场景下，将所提方法与集合卡尔曼滤波（EnKF）、无迹卡尔曼滤波（UKF）和有限差分 4D-Var 基准进行对比，并以 Cramér–Rao 下界（CRLB）为参照评估各估计器的统计效率。结果表明：在瞬态场景下，所提方法对反射层反应性系数的相对误差为 7.5%，优于 4D-Var（10.2%）和卡尔曼类滤波（约 19%）；在部分观测场景下相对误差为 0.4%–0.55%，相较 4D-Var、EnKF、UKF 分别降低 1.6 至 5 倍；正则化伴随估计器的经验方差接近 CRLB，残余偏差约 5×10^{-3}。仅在全观测稳态单参数场景下，序贯滤波器凭借其最佳线性无偏（BLUE）特性保持优势。所提框架将可微物理与伴随灵敏度引入闭式布雷顿气冷堆数字孪生，为部分观测和瞬态工况下安全相关参数的在线辨识提供了精度更高、统计效率更接近理论下界的可行途径，对推进先进反应堆数字孪生从监测向智能监督控制演进具有参考意义。

关键词: 数字孪生；伴随方法；可微物理；参数反演；闭式布雷顿循环；气冷堆；数据同化；Cramér–Rao 下界

Abstract: Digital twins for advanced reactor concepts must perform online parameter inversion under sparse sensing and non-stationary dynamics, conditions in which Kalman variants and four-dimensional variational schemes lose accuracy. We present an adjoint-based differentiable physics framework that couples reverse-mode automatic differentiation through an implicit differential-algebraic plant model with Tikhonov-regularised L-BFGS optimisation, yielding analytical parameter-sensitivity matrices for gradient-based inversion. The framework is built around a fourteen-state closed-Brayton gas-cooled reactor twin retaining six-group point kinetics with three reactivity feedbacks, recuperator and radiator thermal capacitances, duct friction, and a power-management-and-distribution shaft controller. We benchmark the method against the Ensemble Kalman Filter, the Unscented Kalman Filter, and a finite-difference 4D-Variational baseline across full-observation steady-state, full-observation transient, and partial-observation noise-scan scenarios, and we compare every estimator against the Cramér–Rao lower bound. On the transient scenario the proposed method recovers the reflector reactivity coefficient with 7.5% relative error, against 10.2% for 4D-Var and approximately 19% for the sequential filters; on the partial-observation scenario it reaches 0.4%–0.55%, a 1.6× to 5× reduction over the same baselines. The regularised adjoint estimators attain near-CRLB empirical variance with a residual relative bias of order 5×10^{-3}. Sequential filters retain an advantage only on the controlled full-observation steady-state single-parameter case, where they are theoretically Best-Linear-Unbiased optimal. By bringing differentiable physics and adjoint sensitivities into closed-Brayton gas-cooled reactor digital twins, the proposed framework offers a more accurate and statistically more efficient route to online identification of safety-critical parameters under partial observation and transient excitation, supporting the progression of advanced-reactor digital twins from passive monitoring toward intelligent supervisory control.

Keywords: digital twin; adjoint method; differentiable physics; parameter inversion; closed-Brayton cycle; gas-cooled reactor; data assimilation; Cramér–Rao lower bound

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MIPEC 诱导高碘吸附性能共价有机框架的超快合成

Author: 卿琪[1]

[1] *清华大学*

Corresponding Author: qq22@mails.tsinghua.edu.cn

摘要: 共价有机框架（COFs）作为一类晶态多孔有机材料，因具有高比表面积、可调控孔道结构、丰富的活性位点及优异的化学稳定性，在放射性碘吸附领域展现出巨大应用潜力。然而，传统 COFs 合成方法（如溶剂热法）条件较为严苛（≥ 120℃，72 h），严重制约了其规模化制备与实际应

用。开发一种高效、绿色、通用的 COFs 快速合成方法，作为筛选高性能碘吸附 COFs 材料的筛选平台，对保障环境安全与核能可持续发展具有重要意义。基于微等离子体电化学方法（MIPEC）的 COFs 快速合成策略，实现了室温常压下 COFs 的高效制备，所合成材料具有良好结晶性以及高比表面积。进一步对 MIPEC 合成 COFs 机理进行了深入探索，结果表明微等离子体产生的高能活性物种对于引发和加速合成反应具有重要作用，同时水可以促进结晶。相比于传统的溶剂热方法，MIPEC 方法具有低能耗与高时空产率，能耗较溶剂热法降低五个数量级，时空产率高千倍，为现有报道时空产率最高的方法之一。此外，MIPEC 具有一定的通用性，成功合成多种柔性亚胺键 COFs 及不同键型（刚性亚胺键、腙键、烯酮-胺键、吖嗪键）的 COFs，且适用于乙酸水溶液中亚胺基 COFs 的制备，避免有毒有机溶剂的使用。所合成材料性能优异，且热稳定性良好，为碘吸附应用提供了候选材料。基于 MIPEC 的超快合成平台，既可以合成碘吸附性能优异的 COFs 材料，同时提供了一种快速的高通量筛选方式，为未来新型 COFs 材料的设计与理论计算筛选提供参考数据。

关键词: 共价有机框架材料，微等离子体电化学，快速合成，碘吸附

Abstract: Covalent organic frameworks (COFs), as an emerging class of crystalline porous organic materials, have shown remarkable potential for radioactive iodine capture due to their high specific surface area, tunable pore structures, abundant active sites, and excellent chemical stability. However, conventional synthesis methods, such as solvothermal approaches, typically require harsh conditions (≥ 120℃) and long reaction times (72 h), which significantly hinder their scalable production and practical application. Therefore, it's necessary to develop an efficient, green, and generalizable method for rapid COFs synthesis. In this study, we propose a rapid synthesis and screening strategy for COFs based on microplasma electrochemistry (MIPEC), enabling efficient preparation of COFs under ambient temperature and pressure, along with systematic evaluation of their iodine adsorption performance. The synthesis mechanism of MIPEC was explored further, the highly reactive species generated by the microplasma effectively initiate and accelerate the synthesis reactions. Compared to conventional solvothermal methods, the MIPEC approach exhibits notable energy-saving advantages and exceptionally high space-time yield. This method demonstrates good generality, having been successfully applied to synthesize a series of COFs with flexible imine linkages and COFs with diverse linkages (rigid imine, hydrazone, β-ketoenamies and azine linkages). The ultrafast synthesis platform based on MIPEC can be used for high-throughput screening of high-performance COFs for iodine capture. The MIPEC method not only enables the synthesis of materials with superior iodine adsorption performance but also offers an efficient screening pathway, providing valuable reference data for the rational design and computational screening of novel COFs in the future.

Keywords: Covalent organic frameworks, Microplasma electrochemistry, Rapid synthesis, Iodine capture

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Burnup Analysis Capability Based on Unstructured Mesh Geometry in Reactor Monte Carlo code RMC

Authors: 曾国禹[1]; 李庆[1]; 李杰[1]; 王侃[1]; 申鹏飞[1]

[1] *清华大学工程物理系*

Corresponding Author: jie-li22@mails.tsinghua.edu.cn

摘要: 非结构网格（Unstructured Mesh, UM）是蒙卡（Monte Carlo, MC）程序一种先进的几何表述方式，在复杂几何建模、精细计数统计、高保真多物理耦合等方面具有天然优势。尽管在基于 UM 几何的粒子输运方面已有显著研究进展，但对于反应堆全寿期的模拟还需要具备燃耗计算分析能力，MC 程序直接基于 UM 几何的燃耗计算方法仍有待进一步研究。本文聚焦于 MC 程序在 UM 几何框架下的燃耗计算方法研究，在 RMC UM 几何下粒子输运和计数统计能力的基础上，进一步实现了 UM 几何下的燃耗计算功能。为 RMC 建立起 KRUSTY 反应堆的 CSG 和 UM 燃耗计算模型，结果表明，UM 与 CSG 模型在各个燃耗步下的 keff 及重要核素质量变化吻合很好，验证了 RMC 基于 UM 几何进行燃耗计算功能的正确性。

关键词: 蒙卡程序；非结构网格；燃耗计算；RMC

Abstract: Unstructured Mesh (UM) serves as an advanced geometric modeling method in Monte Carlo (MC) codes, offering inherent advantages for representing complex geometries, obtaining high-resolution tally results, and enabling high-fidelity multi-physics coupling. Although significant progress has been made in UM-based particle transport simulation within MC codes, full lifecycle reactor simulation still requires burnup calculation and analysis capabilities. The development of burnup calculation methods based on UM geometry in MC codes remains an area requiring further investigation. This study focuses on burnup calculation methodologies under the UM framework in MC codes. Leveraging the particle transport and tally capabilities of RMC's UM geometry, we have further implemented burnup calculation functionality based on UM in RMC. Both CSG and UM burnup calculation models of the KRUSTY are established for RMC. Results demonstrate consistent agreement between the UM and CSG models in terms of keff and the evolution of key nuclide masses across different burnup time steps, confirming the accuracy of RMC's UM-based burnup calculation capability.

Keywords: Monte Carlo code; Unstructured Mesh; Burnup Calculation; RMC

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基于环境监测数据的核素浓度场修正与监测点位优化研究

Author: 王彦[1]

[1] *中国辐射防护研究院*

Corresponding Author: wangyan_5945@163.com

摘要: 核设施事故后，放射性物质可能会释放到外部环境中。因此，有必要对放射性核素的空间分布进行快速评估。仅使用大气扩散模型预测的放射性核素浓度分布可能会与实际浓度分布产生偏差。为了使预测分布与实际分布更趋一致，本研究开发了一种基于克里金插值的方法，利用少量的环境气溶胶监测数据对预测的浓度分布进行快速修正。此外，还开发了一种基于差分进化算法的环境气溶胶监测点位优化方法，以指导布置更具代表性的监测点，并提高修正后浓度分布的准确性。结果表明，在构建的案例研究中，利用优化后的监测点获取环境监测数据显著提高了重点区域的预测准确性，使假阴性区域减少了 97%。

关键词: 核设施事故，环境监测，监测点位，克里金插值，差分进化算法

Abstract: Radioactive materials can be released into the external environment after nuclear facility accidents. Therefore, it is necessary to rapidly assess the spatial distribution of radioactive nuclides. Using only the concentration distribution of radioactive nuclides predicted by the atmospheric dispersion models may result in deviations from the actual concentration distribution. To make the predicted distribution more consistent with the actual distribution, a method based on Kriging interpolation was developed to rapidly correct the predicted concentration distribution using a small amount of environmental aerosol monitoring data. In addition, a method for optimizing environmental aerosol monitoring locations based on a differential evolution algorithm was developed to guide the placement of more representative monitoring locations and improve the accuracy of the corrected concentration distribution. The results indicated that using optimized monitoring locations to obtain environmental monitoring data enhanced the accuracy of prediction in key areas in the constructed case-studies, reducing false-negative areas by 97%.

Keywords: Nuclear facility accidents, Environmental monitoring, Monitoring locations, Kriging interpolation, Differential-evolutionary algorithm

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Report of Grazing-incidence Focusing Small-Angle Neutron Scattering (gif-SANS) Spectrometer at CPHS

Author: 袁梦[1]

[1] *清华大学工程物理系*

Corresponding Author: yuanm23@mails.tsinghua.edu.cn

摘要: 清华大学紧凑型脉冲强子源（CPHS）的掠入射聚焦小角中子谱仪（gif-SANS）解决了基于紧凑型加速器中子源建造高性能 SANS 仪器的挑战。该谱仪采用具有大收集面积的多层嵌套中子聚焦超镜，在 Qmin<0.007Å^{-1} 处实现了 >10^{5}n/s 的中子通量。此外，由多个孔径光阑组成的后准直系统与聚焦镜配合使用，以阻挡杂散中子并抑制漫散射噪声，从而显著提高分辨率。该谱仪可切换至针孔准直模式以实现更高的 Q 测量。gif-SANS 配备了两个探测器：一个用于常规 Q 范围测量的大面积 ^{3}He 管阵列探测器，以及一个用于将 Qmin 扩展至 10^{-3}Å^{-1} 的高分辨率中子敏感微通道板（nMCP）探测器。整个仪器已通过实验验证，并成功通过了最终验收测试。

关键词: 小角中子散射；中子光学

Abstract: The grazing-incidence focusing Small Angle Neutron Spectrometer (gif-SANS) at Compact Pulsed Hadron Source (CPHS) of Tsinghua University addresses the challenge of building high-performance SANS instrument based on Compact Accelerator-driven Neutron Sources. A multi-layer nested neutron-focusing supermirror with a large collecting area is used to achieve > 10^{5} n/s neutron flux at Qmin < 0.007 Å^{-1} in gif-SANS. In addition, a post-collimation system consisting of multiple aperture blades is employed in conjunction with the focusing mirror to block stray neutrons and suppress diffuse scattering noise, thereby significantly improving the resolution. The spectrometer can be switched to a pinhole collimation mode for higher Q measurements. Two detectors are equipped on gif-SANS: a large-area He-3 LPSD detector for normal Q-range measurements, and a high-resolution neutron-sensitive microchannel plate (nMCP) detector to extend the Qmin down to 10^{-3} Å^{-1}. The entire instrument has been experimentally validated and has successfully passed the final acceptance tests.

Keywords: SANS; Neutron optics

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平壁面附着颗粒脱离前的湍流诱导共振

Authors: 尤志凯[1]; 赵淑苗[1]

[1] *清华大学*

Corresponding Authors: youzk21@mails.tsinghua.edu.cn, zhaosm23@mails.tsinghua.edu.cn

摘要: 颗粒再悬浮是自然界和工业过程中的常见现象，但其机理尚未被充分理解。本文报道了壁面附着颗粒在脱离前发生湍流诱导共振的直接实验证据。实验记录到的共振频率比通常由 Rock n’Roll 模型预测的频率低 1–2 个数量级。研究发现，颗粒黏附固有频率与近壁湍流频率之间的频率比 φ，是决定湍流诱导共振是否发生的关键参数。该研究有望为利用共振增强机制清除极小颗粒提

关键词: 颗粒再悬浮；湍流诱导共振；临界频率比

Abstract: Particle resuspension is a common phenomenon in nature and industries but not fully understood yet. In this work, we report direct
experimental evidence for turbulence-induced resonance of wall-adhered particles before detachment. The recorded frequency is one or two
orders of magnitude lower than that normally predicted by the Rock n’Roll model. The frequency ratio /, between the natural frequency of
particle adhesion and wall turbulence frequency, is found to be the key parameter that determines the occurrence of turbulence-induced reso
nance. This work may shed light on the resonance-enhanced cleaning of very small particles.

Keywords: particle resuspension; turbulence-induced resonance; critical frequency ratio

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Cosmic-ray background in the RECODE experiment

Author: Tao Guo[1]

[1] *清华大学*

Corresponding Author: guo-t22@mails.tsinghua.edu.cn

摘要: 相干弹性中微子-核散射（CEνNS）为探测中微子属性和检验超出标准模型的新物理提供了独特的探测渠道。反应堆相干中微子散射探测实验（RECODE）旨在利用高纯度锗（HPGe）探测器测量反应堆 CEνNS 过程。本研究通过蒙特卡罗（MC）模拟，对主导实验本底——宇宙射线辐射——进行了系统评估与优化。分析表明，μ 子诱导的本底在高能区占主导地位，而中子诱导的本底在低能区迅速上升，且其反符合效率显著低于 μ 子诱导事例。在屏蔽系统的作用下，主导实验本底为宇宙射线本底。若无覆岩层遮挡（<5m.w.e），中子诱导本底将变得比 μ 子诱导本底更为显著，后续改进中需要着重考虑进一步屏蔽宇宙线中子。而对于高穿透性的 μ 子，将塑闪时间窗口延长至 100 微秒可使 μ 子诱导本底进一步降低一倍。

关键词: 中微子弹性散射、宇宙射线、蒙卡模拟

Abstract: Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) offers a unique channel for probing neutrino properties and testing physics beyond the Standard Model. The REactor COherent neutrino scattering Detection Experiment (RECODE) aims to measure reactor CEνNS using high-purity germanium (HPGe) detectors. In this work, the dominant experimental background—cosmic-ray radiation—is systematically evaluated and optimized through Monte Carlo (MC) simulations. The analysis reveals that the muon-induced background dominates at high energies, whereas the neutron-induced component rises rapidly in the low-energy regime and exhibits a substantially lower veto efficiency compared to that achieved for muon-induced events. With the shielding system, the dominant experimental background is cosmic-ray background. In the absence of overburden, the neutron-induced background becomes more significant than the muon-induced background, and further shielding of cosmic-ray neutrons should be a key consideration in subsequent improvements. For highly penetrating muons, extending the time window of the plastic scintillator to 100 μs would reduce the muon-induced background by an additional factor of two.

Keywords: CEvNS、Cosmic-ray、Monte Carlo

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Study on the Structure and Properties of the $Dy_2(Ti/Zr)O_5$ Neutron Absorber Material

Author: 周嘉宇[1]

[1] *兰州大学*

Corresponding Author: 320220918921@lzu.edu.cn

摘要: 针对传统中子吸收材料辐照肿胀、高温稳定性差等缺陷，本文以 $Dy_2(Zr_xTi_{1-x})O_5$（x=0、0.25、0.5、0.75、1）系列陶瓷为研究对象，采用高温固相反应法经二次烧结制备样品，系统探究 Zr 掺杂对材料晶体结构、热稳定性、热膨胀及力学性能的调控规律。结果表明：未掺杂 Zr 的 Dy_2TiO_5 难以形成纯净立方相，伴随杂相及烧绿石超晶格结构；低 Zr 掺杂（x=0.25）为烧绿石相，高 Zr 掺杂（x=0.5~1）可获得单相立方萤石结构。所制样品晶粒尺寸均匀（10~15 μm）、致密度高、元素分布均匀。600 ℃ 退火后物相仍能保持稳定，且含锆组分热匹配性更优。纳米压痕实验显示 Dy_2ZrO_5 硬度最高，综合性能优于 Dy_2TiO_5。研究表明 Dy_2ZrO_5 具备优异的高温稳定性与力学性能，是新型控制棒中子吸收材料的理想候选材料，可为先进稀土基核用陶瓷的设计与应用提供实验支撑与理论参考。

关键词: 中子吸收材料；锆掺杂；晶体结构；热稳定性；力学性能

Abstract: In response to the shortcomings of traditional neutron-absorbing materials, such as radiation swelling and poor high-temperature stability, this study focuses on the Dy2(ZrxTi1−x)O5 (x = 0, 0.25, 0.5, 0.75, 1) ceramic series. Samples were prepared using a high-temperature solid-state reaction method with secondary sintering, and the effects of Zr doping on the material's crystal structure, thermal stability, thermal expansion, and mechanical properties were systematically investigated. The results show that Dy2TiO5 without Zr doping cannot form a pure cubic phase; instead, it exhibits impure phases and pyrochlore superstructure structures. Lower Zr doping (x = 0.25) results in a pyrochlore phase, while higher Zr doping (x=0.5 to 1) yields a single-phase cubic fluorite structure. The fabricated samples have uniform grain sizes (10–15 μm), high density, and evenly distributed elements. After annealing at 600℃, the phases remain stable, and the zirconium-containing components exhibit better thermal compatibility. Nanoindentation experiments indicate that Dy2ZrO5 has the highest hardness, outperforming Dy2TiO5 in terms of overall performance. The study demonstrates that Dy2ZrO5 possesses excellent high-temperature stability and mechanical properties, making it an ideal candidate material for new control rod neutron-absorbing materials. This research provides experimental support and theoretical references for the design and application of advanced rare earth-based nuclear ceramics.

Keywords: Neutron absorption material; Zirconium doping; Crystal structure; Thermal stability; Mechanical properties.

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考虑颗粒床流动不稳定性的流动传热模型开发

Author: 陈友纯[1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Author: 1442186363@qq.com

摘要: 核热推进系统反应堆为紧凑型超高温气冷堆，极高的功率密度使其很有可能出现流动不稳定，不稳定性与堆芯流量-传热-压降的耦合与反馈有关。考虑到颗粒床特殊的堆积结构类似于多孔介质，可以将其简化为多孔介质模型分析。目前对颗粒床的流动传热特性研究还很少，选用的压降与换热模型与颗粒床实际结构存在较大差异。本文广泛调研各种填充床流动传热模型，分析关键影响因素，结合颗粒床的结构特征评估适用模型。同时基于简化的颗粒床二维模型，采用计算流体力学方法分析流动传热模型的两项参数对不稳定性边界的影响，从不稳定性安全分析的保守性出发，开发出建议的阻力与换热模型。

关键词: 颗粒床反应堆；流动不稳定性；多孔介质模型；流动传热模型

Abstract: The reactor of the Nuclear Thermal Propulsion System is a compact ultra-high-temperature gas-cooled reactor, whose extremely high-power density makes it highly likely to experience flow instability, which is related to the coupling and feedback of core flow, heat transfer and pressure drop. Considering the special packing structure of the particle bed is similar to that of a porous medium, it can be simplified as a porous medium model for analysis. At present, there are few studies on the flow and heat transfer characteristics of particle beds, and the pressure drop and heat transfer models selected have significant differences from the actual structure of the particle beds. This paper conducts a comprehensive investigation of flow and heat transfer models for various packed beds, analyzes the key influencing factors, and evaluates the applicable models with the structural characteristics of the particle beds. Based on the simplified two-dimensional model of the particle bed, the influence of two parameters of the flow heat transfer model on the instability boundary was analyzed using the computational fluid dynamics method. Starting from the conservativeness of the instability safety analysis, a recommended resistance and heat transfer model was developed.

Keywords: Particle bed, Flow instability, Porous medium, Flow and heat transfer model

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宽带速调管放大器三间隙输入腔中束波能量交换研究

Authors: 曹亦兵; 吴平; 王昱力[1]; 白现臣; 侯瑞东; 孙钧

[1] *清华大学工程物理系*

Corresponding Author: yuli-wan21@mails.tsinghua.edu.cn

摘要: 本文提出了一种用于分析宽带速调管放大器三间隙输入腔中电子与电磁场能量交换的方法。通过在每个间隙的轴向驻波电场幅值中添加一个和频率相关的系数，得到了工作频率范围内轴向电场的表达式。基于小信号理论，对电子运动过程进行了分析，推导出了三间隙腔中电子束与电磁场的能量交换表达式。基于计算结果对一个特定结构的三间隙输入腔进行了分析，并利用仿真软件对电子的能量变化情况进行了模拟。模拟结果与理论分析结果吻合良好，验证了方法的有效性。因此本研究可为宽带速调管放大器中的三间隙输入腔设计提供理论指导。

关键词: 高功率微波，宽带速调管，三间隙输入腔，自激振荡

Abstract: This paper proposes an analytical method for characterizing the energy exchange between electrons and the electromagnetic field in the triple-gap injection cavity of a broadband klystron amplifier. By adding a frequency-dependent coefficient to the electric field amplitude of the axial standing wave of each gap, the axial electric field expression across the operating frequency band is obtained. Based on small-signal theory, the electron dynamics is analyzed, and an expression for the energy exchange between the electron beam and the electromagnetic field in the triple-gap cavity is derived. The analysis of a triple-gap injection cavity with a specified structure is conducted by the use of the results derived above. To validate the analysis, the energy absorption of electrons is examined in PIC simulations. The outcome is consistent with the results obtained from theoretical analysis. Therefore, the analytical results derived in this work provide guidance for designing triple-gap injection cavities in broadband klystron amplifiers.

Keywords: High power microwave, Broadband klystron, Triple-gap injection cavity, Delf-oscillation

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Research on Fault Monitoring Method for GIL Electrical Equipment Based on Statistical Characteristics of Partial Discharge in Optical Signals

Author: 伍浩[1]

Co-authors: 朱佳宇 [2]; 黄佳钰 [1]; 苏光 [3]; 熊再豹 [3]; 朱振一 [4]; 陶宁蒋 [3]

[1] *国核浙能核能有限公司*

[2] *华北电力大学*

[3] *国核电力规划设计研究院*

[4] *西安交通大学*

Corresponding Author: wuhao01@spic.com.cn

摘要: 摘要：为实现电力设备绝缘状态的非接触式可靠监测，本文提出了一种基于光学信号局部放电（PD）统计特性的故障诊断方法。研究在充有 0.2 MPa SF6 气体的针型 GIL 实验腔体中，模拟了针尖缺陷、悬浮缺陷和沿面缺陷三种典型局部放电模型。采用高增益、抗磁场干扰的硅光电倍增管（SiPM）采集 PD 产生的光辐射信号，并通过最大值池化（Max-Pooling）算法进行降采样预处理以保留脉冲瞬态特征。本文提取了基于 PRPD 谱图的 21 维统计特征向量，包括由最大放电量分布构成的特征集 Mx 和由平均放电幅值（放电频次）分布构成的特征集 Mn。通过引入偏斜度 Sk、陡峭度 Ku 及修正互相关系数 MCC 等算子定量描述图谱形状。最后，构建了基于 BP 神经网络、SVM 及随机森林的决策层融合（DLF）诊断框架。实验结果表明，该决策层融合模型在测试集上的准确率达到 90.56%，显著优于单一分类模型，为气体绝缘设备的运行维护提供了有效参考。

关键词: 局部放电，光信号，决策级融合，统计特性

Abstract: Abstract. To achieve non-contact and reliable monitoring of insulation status in power equipment, this paper proposes a fault diagnosis method based on the statistical characteristics of Partial Discharge (PD) optical signals. Three typical PD models—needle, floating, and surface defects—were simulated in a needle-type GIL experimental chamber filled with SF6 gas. A high-gain, magnetic-interference-resistant Silicon Photomultiplier (SiPM) was employed to capture PD optical radiation signals. A Max-Pooling algorithm was used for downsampling to retain pulse transient features while reducing data redundancy. A 21-dimensional statistical feature vector was extracted based on Phase Resolved Partial Discharge (PRPD) patterns, including feature set Mx derived from the maximum discharge distribution and Mn from the pulse repetition rate distribution. Statistical operators such as skewness (Sk), kurtosis (Ku, and modified cross-correlation coefficient (MCC) were introduced to quantify pattern shapes. Finally, a Decision-Level Fusion (DLF) framework based on BP Neural Network, SVM, and Random Forest was constructed. Experimental results show that the DLF model achieves an accuracy of 90.56% on the test set, significantly outperforming single-classification models.

Keywords: Partial Discharge,Optical Signal,Decision-Level Fusion,Statistical Characteristics

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加热圆管内氦氙分布影响因素及其对流动换热的影响研究

Authors: 孙俊[1]; 单思钧; 孙玉良[1]

[1] *清华大学核能与新能源技术研究院*

Corresponding Author: ssj21@mails.tsinghua.edu.cn

摘要: 氦氙混合气体作为空间堆冷却工质，在温度梯度影响下会出现热致扩散现象，导致氦氙混合不均匀。现有氦氙流动换热相关研究均将氦氙作为一种纯气体，不考虑混合不均匀的问题。但氦气、氙气性质差异大，混合不均匀对流动换热特性可能存在较大影响。本文以 Taylor 的氦氙流动换热实验为基础，基于 Fluent 针对圆管内氦氙在温度梯度下分离的影响因素以及对流动换热的影响开展研究。结果表明温度梯度下氦氙分离主要受热流密度、来流雷诺数以及来流温度的影响，热流密度越大、来流雷诺数越小、来流温度越低，氦氙分离越明显。同时圆管上游的弯管形式对圆管内的换热无明显影响。由于氦氙分离主要存在于近壁面区域，加热促使氦气在壁面处聚集，反而抑制了热致扩散，导致氦氙分离程度有限，对管内换热影响无明显影响。

关键词: 氦氙混合气体；组分输运；热致扩散；流动换热

Abstract: Helium-xenon gas mixture is used as the coolant for space nuclear power plants. Under the influence of temperature gradients, thermal diffusion occurs, leading to an uneven mixture of helium and xenon. Existing research on helium-xenon flow and heat transfer treats the mixture as a pure gas, ignoring the issue of uneven mixing. However, due to the significant differences in the properties of helium and xenon, the uneven mixing may have a considerable impact on the flow and heat transfer characteristics. This paper is based on Taylor’s helium-xenon experiment and uses Fluent to study the factors influencing the separation of helium and xenon in a circular tube under temperature gradients and its impact on flow and heat transfer. The results show that the separation of helium and xenon under temperature gradients is mainly affected by heat flux density, inlet Reynolds number, and inlet temperature. When the heat flux density is high, the incoming flow Reynolds number is low, and the incoming flow temperature is low, helium and xenon are more easily separated. Meanwhile, the form of the upstream elbow in the circular tube has no significant effect on the heat transfer within the tube. Since the separation of helium and xenon mainly occurs in the near-wall region, heating causes helium to accumulate at the wall, which instead suppresses thermal diffusion, resulting in a limited degree of separation and no significant impact on the heat transfer within the tube.

Keywords: Helium-xenon gas mixture; Flow and heat transfer characteristics; Species transport; Thermal diffusion

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基于克朗方法和随机耦合模的腔体耦合统计性预测

Authors: 冯博伦[1]; 刘驰骋[1]

[1] *清华大学*

Corresponding Author: fbl21@mails.tsinghua.edu.cn

摘要: 本文提出了一种基于克朗方法的腔体孔缝耦合模型，适用于带矩形或圆形孔缝的矩形腔体在外部入射电磁脉冲时，求解内部屏蔽效能或内部端口耦合强度。根据外部入射电磁波情形下腔体波导传输特性以及孔缝特性，建立起干扰源-孔缝-腔体外壳的克朗-布朗宁拓扑模型，建立起张量方程并进行计算。同时还将此方法与随机耦合模结合起来，使其拓展到可以应用于预测腔体内为波混沌状态下时，内部端口耦合电压的概率分布情况。设计并搭建了波混沌腔体实验平台，通过实验结果验证了此方法的有效性。

关键词: 孔缝耦合；高功率微波；克朗方法；随机耦合模

Abstract: This paper proposes a cavity aperture coupling model based on the Kron’s method, which is applicable for evaluating the internal shielding effectiveness (SE) or internal port coupling strength of a rectangular cavity—featuring either rectangular or circular apertures under external electromagnetic pulse incidence. Based on the waveguide propagation characteristics and aperture properties under external incidence, a Kron-Branin topological model encompassing the interference source, aperture, and cavity enclosure is established to formulate and solve the corresponding tensor equations. Furthermore, by integrating this approach with the Random Coupling Model (RCM), the method is extended to predict the probability distribution of coupling voltages at internal ports when the cavity is in a wave-chaotic state. Finally, a wave-chaotic cavity experimental platform was designed and constructed, with experimental results validating the effectiveness of the proposed method.

Keywords: Aperture coupling；High power microwave；Kron’s method；Random coupling model

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基于中子活化法制备 99Mo 的新型 99Mo/99mTc 发生器关键技术研究

Author: 罗旭[1]

Co-authors: 俊舒翔 [1]; 向程新 [2]; 杨锐 [1]

[1] *中国同辐股份有限公司*

[2] *清华大学*

Corresponding Author: luoxu@circ.com.cn

摘要: 99mTc 作为单光子发射计算机断层成像（SPECT）全球范围应用最广的放射性核素，其稳定供应对于现代核医学至关重要。当前，我国临床使用的 99mTc 主要依赖进口裂变 99Mo 制备的发生器。随着 99Mo 主要生产堆临近寿期，全球 99Mo 供应稳定性面临巨大挑战。为实现医用同位素的自主可控并充分利用国内现有反应堆资源，本文聚焦基于中子活化法制备低比活度 99Mo 的新型 99Mo/99mTc 发生器关键技术研究，旨在避免采用浓缩铀为原料的裂变技术路线，攻克低比活度 99Mo /99mTc 高效分离纯化的技术瓶颈，开发一套符合药品生产质量管理规范（GMP）要求的生产工艺及全自动工程化装备，以期为我国 99mTc 的自主化、规模化生产提供切实可行的解决方案。
通过三批次（辐照时间分别为 3 天、5 天、7 天）的反应堆辐照实验，系统研究了天然 MoO3 与富集 98MoO3 靶材辐照的理论计算和辐照工艺参数。根据结果分析了两种辐照路线的 99Mo 产额及放射性杂质，确定了工程阶段的辐照时间和路线。
筛选活性炭进行 99Mo /99mTc 的分离研究。利用化学性质相似的 Re 稳定同位素模拟 99mTc 进行

系统冷实验，全面探究了溶液初始 pH 值、色谱柱径高比、吸附流速、淋洗剂组成与体积、洗脱温度等关键参数对 Mo/Re 分离效率的影响规律。确定工艺路线后，冷实验实现约 83% 的 Re 回收率，热实验表明对实际 99mTc 的回收率达 82.1%，且最终产品中 99Mo 残留低于检测限，初步验证了技术可行性。基于此，研制了初代自动化分离样机，在模拟处理 5 Ci 99Mo 的放大实验中，获得 81.7% 的 99mTc 回收率，展现了工程化潜力。
鉴于后续实验发现活性炭批次间性能差异，进而深入探索了 PEG 树脂分离体系。研究发现，在 5.0 mol/L NaOH 强碱性环境中，PEG 树脂对以 ReO4-形式存在的 99mTc 模拟物具有极高的选择性吸附能力。通过系统柱实验优化确立了最佳工艺条件，冷实验 Re 回收率稳定在 94% 以上。在三次不同 99Mo 活度（2.3 至 8.7 mCi）投料的热实验中，99mTc 平均回收率超过 85%，且产品放射性核纯度完全达标。以此为核心，成功设计并开发了新型 GMP 级全自动 99Mo/99mTc 分离纯化工程样机，其运行稳定可靠，分离效率持续高于 85%，产品中 99Mo 残留始终低于检出限。
工程化开发与验证阶段，在 C 级洁净区对生产热室、关键设备（活度计）及自动化样机各模块性能验证基础上，采用 PEG 树脂工艺开展了连续三个批次的工艺性能验证。结果表明，99mTc 平均回收率达到 84.67%，所制备的最终产品溶液为无色澄明液体，其 pH 值、放射性核纯度、放射化学纯度、无菌检查、细菌内毒素含量及标记合成效率等质量指标，均符合《中华人民共和国药典》对高锝 [99mTc] 酸钠注射液的法定标准。这标志着从实验室工艺到符合药品生产质量规范的成功转化。
通过本文的研究，成功构建了一套基于中子活化法制备的 99Mo 的新型 99Mo /99mTc 发生器工程样机。该装置已在 GMP 环境下完成工程化验证，连续三批次产品全部符合《中国药典》标准，单批次处理能力达 4000 mCi，99mTc 平均回收率 84.67%，具备明确的产业化前景。本研究为满足核医学诊疗需求和保障医用同位素供应链安全提供了切实可行的工程解决方案。

关键词: 新型 99Mo/99mTc 发生器；低比活度；中子活化；活性炭；PEG 树脂；工程样机

Abstract:

As the most widely used radionuclide globally for Single Photon Emission Computed Tomography (SPECT), the stable supply of 99mTc is critically important for modern nuclear medicine. Currently, clinical 99mTc in China primarily relies on generators prepared from imported fission-produced 99Mo. As the main production reactors for 99Mo approach the end of their operational lives, the stability of the global 99Mo supply faces significant challenges. To achieve self-sufficiency in medical isotopes and fully utilize existing domestic reactor resources, this study focuses on key technologies for a novel 99Mo/99mTc generator based on neutron-activated, low-specific-activity 99Mo. The aim is to avoid the fission technology route that uses enriched uranium as feedstock, overcome the technical bottleneck of efficiently separating and purifying 99mTc from low-specific-activity 99Mo, and develop a production process and fully automated engineering equipment compliant with Good Manufacturing Practices (GMP). This research intends to provide a feasible solution for the autonomous, large-scale production of 99mTc in China.

Through three batches of reactor irradiation experiments (with irradiation times of 3, 5, and 7 days, respectively), the theoretical calculations and irradiation process parameters for natural MoO_3 and enriched $^{98}MoO_3$ targets were systematically investigated. Based on the results, the ^{99}Mo yield and radioactive impurities from the two irradiation routes were analyzed, leading to the selection of the irradiation time and route for the engineering phase.

Activated carbon was selected for ^{99}Mo/^{99m}Tc separation studies. Stable rhenium (Re) isotopes, which have similar chemical properties, were used as a surrogate for ^{99m}Tc to conduct systematic cold tests. The influence of key parameters on Mo/Re separation efficiency was comprehensively investigated, including initial solution pH, column aspect ratio, adsorption flow rate, eluent composition and volume, and elution temperature. After determining the process route, cold tests achieved an Re recovery rate of approximately 83%, and hot tests demonstrated an actual ^{99m}Tc recovery rate of 82.1%, with residual ^{99}Mo in the final product below the detection limit, preliminarily validating the technical feasibility. Based on this, a first-generation automated separation prototype was developed. In scale-up experiments simulating the processing of 5 Ci of ^{99}Mo, a ^{99m}Tc recovery rate of 81.7% was achieved, demonstrating its engineering potential.

Subsequently, due to observed performance variability between batches of activated carbon, the research explored the PEG resin separation system in greater depth. The study found that in a highly alkaline environment of 5.0 mol/L NaOH, PEG resin exhibits exceptionally high selective adsorption capacity for the ^{99m}Tc surrogate, present as ReO_4^-. Optimal process conditions were established through systematic column experiments, achieving a stable Re recovery rate above 94% in cold tests. In three hot tests with varying ^{99}Mo activities (2.3 to 8.7 mCi), the average ^{99m}Tc recovery rate exceeded 85%, and the radionuclidic purity of the product fully met the required standards. Based on this core technology, a

novel GMP-grade fully automated ^{99}Mo/^{99m}Tc separation and purification engineering prototype was successfully designed and developed. Its operation is stable and reliable, with separation efficiency consistently exceeding 85% and residual ^{99}Mo in the product always below the detection limit.

During the engineering development and validation phase, after verifying the performance of the production hot cell, key equipment (dose calibrator), and various modules of the automated prototype in a Grade C cleanroom, three consecutive process performance validation runs were carried out using the PEG resin process. The results showed an average ^{99m}Tc recovery rate of 84.7%. The final product solution was a colorless, clear liquid, and its quality indicators—including pH, radionuclidic purity, radiochemical purity, sterility test, bacterial endotoxin content, and labeling synthesis efficiency—all complied with the statutory standards of the Pharmacopoeia of the People's Republic of China for Sodium Pertechnetate [^{99m}Tc] Injection. This marks the successful translation of the laboratory process to compliance with GMP standards.

Through this research, a novel engineering prototype of a ^{99}Mo/^{99m}Tc generator based on neutron-activated ^{99}Mo was successfully established. The device has undergone engineering validation in a GMP environment. Three consecutive batches of the product all met the standards of the Chinese Pharmacopoeia. This system demonstrates clear prospects for industrialization. This study provides a practical engineering solution to meet the diagnostic and therapeutic demands of nuclear medicine and ensure the security of the medical isotope supply chain.

Keywords: Novel 99Mo-99mTc generator; low-specific-activity; Neutron activation; Activated carbon; PEG resin; Engineering prototype

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轴流压缩机动叶片仿真计算

Author: 黄宽[1]

[1] *清华大学工程物理系*

Corresponding Author: hk22@mails.tsinghua.edu.cn

摘要: 进入二十一世纪以来，经济的蓬勃发展离不开能源的稳定保障。随着“3060”双碳目标的提出，以及十五五规划建设，清洁能源在能源板块的占比越来越大。核能作为是清洁能源之一，推进核能民用有利于减少碳排放，其中一个重要途径就是核电。核电燃料的生产离不开同位素分离级联。
压缩机作为同位素分离级联系统中的关键设备，对于分离过程中的压强稳定、生产丰度、以及级联效率具有关键影响，其相关性能会直接影响整个分离工厂的经济型。
自上世纪开始，压缩机设计方案逐渐从一维设计、二维通流设计、准三维设计，已经发展到现在的全三维优化设计模拟。为进一步提升压缩机的效率、工作裕度等性能，需要对现有的压缩机方案进行优化设计。现有压缩机主要分为容积式和透平式，透平式又主要分为往复式、离心式和轴流式。往复式压缩机压力稳定，但单台流量小，且易产生脉冲气流，需额外配置稳压系统；离心式压缩机，具有压比高，但是流量工作范围窄；周六式压缩机可以实现大流量输入输出，但是单级压比小，流量工作范围宽。
本研究在一维设计的基础上，直接设计三维动叶片，进行仿真计算，旨在为后续压缩机的研发提供经验。

关键词: 轴流压缩机、数值模拟

Abstract: Since the beginning of the 21st century, the robust growth of the global economy has relied on the stable supply of energy. With the proposal of China's “30·60” dual carbon goals and the formulation of the 15th Five-Year Plan, the share of clean energy in the overall energy mix has been expanding continuously. As one type of clean energy, advancing the civilian application of nuclear power contributes to carbon emission reduction, and the development of nuclear power plants constitutes a critical approach for such implementation. The production of nuclear fuel relies on isotope separation cascades.

As a core piece of equipment in isotope separation cascade systems, compressors exert a pivotal influence on pressure stability, product enrichment and cascade efficiency during the separation process, and their performance directly determines the economic efficiency of the entire separation plant.

Since the last century, compressor design methodology has gradually evolved from one-dimensional design, two-dimensional flow design, and quasi-three-dimensional design to the current full three-dimensional optimal design and simulation. To further improve the performance of compressors such as efficiency and operating margin, optimization design is required for existing compressor schemes. Existing compressors are mainly categorized into positive displacement compressors and turbocompressors, among which turbocompressors are further divided into reciprocating compressors, centrifugal compressors and axial flow compressors. Reciprocating compressors deliver stable pressure but feature small single-unit flow rate and are prone to generating pulsed airflow, requiring additional configuration of pressure stabilization systems; centrifugal compressors feature high pressure ratio but a narrow operating flow range; axial flow compressors enable large flow input and output but feature small single-stage pressure ratio and a wide operating flow range.

Based on one-dimensional design, this study directly constructs three-dimensional moving blades and conducts simulation calculations, aiming to provide empirical references for the subsequent research and development of compressors.

Keywords: Axial flow compressor, numerical simulation

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一种基于协同边界调控的载荷可调式准零刚度隔振器

Author: 张宸[1]

[1] *清华大学*

Corresponding Author: c-zhang23@mails.tsinghua.edu.cn

摘要: 准零刚度（QZS）隔振器在低频隔振方面具有显著优势，但其工程应用往往受限于对承载载荷的高度敏感性。针对这一问题，本文提出了一种基于协同边界调控的额定载荷可调式准零刚度隔振器。该隔振器由特定构型的曲梁与集成调节机构组成，可实现额定载荷的连续调节。通过协同调控曲梁端部的横向位移和转角，隔振器的准零刚度特性能够被重构，从而适应设计范围内的任意载荷。

本文首先采用非线性有限元分析，揭示边界条件对曲梁载荷-位移特性的协同影响机制；随后建立多目标优化设计策略，在满足预设载荷调节需求的同时兼顾结构强度约束。优化算例表明，该隔振器能够在一定载荷范围内通过结构重构保持准零刚度特性，例如优化设计可覆盖名义载荷 50% 至 150% 的变化范围。进一步地，本文开展了非线性动力学分析，评估不同边界条件和载荷工况下的隔振性能，结果表明协同边界调控能够有效恢复系统的低频隔振能力。最后，本文制作了 3D 打印样机，并通过静态和动态实验进行了验证。实验结果表明，借助额定载荷调节策略，该隔振器在三种显著不同载荷下均能保持基本一致的低截止频率。所提出的准零刚度隔振器兼具结构紧凑性、被动可靠性和载荷适应性，可为复杂工程环境中的高性能低频振动控制提供一种有效方案，尤其适用于有效载荷难以精确预测的应用场景。

关键词: 准零刚度隔振器；低频振动隔离；非线性动力学；曲梁；额定载荷调节；边界条件调控

Abstract: Quasi-zero-stiffness (QZS) vibration isolators offer a superior solution for low-frequency vibration isolation; however, their application remains constrained by an inherent sensitivity to the supported load. To address this limitation, this paper proposes a novel QZS isolator comprising specifically shaped curved-beams and integrated regulation mechanisms to achieve a continuously tunable rated load. Through the synergistic regulation of the lateral displacement and the rotation angle at the curved-beam boundaries, the isolator's QZS characteristic can be reconfigured to accommodate arbitrary payloads within a design range. The research first employs nonlinear finite element analysis to elucidate the synergistic effects of boundary conditions on load–displacement characteristics of the curved-beam.

Subsequently, a multi-objective optimization strategy is developed for designing the curved-beam, aiming to satisfy the predefined load-tuning requirements while adhering to strength constraints. In the optimization case presented herein, the isolator can be reconfigured to maintain QZS characteristics across a payload range–as exemplified by an optimized design spanning 50% to 150% of the nominal load. Nonlinear dynamic analysis is further conducted to evaluate the isolation performance under different boundary conditions and payloads, demonstrating the effectiveness of the synergistic regulation in restoring system performance. Finally, a 3D-printed prototype was fabricated and validated through comprehensive static and dynamic experiments. The results demonstrate that the isolator maintains a consistent low cut-off frequency under three significantly different loads through the rated-load tuning strategy. The proposed QZS isolator offers a compact and robust solution for high-performance passive vibration control in complex engineering environments, with its QZS characteristic reconfigurability ensuring practical viability in scenarios where precise payload prediction is challenging.

Keywords: Quasi-zero-stiffness isolator; Low-frequency vibration isolation; Nonlinear dynamics; Curved-beam; Rated-load tuning; Boundary-condition regulation

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CDEX-10 高纯锗探测器对轻费米子暗物质电子吸收的首次搜寻

Author: 刘家璇[1]

[1] *清华大学*

Corresponding Author: liujiaxu21@mails.tsinghua.edu.cn

摘要: 本文基于 CDEX-10 实验中 C10B-Ge1 高纯锗探测器的 205.4 kg·day 曝光数据，首次利用锗原子电子靶搜寻亚 MeV 费米子暗物质吸收过程 $\chi + e^- \rightarrow \nu + e^-$。该分析采用 160 eVee 的低能阈值，并使用 0.16–2.16 keVee 能区的实验能谱，对 0.1–10 keV/c² 质量范围内的暗物质信号进行检验。理论信号模型考虑矢量型与轴矢量型有效相互作用算符，锗原子按孤立原子近似处理，并主要采用 K、L、M 壳层核心电子贡献，从而给出相对保守的预期信号谱。数据分析中，背景模型包括宇宙成因放射性同位素的 L/M 壳层 X 射线峰以及高能 γ 射线康普顿散射连续本底，并通过 χ^2 拟合结合探测效率和本底强度的不确定性进行约束。实验结果未发现显著超出本底的暗物质信号，因此采用 Feldman-Cousins 方法给出 90% 置信水平上限。在 $m\chi = 5$ keV/c² 处，矢量相互作用截面上限为 6.8×10^{-46} cm²，轴矢量相互作用截面上限为 2.3×10^{-46} cm²。该结果在 10 keV/c² 以下质量区间给出了新的直接探测限制，并将费米子暗物质电子吸收过程的直接探测灵敏质量推进到目前最低范围。

关键词: 费米子暗物质，电子吸收，直接探测实验，高纯锗探测器

Abstract: This work reports the first search for sub-MeV fermionic dark matter absorption on electron targets in germanium using 205.4 kg·day of data from the CDEX-10 C10B-Ge1 high-purity germanium detector. Benefiting from a low analysis threshold of 160 eVee, the study probes fermionic dark matter in the mass range of 0.1–10 keV/c² through the absorption process $\chi + e^- \rightarrow \nu + e^-$. Signal models are constructed for vector and axial-vector effective interaction operators. Germanium atoms are treated as isolated atoms, and only the core-electron contributions from the K, L, and M shells are included, leading to conservative signal predictions. The analysis uses the measured spectrum from 0.16 to 2.16 keVee and performs a χ^2 fit including detector efficiency uncertainties and background components from cosmogenic isotope L/M-shell x-ray peaks and Compton scattering of high-energy γ rays. No significant excess above the expected background is observed. Upper limits at 90% confidence level are therefore derived using the Feldman-Cousins method. At a dark matter mass of 5 keV/c², the obtained limits on the interaction cross section are 6.8×10^{-46} cm² for the vector operator and 2.3×10^{-46} cm² for the axial-vector operator. These results provide new constraints below 10 keV/c² and reach the lowest fermionic dark matter mass region explored so far by direct detection experiments.

Keywords: fermionic Dark Matter, electron absorption, direct detection experiment, high purity germanium detector

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一种在 MARC 级联下的 Q 迭代优化方法

Author: 庞承辉[1]

[1] *清华大学工程物理系*

Corresponding Author: 493034963@qq.com

摘要: 碳的同位素 C-13 在能源、医疗以及环境等领域拥有广阔应用前景。本研究以碳同位素的分离为目标，基于 MARC 模型级联提出了一种融合模糊控制算法的自适应松弛因子优化方法，用于提升 Q 迭代过程的收敛性能。通过构建高斯-三角混合隶属度函数，设计模糊控制器，并采用 Mamdani 最小-最大推理机制，实现了对级联丰度分布迭代过程的智能优化。该方法通过动态调节松弛因子，有效提升了迭代收敛效率。以二氧化碳作为分离对象，通过不同分离级数和收敛精度的对比验证了模型的有效性。结果表明，本研究设计的数值优化算法不仅具有较好的收敛加速效果，还展现出良好的鲁棒性，可以为 Q 迭代方法的高效求解提供新的优化策略，提高迭代效率。

关键词: 模糊控制；Q 迭代；MARC 级联；松弛因子

Abstract: The carbon isotope C-13 has broad application prospects in the fields of energy, medicine and environment. This research aims at the separation of carbon isotopes and proposes an adaptive relaxation factor optimization method based on the MARC model cascade and integrating the fuzzy control algorithm, which is used to improve the convergence performance of the Q iteration process.By constructing a Gaussian-triangular hybrid membership function, designing a fuzzy controller, and employing the Mamdani minimum-maximum reasoning mechanism, the intelligent optimization of the iterative process of the cascaded abundance distribution was achieved.This method effectively improves the iterative convergence efficiency by dynamically adjusting the relaxation factor. Using carbon dioxide as the separation target, the validity of the model was verified through comparisons of different separation stages and convergence accuracies.The results show that the numerical optimization algorithm designed in this study not only has a good convergence acceleration effect, but also demonstrates excellent robustness. It can provide new optimization strategies for the efficient solution of the Q iteration method and improve the iteration efficiency.

Keywords: Fuzzy control; Q iteration; MARC cascade; relaxation factor

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飞秒激光驱动高密度等离子体的 betatron 辐射源模拟

Authors: 王恒[2]; 盛亮[1]

Co-authors: 龙曾 [2]; 刘军 [1]; 李阳 [1]

[1] *西北核技术研究所*

[2] *清华大学工程物理系*

Corresponding Authors: shengliang@nint.ac.cn, wangheng21@mails.tsinghua.edu.cn

摘要: 激光驱动高密度等离子体中产生激光尾场加速，可以获得更大电荷量的电子束，从而得到提高 betatron 辐射产额的可能性。本文利用 EPOCH 模拟了飞秒激光驱动尾场加速产生高能电子束以及电子束振荡产生的 X 射线。X 射线的脉冲宽度与驱动激光的脉冲宽度相当，因此单次能够产生时间尺度在 30 飞秒以内的高产额 X 射线。研究发现，增加等离子体密度一般情况下会增加出射 X 射线的散角。本文对比了激光驱动时不同材料时产生的 X 射线的过程。研究表明，在一定范围内，原子序数的提高有助于 X 射线产额的提高。本研究可以为推进飞秒激光驱动 X 射线源的实验提供参考。

关键词: 激光等离子体，X 射线，粒子云模拟

Abstract: Laser wakefield acceleration in high-density plasma can produce elec-tron beams with higher charge, thereby enhancing the yield of betatron radiation. In this study, the EPOCH code was employed to simulate the generation of high-energy electron beams via femtosecond laser-driven wakefield acceleration, as well as the Xray emission resulting from electron beam oscillations. The pulse duration of the generated X-rays is comparable to that of the driving laser, enabling the generation of high-yield X-rays with a time scale of less than 30 femtoseconds in a single shot. It was found that, under normal conditions, increasing the plasma density leads to a larger divergence angle of the emitted X-rays. Moreover, we compare the X-ray generation processes when lasers interact with different target materials. The results show that, within a certain range, an increase in atomic number contributes positively to the X-ray yield. This study may offer valuable insights for the development of femtosecond laser-driven X-ray sources.

Keywords: Laser plasma, X ray, Particle-In-Cell simulation

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基于随机森林的核电厂系统故障诊断方法

Author: 刘文诗[1]

[1] *工程物理系*

Corresponding Author: 348500645@qq.com

摘要: 实施快速、准确的故障诊断对于保障核安全十分重要，针对现有随机森林方法在核电厂故障诊断中未充分利用“类型-程度”关联信息的不足，建立了四种分类和回归融合随机森林的核电厂系统故障类型和程度协同诊断模型，结合故障仿真模拟数据测试对比了四种诊断模型的性能。测试结果表明，建立的四种分类和回归融合随机森林方法均可以实现核电厂系统故障类型及故障程度的协同诊断，相较而言，分层回归模型表现出较好的鲁棒性，诊断准确性显著优于其他方法。

关键词: 核电厂；故障诊断；随机森林；分类和回归融合；分层回归；条件回归；多任务学习

Abstract: Implementing rapid and accurate fault diagnosis is crucial for ensuring nuclear safety. To address the limitation of existing random forest methods that fail to fully utilize the “type–severity” correlation information in fault diagnosis of nuclear power plants, four collaborative diagnosis models integrating classification and regression with random forests are established for identifying both fault types and severities in nuclear power plant systems. The performance of these four models is compared and evaluated using fault simulation data. The test results show that all four proposed classification–regression integrated random forest methods can achieve collaborative diagnosis of fault types and severities. Among them, the hierarchical regression model demonstrates better robustness, with diagnostic accuracy significantly superior to the other methods.

Keywords: Nuclear power plant; Fault diagnosis; Classification-regression fusion；Random forest; Hierarchical regression; Conditional regression; Multi-task learning

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飞秒激光驱动高密度等离子体的 betatron 辐射源模拟

Authors: 盛亮[1]; 王恒[2]

Co-authors: 刘军 [1]; 李阳 [1]; 龙曾 [2]

[1] *西北核技术研究所*

[2] *清华大学工程物理系*

Corresponding Authors: wangheng21@mails.tsinghua.edu.cn, shengliang@nint.ac.cn

摘要: 激光驱动高密度等离子体中产生激光尾场加速，可以获得更大电荷量的电子束，从而得到提高 betatron 辐射产额的可能性。本文利用 EPOCH 模拟了飞秒激光驱动尾场加速产生高能电子束以及电子束振荡产生的 X 射线。X 射线的脉冲宽度与驱动激光的脉冲宽度相当，因此单次能够产生时间尺度在 30 飞秒以内的高产额 X 射线。研究发现，增加等离子体密度一般情况下会增加出射 X 射线的散角。本文对比了激光驱动时不同材料时产生的 X 射线的过程。研究表明，在一定范围内，原子序数的提高有助于 X 射线产额的提高。本研究可以为推进飞秒激光驱动 X 射线源的实验提供参考。

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Abstract: Laser wakefield acceleration in high-density plasma can produce elec-tron beams with higher charge, thereby enhancing the yield of betatron radiation. In this study, the EPOCH code was employed to simulate the generation of high-energy electron beams via femtosecond laser-driven wakefield acceleration, as well as the Xray emission resulting from electron beam oscillations. The pulse duration of the generated X-rays is comparable to that of the driving laser, enabling the generation of high-yield X-rays with a time scale of less than 30 femtoseconds in a single shot. It was found that, under normal conditions, increasing the plasma density leads to a larger divergence angle of the emitted X-rays. Moreover, we compare the X-ray generation processes when lasers interact with different target materials. The results show that, within a certain range, an increase in atomic number contributes positively to the X-ray yield. This study may offer valuable insights for the development of femtosecond laser-driven X-ray sources.

Keywords: Laser plasma, X ray, Particle-In-Cell simulation