2025 年” 核理安邦“联合博士生学术论坛

Saturday 17 May 2025 - Sunday 18 May 2025

Location: 清华大学核能与新能源技术研究院

Book of Abstracts

Contents

AI+ / 13

Unsupervised anomaly detection of industrial building energy consumption

Authors: 怡宋[1]; 森楠旷[2]; 俊灵黄[3]; 达张[1]

[1] 清华大学

[2] 中国人民大学

[3] 三峡集团

Corresponding Authors: huang_junling@ctg.com.cn, y-song22@mails.tsinghua.edu.cn, zhangda@mail.tsinghua.edu.cn, 2020201271@ruc.edu.cn

摘要:

检测建筑能耗中的异常数据，可以有效减少能源浪费并提升用能效率。这一技术在工业建筑领域具有特殊应用价值，此类建筑不仅具有高能耗特征，其异常能耗事件还可能引发安全隐患。虽然智能电表采集的海量数据印证了数据挖掘技术在异常检测中的优势，但实际应用场景中往往面临标注数据缺失的瓶颈。为此，本研究构建了集成学习框架，融合局部离群因子（LOF）、深度孤立森林（DIF）和异常变换器（Anomaly Transformer）三种无监督算法，重点针对能耗子序列异常进行精准识别。本研究还基于 Transformer 模型实现了数据缺失值的精确填补，从而提升检测系统的鲁棒性。两栋工业建筑逐时能耗数据的案例分析表明，该集成方法在无监督场景下可以有效检测出异常的用电行为。为深入解析异常成因，本研究采用 XGBoost 算法构建特征解释模型，揭示了工作日状态与露点温度等关键因素对异常用电模式的显著影响。在分类性能评估中，ROC 曲线下的面积（AUC）的平均值达到 0.96 以上，充分验证了方法的可靠性。本研究通过构建" 检测-解释" 一体化方法，为智能建筑能源管理提供了新的提升方法，其成果对实现能耗异常趋势的实时预警和能源系统的优化调度具有重要实践价值。

关键词:

工业建筑；深度异常检测；能源管理；无监督学习；缺失值填补

Abstract:

Detecting anomalies in building energy consumption can reduce unnecessary energy waste and improve energy efficiency. The role of anomaly detection has become particularly pivotal in industrial buildings because of their high energy consumption and the potential risks associated with abnormal events. Although extensive data collected through smart meters has indicated the advantages for anomaly detection using data mining techniques, labeled data are often unavailable in practical situations. Therefore, this study develops an ensemble framework that combines three unsupervised learning algorithms, including Local Outlier Factor, Deep Isolation Forest, and Anomaly Transformer, to identify anomalous power consumption with a focus on subsequence anomaly. The transformer-based network is established to precisely impute missing values and enhance the reliability of anomaly detection. The experimental results based on hourly cooling energy consumption in the two industrial buildings confirmed the effectiveness of the proposed method. To better interpret the anomaly detection results, the Extreme Gradient Boosting is applied to construct the relationship between influencing factors and anomalous consumption. The area under the Receiver Operating Characteristic curve is used as a metric for the classification task, and an average of over 0.96 indicates robust performance. Weekday and dew point temperature are found to have significant impacts on the electricity usage pattern. The research findings provide valuable insights for developing effective solutions to identify unexpected trends in building energy consumption and support efficient energy management.

Keywords:

Industrial building; deep abnormality detection; energy management; unsupervised learning; missing value imputation

AI+ / 16

基于神经网络的气泡分布超分辨率重建方法研究

Authors: 孙志远[1]; 薄涵亮[1]

[1] 清华大学核研院

Corresponding Author: sunzy22@mails.tsinghua.edu.cn

摘要:

气液两相流气泡空间分布的精确预测在核能装备的设计与运行中至关重要，然而高精度的实验数据和数值模拟数据通常获取难度大，且具有高昂的成本和长时间的计算需求。传统实验方法和数值模拟技术通常只能提供低分辨率的气泡分布信息，难以满足高精度气液两相流研究的需求。为此，本文提出了一种基于神经网络的多尺度超分辨率重建方法，通过训练模型实现低分辨率气泡分布数据的高分辨率重建。结果表明，在 4 倍池化测试算例中，多尺度模型的 MSE 误差低于 0.2%，SSIM 可达 98% 以上。在难度较高的 8 倍池化测试算例中，多尺度模型的 MSE 最高较双三次插值减少 91.9%，SSIM 最高提升 282%，显示出优异的重建效果。本文还探讨了训练集数量对模型性能的影响，发现训练集数量存在一个平稳的转折点，进一步增加数据集规模对模型性能的提升效果逐渐减弱。本文的方法展示了超分辨率重建在气泡分布精细化领域的潜力，为气液两相流的超分辨率重建应用提供了新的研究方向。未来研究可进一步引入物理先验知识，提升模型性能，推动超分辨率技术在复杂气液两相流场中的应用。

关键词:

气泡空间分布，超分辨率重建，神经网络，机器学习

Abstract:

Accurate prediction of the spatial distribution of gas-liquid two-phase flow bubbles is crucial in the design and operation of nuclear energy equipment, however, high-precision experimental and numeri-cal simulation data are usually difficult to obtain, with high cost and long computation time. Tradition-al experimental methods and numerical simulation techniques can only provide low-resolution bubble distribution information, which is difficult to meet the needs of high-precision gas-liquid two-phase flow research. For this reason, a neural network-based multiscale super-resolution reconstruction method is proposed in this paper, which realizes high-resolution reconstruction of low-resolution bub-ble distribution data by training the model. The results show that in the 4-fold pooling test case, the MSE error of the multiscale model is lower than 0.2%, and the SSIM can reach more than 98%. In the more difficult 8-fold pooling test case, the MSE of the multiscale model is reduced by up to 91.9% compared with double triple interpolation, and the SSIM is improved by up to 282%, showing excel-lent reconstruction results. This paper also explores the effect of the number of training sets on the model performance, and finds that there is a smooth turning point in the number of training sets, and the effect of further increasing the dataset size on the model performance improvement gradually di-minishes. The method in this paper demonstrates the potential of super-resolution reconstruction in the field of bubble distribution refinement and provides a new research direction for the application of super-resolution reconstruction in gas-liquid two-phase flow. Future research can further introduce physical a priori knowledge to enhance the model performance and promote the application of super-resolution technology in complex gas-liquid two-phase flow fields.

Keywords:

Bubble Distribution, Super-Resolution Reconstruction, Neural Networks, Machine Learning

AI+ / 86

基于深度网络先验和稀疏性约束的时空核素源项重建方法及其对 **2020** 年切尔诺贝利野火事件的应用

Authors: Sheng Fang[1]; Yuhan Xu[1]

[1] *Tsinghua University*

Corresponding Authors: fangsheng@tsinghua.edu.cn, xuyh21@mails.tsinghua.edu.cn

摘要:

放射性核素大气释放源项的精准重建是核事故后果评估与应急响应中的关键科学问题。由于实际放射性事件中源项位置往往未知，相关信息需通过对观测到的核素大气活度浓度数据进行反演获取。源项参数可表征为一个包含经度、纬度、时间、释放高度和颗粒粒径的五维特征张量。然而，该类反演问题具有显著的不适定性，而可用测量数据通常不足，难以支撑对完整张量的可靠估计，因此引入合理的先验信息至关重要。为此，本文首次在该领域提出融合深度图像先验与稀疏性约束的策略，在变分优化框架下，结合卷积神经网络结构与稀疏正则化手段，对源项的时空分布施加有效约束。以 2020 年切尔诺贝利森林野火引发的 137Cs 释放事件为案例验证，本方法在无需初始猜测的前提下，成功获得了紧凑且物理合理的源项时空分布，估算总释放量为 254.938 GBq。在源项位置、释放时序及释放总量方面的重建结果与已有文献报道高度一致，且模拟结果与观测数据表现出良好的吻合度。

关键词:

核事故后果评价；时空源项重建；深度图像先验；稀疏正则化；切尔诺贝利野火。

Abstract:

Accurate reconstruction of atmospheric release source terms for radionuclides is a critical scientific challenge in nuclear accident consequence assessment and emergency response. In practical radiological events, the source location is typically unknown, and relevant information must be inferred from observed atmospheric activity concentration data. The source term can be represented as a five-dimensional feature tensor comprising longitude, latitude, time, release height, and particle size. However, such inverse problems are inherently ill-posed, and the available measurements are often insufficient to support a reliable estimation of the complete tensor, highlighting the importance of incorporating appropriate prior information. To address this, we propose for the first time in this field a novel strategy that integrates deep image priors with sparsity constraints. Within a variational optimization framework, the method employs convolutional neural networks combined with sparsity regularization to effectively constrain the spatiotemporal characteristics of the source term. Using the 137Cs release event triggered by the 2020 Chernobyl forest fire as a case study, the proposed approach successfully reconstructs a compact and physically plausible spatiotemporal source distribution without requiring an initial guess, with an estimated total release of 254.938 GBq. The reconstructed results, including source location, temporal profile, and total release, show strong agreement with previously reported values, and the simulated concentrations exhibit good consistency with observations.

Keywords:

consequence assessment for nuclear accidents; spatiotemporal source term reconstruction; deep image prior; sparsity regularization; Chernobyl wildfire

AI+ / 91

基于大模型的公共安全监控文本到图像行人检索研究

Author: 炳君骆[None]

Corresponding Author: lbj21@mails.tsinghua.edu.cn

摘要:

随着智慧城市建设的发展，文本到图像行人检索在公共安全监控中的应用价值日益凸显。针对现有行人检索方法对大量标注数据的依赖及其在跨场景部署中的泛化瓶颈，本研究提出一种基于图结构的跨域知识蒸馏方法（GCKD），实现大模型驱动下的无监督跨域检索能力。该方法通过图结构多域传播与对比式动量蒸馏模块，解决了跨场景语义迁移与模态差异问题。实验在多个行人检索基准数据集上进行了验证，平均 Rank-1 检索精度提升超过 4%。研究成果已被人工智能领域国际顶级会议、中国计算机学会推荐 A 类会议 AAAI 2025 接收。

关键词:

文本到图像行人检索；多模态大模型；智慧城市；公共安全

Abstract:

With the advancement of smart city development, text-to-image person retrieval has shown increasing value in public security surveillance applications. To address the reliance of existing retrieval meth-

ods on large-scale annotated data and their limited generalization across diverse deployment scenarios, this study proposes a Graph-Based Cross-Domain Knowledge Distillation (GCKD) method, enabling large-model-driven unsupervised cross-domain retrieval. The proposed approach leverages a graph-based multi-domain propagation module and a contrastive momentum distillation module to tackle the challenges of semantic transfer and modality discrepancy across scenarios. Experiments on multiple benchmark person retrieval datasets demonstrate that our method achieves an average improvement of over 4% in Rank-1 retrieval accuracy. This work has been accepted as an oral presentation at AAAI 2025, a top-tier international conference in artificial intelligence and a CCF-A recommended venue.

Keywords:

Text-to-Image Person Retrieval; Multimodal Large Model; Smart City; Public Security

安全科学与技术 / **23**

天然气站场泄漏扩散源项反演方法研究

Author: 后佳徐[1]

Co-author: 云涛李 [1]

[1] 中国石油大学（北京）

Corresponding Author: xuhj3020@163.com

摘要:

当有害气体意外释放后，准确、高效的源项估计方法对确保天然气站场的安全平稳运行至关重要[1]。合理的传感器布置作为源项估计（Source term estimate，STE）的基础，直接影响到了 STE 方法的精度。现有的传感器布置方法大多都只针对特定工况且需事先了解泄漏来源，这在 STE 工作中是不切实际的 [2]。加之现有的 STE 方法实时性差，难以应对动态场景 [3]。本文提出一种天然气站场泄漏的传感器优化配置方法和 STE 深度学习模型，用于实现复杂结构和风向条件下泄漏点强度和位置的快速精准估计。该模型引入信息熵理论 [4]，建立了多目标工况下的目标函数用于优化传感器配置，并将风向频率作为权重系数引入到目标函数中，通过遗传-粒子群全局优化算法（GA-PSO）实现了复杂风向条件下的最优化配置 [5]。在此基础上，搭建天然气泄漏扩散实验平台和 CFD 模型，构建了 BiTCN-BiGUR 的双向深度神经网络，捕捉浓度时序数据的时空依赖关系，实现了复杂结构和风向条件下天然气站场泄漏源的位置和强度的精准估计。

关键词:

信息熵；传感器优化配置；源项估计；CEEMDAN-BiTCN-BiGRU 模型

Abstract:

When the harmful gas is accidentally released, accurate and efficient source term estimation method is very important to ensure the safe and stable operation of the natural gas station. As the basis of Source term estimate (STE), reasonable sensor layout directly affects the accuracy of STE method. Most of the existing sensor layout methods are only for a specific job and need to know the leak source in advance, which is impractical in STE work. In addition, the existing STE method has poor real-time performance, which is difficult to deal with dynamic scenes. In this paper, an optimal sensor configuration method and STE deep learning model for gas station leakage are proposed, which can be used to achieve fast and accurate estimation of leak point strength and location under complex structure and wind direction. The model introduces information entropy theory, establishes an objective function under multi-objective conditions to optimize the sensor configuration, and introduces the wind direction frequency as the weight coefficient into the objective function. The genetic particle swarm optimization algorithm (GA-PSO) is used to achieve the optimal configuration under complex wind direction conditions. On this basis, a natural gas leakage and diffusion experiment platform and CFD model were built, and a bidirectional deep neural network of BiTCN-BiGUR was constructed to capture the spatio-temporal dependence of concentration time series data, thus achieving accurate estimation of the location and intensity of leakage sources in natural gas stations and yards under complex structure and wind direction conditions.

Keywords:

Information entropy; Sensor optimization configuration; Source term estimation; CEEMDAN-BiTCN-BiGRU model

安全科学与技术 / **26**

基于宽光谱散射的火灾探测模拟研究

Author: 煜欣康[1]

[1] 清华大学

Corresponding Author: kyx21@mails.tsinghua.edu.cn

摘要:

光电火灾烟雾探测器对干扰气溶胶非常敏感，会因为干扰源颗粒物和光源进行散射而引发误报，造成损失。为解决这一问题，本文提出了一种创新方法，即利用宽带光源（400-800 纳米）而非激光对颗粒物进行散射，获取散射光谱的高维信息，增强颗粒识别能力。该方法通过米氏散射理论进行数值模拟验证，生成了五种火灾烟雾和五种干扰气溶胶在不同角度下的散射光谱。将这些光谱输入五种机器学习模型进行颗粒分类，并引入随机测量噪声测试鲁棒性。结果表明，前向散射角（60°-90°）结合随机森林和 XGBoost 等非线性机器学习模型，在区分火灾烟雾与干扰气溶胶时实现了接近 100% 的精确率和召回率。本研究彰显了宽带可见光源在火灾探测中的潜力，为减少误报和提升检测精度提供了可靠解决方案。

关键词:

火灾探测、宽光谱、数值模拟、颗粒散射、干扰源气溶胶

Abstract:

Photoelectric fire smoke detectors are sensitive to false alarms caused by nuisance aerosols, which causes massive losses. To address this, techniques such as multiple optical channels and wavelengths have been developed to capture more particle scattering information. This paper presents an innovative method using broadband light (400–800 nm) to obtain multi-dimensional scattering information in a single measurement, enhancing particle discrimination. The approach was proved to be effective through numerical simulations using Mie scattering theory, which generated scattering spectrum for five types of fire smoke and five types of nuisance aerosols across various angles. These spectrum were input into five machine learning models for particle classification, with random measurement noise introduced to test robustness. These results indicate that forward scattering angles (60°–90°) combined with nonlinear machine learning models like Random Forest and XGBoost achieved almost 100% precision and recall in discriminating fire smoke from nuisance aerosols. This study highlights the potential of broadband visible light sources in fire detection, offering a robust solution to reduce false alarms and improve detection accuracy.

Keywords:

Fire detection, Nuisance Aerosols, Broadband Light, Particle Scattering, Numerical Study

安全科学与技术 / **28**

管道输送过程中典型粮食粉尘火焰燃爆特性

Author: 靖林张[1]

[1] 东北大学

Corresponding Author: zjl962784602@126.com

摘要:

粮食粉尘在管道输送时易爆炸，严重威胁人员和生产安全，探究其火焰燃爆特性意义重大。本研究以 13.85μm 玉米淀粉为材料，结合实验与模拟，分析单侧障碍物、管道倾角等因素对玉米淀粉粉尘火焰传播特性的影响。研究发现，单侧障碍物会使火焰形态不规则，火焰传播速度先增后缓，温度峰值变化趋势与之相同，堵塞率越高影响越显著；弯曲管道障碍物条件下，火焰向上传播占优，弯曲角度增加会使火焰形态更复杂，90° 弯曲时火焰速度和湍流动能变化明显，粉尘云浓度越高出口扰动越剧烈，MFSV 和 AFSV 先升后降，弯曲角度增加二者呈上升趋势。单侧障碍物和弯管障碍物会增加湍流动能，对火焰传播影响重大。本研究为预防粉尘爆炸、优化工业设计和制定安全标准提供了理论和数据支持，企业可据此优化设备、控制粉尘浓度和加强通风来降低事故风险。

关键词:

单侧障碍物；管道弯曲角度；火焰传播速度

Abstract:

Grain dust is prone to explosion during pipeline transportation, posing a serious threat to personnel and production safety. Exploring its flame explosion characteristics is of great significance. This study uses 13.85 μ m corn starch as the material, and combines experiments and simulations to analyze the effects of factors such as single-sided obstacles and pipeline inclination on the flame propagation characteristics of corn starch dust. Research has found that single-sided obstacles can cause irregular flame shapes, with flame propagation speed increasing first and then slowing down. The trend of temperature peak changes is the same, and the higher the blockage rate, the more significant the impact; Under the condition of curved pipeline obstacles, flame propagation is dominant, and increasing the bending angle will make the flame shape more complex. When bending at 90 °, the flame velocity and turbulent kinetic energy change significantly. The higher the dust cloud concentration, the more intense the outlet disturbance. MFSV and AFSV first increase and then decrease, and both show an upward trend with increasing bending angle. Unilateral obstacles and curved obstacles can increase turbulent kinetic energy and have a significant impact on flame propagation. This study provides theoretical and data support for preventing dust explosions, optimizing industrial design, and developing safety standards. Enterprises can use this to optimize equipment, control dust concentration, and strengthen ventilation to reduce accident risks.

Keywords:

Unilateral obstacle; Pipe bending angle; flame propagation speed

安全科学与技术 / **31**

涡场效应：隧道流淌火火焰行为及烟气扩散的实验和数值研究

Author: 成豪叶[1]

Co-author: 培红张 [1]

[1] 东北大学

Corresponding Authors: 1096143053@qq.com, zhangpeihong@mail.neu.edu.cn

摘要:

研究涡旋结构有助于阐明隧道流淌火的火焰行为和烟雾扩散的内在演化机制。本研究采取数值模拟与实验分析相结合的方法，研究了流淌火从扩散和稳定阶段的火羽流行为和顶棚温度分布，特别强调了温度流场、速度流场和涡度场。研究结果表明，冷空气和热烟气的相互作用会产生不稳定的涡旋结构，从而影响火焰的形态。在扩散阶段，涡旋结构撕裂火焰，产生分叉行为。相反在稳定阶段，涡旋结构的减少促使火焰稳定并进行融合。从扩散到稳定阶段，火焰振荡频率逐渐减小并趋于恒定值，这主要是由于火焰根部流场的偏转以及热烟气与冷空气之间的热交换，建立了整个过程中火焰振荡频率的预测模型。顶棚温度变化受燃烧过程的影响，因此建立了整个燃烧

过程的最大温升和纵向温度衰减模型。在扩散阶段，涡度的增加导致湍流程度增大，进而导致顶棚温度逐渐升高。相反，在稳定阶段，顶棚附近涡旋结构的消失导致顶棚温度没有出现明显变化。在高涡度区，顶棚温度上升明显，而在低涡度区，热烟气与冷空气混合趋于平衡，温度上升较为平缓。

关键词:

流淌火，涡流场，火羽流行为，温度分布

Abstract:

The study of vortex structures is instrumental in elucidating the flame behavior and smoke dispersion mechanisms during tunnel spill fires. This work combines numerical simulations with experimental analysis to investigate the flame plume behavior and ceiling temperature distribution throughout both the diffusion and stable stages of spill fires, with a particular emphasis on the temperature-flow field, velocity-flow field and vorticity field. The findings indicate that the interaction of cold air and hot smoke generates unstable vortex structures, which subsequently affect the flame morphology. During the diffusion stage, the vortex structures tear the flame, resulting in bifurcation behavior. In contrast, in the stable stage, the diminishing vortex structures allow the flame to stabilize and merge. From the diffusion to the stable stage, the flame oscillation frequency gradually decreases and approaches a constant value, primarily due to the deflection of the flow field at the flame root and the heat exchange between the hot smoke and cold air, a predictive model for the flame oscillation frequency throughout the entire process has been developed. Ceiling temperature variations are influenced by the combustion process, leading to the establishment of models for maximum temperature rise and longitudinal temperature attenuation over the entire process. During the diffusion stage, increased turbulence from vortex structures gradually elevates ceiling temperatures. Conversely, in the stable stage, the disappearance of vortex structures near the ceiling results in no significant changes in ceiling temperature. In the high vorticity zone, there is a pronounced rise in ceiling temperature, whereas in the low vorticity zones, the mixing of hot smoke and cold air tends to reach equilibrium, resulting in a gentler temperature increase.

Keywords:

Spill fire, Vortex fields, Flame plume behavior, Temperature distribution

安全科学与技术 / **89**

Lithium-ion battery thermal runaway inhalable particle characterization

Author: 祺张[None]

Co-author: Xiaole Zhang [1]

[1] *Tsinghua University*

Corresponding Authors: zhangxiaole@tsinghua.edu.cn, zhangq24@mails.tsinghua.edu.cn

摘要:

锂离子电池（LiB）因其高能量密度和效率，被广泛应用于电子设备、电动车和储能系统。然而在热、电或机械滥用下，电池容易发生热失控（TR）并可能引发火灾或爆炸。在热失控时，电池会排放含有有毒成分的气体和大量的可吸入颗粒，这些排放物对环境与人体健康存在危害。本研究在半开放空间内对一颗 3.4Ah 的圆柱形电池使用加热的方式触发热失控。试验结果表明，一颗圆柱形电池在热失控期间电池温度最高可达 642.3 ℃，产生的颗粒数浓度最高可达 1*107 #/cm3。结论表明锂离子电池在热失控期间存在显著的安全风险，并为日后改进锂电池设计以及颗粒危害评估提供科学参考。

关键词:

锂离子电池；热失控；颗粒表征；颗粒数浓度；热失控温度

Abstract:

Lithium-ion batteries (LiBs) are widely used in electronic devices, electric vehicles, and energy storage systems due to their high energy density and efficiency. However, under thermal, electrical, or mechanical abuse, batteries are prone to thermal runaway (TR) and may cause fire or explosion. During TR, the battery will emit gases containing toxic components and a large number of inhalable particles, which are harmful to the environment and human health. In this study, a 3.4Ah cylindrical battery was heated in a semi-open space to trigger TR. The experimental results show that the battery temperature of a cylindrical battery can reach up to 642.3 ℃ during TR, and the particle number concentration generated can reach up to 1*107 #/cm3. The conclusion shows that LiBs have significant safety risks during TR, and provides a scientific reference for future improvements in LiBs design and particle hazard assessment.

Keywords:

Lithium-ion battery; Thermal runaway; Particle characterization; Particle number concentration; Thermal runaway temperature

安全科学与技术 / **98**

考虑分层效应的倾斜隧道浮力驱动通风流量预测模型

Authors: 东阳[1]; 鑫郭[1]; 立蒋[1]; 涛杜[2]

[1] 重庆大学

[2] 长安大学

Corresponding Authors: yangdong@cqu.edu.cn, 729627740@qq.com, chddt@foxmail.com, lijiang20000505@126.com

关键词:

倾斜隧道；浮力流分层模式；自然通风流量；烟囱效应

摘要:

在如隧道等倾斜狭长空间中，由于长宽比巨大，由浮力驱动的气流模式及其导致的通风流量与围护结构类建筑存在显著差异。本研究针对倾斜隧道内局部热源引发的浮力驱动通风流量进行了探究，通过理论分析并结合非等温/等温浮力源的三组实验（包括大尺度火灾实验、盐水-清水实验及氦气-空气实验），揭示了两种典型的浮力流态：分层流与充分混合流。实验证实温度升高的纵向衰减率及分层模式均与无量纲因子 η=B01/3ΔLsinα/(g0'1/2H3/2) 密切相关，该因子综合了浮力源特征参数与几何构型参数。分层流会导致烟囱效应衰减，进而降低通风流量。研究提出了针对此类空间的浮力驱动流量预测模型，重点考量了分层流态的影响。模型预测结果与实验数据验证吻合，证实了考虑分层所致烟囱效应衰减的必要性。该预测模型具有显式表达式，可为工程设计计算提供便捷工具。

Abstract:

In inclined narrow and long spaces such as tunnels, the buoyancy-driven flow pattern and the resulting ventilation flow rate are different from those in enclosure-type buildings, because of their large length-to-width aspect ratios. In this paper, the buoyancy-driven flow rate induced by a localized heat source in inclined tunnels was investigated. Theoretical analysis and three series of experiments including non-isothermal or isothermal buoyancy sources, i.e., large-scale fire tests, brine-water tests and helium-air tests were performed. Two typical buoyant flow patterns were identified in the experiments, which are stratified and well-mixed patterns, respectively. Both the stratification pattern and the longitudinal decay rate of temperature rise were proved to be correlated with a dimensionless factor, η=B01/3ΔLsinα/(g0'1/2H3/2) , which is composed of characteristic parameters referring to both buoyancy source and geometrical configuration. The flow stratification results in stack effect attenuation and consequently ventilation flow rate reduction. A model for predicting the buoyancy-driven flow rate in such spaces was proposed, with special emphasis on the effects of stratification pattern. The predictions were validated with the experimental data, and the necessity for accounting for the stack effect attenuation caused by stratification was proved. The prediction model possesses an explicit expression and can thus provide a convenient tool for design calculations.

Keywords:

Inclined tunnel; Flow stratification pattern; Natural ventilation flow rate; Stack effect

安全科学与技术 / **124**

高层建筑火灾烟气蔓延全尺寸实验研究

Authors: 乐昊[1]; 茂华钟[1]

[1] 清华大学

Corresponding Authors: mhzhong@tsinghua.edu.cn, wu-l20@mails.tsinghua.edu.cn

摘要:

高层建筑楼层多、结构复杂、人员密集，火灾事故中毒性烟气蔓延路径与人员避险和逃生路径交叉，烟气在建筑内的快速蔓延对人员逃生和应急救援造成严重威胁。全尺寸火灾实验是一种有效的探究火灾蔓延规律的手段。为了探究高层建筑中火灾烟气在水平和竖直方向的蔓延规律，选取某高层建筑内地下室、多房间走廊、楼梯间三种典型展开全尺寸火灾实验，
针对地下室火灾，通过测量起火区域、临近房间、楼梯间的水平方向和竖直方向烟气温度，对地下空间烟气多区域蔓延特性进行分析。结果表明：在起火区域，房间内起火后的烟气蓄积作用显著，而楼梯间及其前室与多区域连通，大量烟气向邻近区域扩散导致烟气蓄积作用降低，形成稳定的烟气分层；在起火区域邻近房间，起火初期烟气在相互连通的多区域蔓延，在空间受限程度较低的楼梯间前室烟气分层作用明显，蔓延至远距离房间的低温烟气与空气掺混较严重，下部空间烟气温度有明显升高趋势；在楼梯间内烟气竖向蔓延较快，0.125 MW 火灾场景下，烟气在 300 s 内可蔓延至 4—5 层区域，且在楼梯间拐角处烟气层高度降至 2.00 m，对人员疏散威胁较大。
针对多房间走廊结构火灾，考虑了自然通风条件下火源位置的影响，并测量了火灾区域、相邻房间和楼梯间烟雾的水平和垂直温度分布。本研究分析了高层建筑中典型多房间走廊结构的烟气传播特性，探讨了 L 形和 T 形结构中天花板烟气主路径和分支路径的烟气分布模式，并推导出了天花板烟气温度衰减的预测模型。研究结果表明，烟气温度在不同路径下表现出不同的衰减率，恒定系数和衰减系数都受到分流次数的影响。基于全尺寸实验数据，获得了天花板烟气温度衰减模型和垂直温度分布模型的相关参数，并获得了建筑内任何空间位置的温度预测函数表达式。
针对楼梯间火灾，在某建筑 3-10 层研究了不同火源热释放速率对楼梯间烟气竖向蔓延的影响，实验表明火源的长宽比对火源正上方温度分布存在较大影响，热释放速率为 407 kW 工况，火源长宽比可达 3.5:1，过高的长宽比对火源上方的温度分布产生了一定的影响。随着高度的增加，烟气前锋到达时间与距离火源高度的斜率呈现增大趋势，反映出烟气在向上蔓延过程中，经过相同距离所需时间逐渐增多，即烟气速度减慢。随着油盘功率的增大，燃烧所释放的热量相应增多，从而使得相同测点的温升呈现出明显的上升趋势。在高度逐渐增加的过程中，测点处的温升曲线呈现多峰特性。这是由于油盘燃烧产生的烟气在封闭的楼梯间内传播时，遇到墙壁会发生反弹，进而获得了水平方向的加速度。当垂直上升的烟气与这些反弹的烟气相互叠加时，便导致了温升曲线上多个峰值的出现。
本研究为高层建筑内部空间的防火、排烟和应急响应提供了数据和技术支持。

关键词:

高层建筑；火灾烟气蔓延；全尺寸实验；地下室火灾；楼梯间火灾

Abstract:

High rise buildings have multiple floors, complex structures, and dense personnel. The path of toxic smoke spread in fire accidents intersects with the evacuation and escape routes of personnel. The rapid spread of smoke inside the building poses a serious threat to personnel evacuation and emergency rescue. Full scale fire experiments are an effective means of exploring the laws of fire spread. This study conducted full-scale fire experiments on three typical types of high-rise buildings: basements, multi room corridors, and stairwells. Focusing on the composite system of vertical through structures and horizontal separated spaces in high-rise buildings, key parameters such as heat release rate, smoke layer temperature gradient, and CO concentration distribution were monitored to quantitatively reveal the dynamic characteristics of smoke propagation in heterogeneous spaces such as underground confined spaces, narrow corridors, and enclosed stairwells.
In response to basement fires, the multi zone spread characteristics of smoke in underground spaces are analyzed by measuring the horizontal and vertical smoke temperatures in the ignition area, adjacent rooms, and stairwells. The results showed that in the fire area, the accumulation of smoke in the room after the fire was significant, while the staircase and its front room were connected to multiple areas,

and a large amount of smoke diffused to adjacent areas, resulting in a decrease in smoke accumulation and the formation of stable smoke stratification; In the adjacent rooms of the fire area, smoke spreads in multiple interconnected areas during the initial stage of the fire. The smoke stratification effect is obvious in the front room of the staircase with lower spatial restrictions. The low-temperature smoke that spreads to distant rooms is more severely mixed with air, and the temperature of the smoke in the lower space shows a significant upward trend; The vertical spread of smoke in the stairwell is relatively fast. In a 0.125 MW fire scenario, smoke can spread to the 4-5 story area within 300 seconds, and the height of the smoke layer at the corner of the stairwell drops to 2.00 meters, posing a significant threat to personnel evacuation.
In response to multi room corridor structure fires, the influence of fire source location under natural ventilation conditions was considered, and the horizontal and vertical temperature distribution of smoke in the fire area, adjacent rooms, and stairwells was measured. This study analyzed the smoke propagation characteristics of typical multi room corridor structures in high-rise buildings, explored the smoke distribution patterns of the main and branch paths of ceiling smoke in L-shaped and T-shaped structures, and derived a prediction model for the temperature attenuation of ceiling smoke. The research results indicate that the flue gas temperature exhibits different attenuation rates under different paths, and both the constant coefficient and attenuation coefficient are affected by the number of diversion times. Based on full-scale experimental data, the relevant parameters of the ceiling smoke temperature attenuation model and the vertical temperature distribution model were obtained, and the temperature prediction function expression for any spatial position inside the building was obtained.
In response to a stairwell fire, the influence of different heat release rates of the fire source on the vertical spread of smoke in the stairwell was studied on floors 3-10 of a building. The experiment showed that the aspect ratio of the fire source had a significant impact on the temperature distribution directly above the fire source. Under the condition of a heat release rate of 407 kW, the aspect ratio of the fire source could reach 3.5:1, and an excessively high aspect ratio had a certain impact on the temperature distribution above the fire source. As the height increases, the slope between the arrival time of the smoke front and the distance from the fire source shows an increasing trend, reflecting that during the upward spread of smoke, the time required to travel the same distance gradually increases, that is, the smoke velocity slows down. As the power of the oil pan increases, the heat released by combustion also increases, resulting in a significant upward trend in temperature rise at the same measuring point. As the height gradually increases, the temperature rise curve at the measuring point exhibits a multimodal characteristic. This is because when the smoke generated by the combustion of the oil pan spreads in the enclosed staircase, it bounces back when it encounters the wall, thereby obtaining horizontal acceleration. When the vertically rising smoke overlaps with these rebounding smoke, multiple peaks appear on the temperature rise curve.
This study provides data and technical support for fire prevention, smoke exhaust, and emergency response in the interior spaces of high-rise buildings.

Keywords:

High rise building; Fire smoke spread; Full-size experiment; Basement fire; Staircase fire

安全科学与技术 / **123**

一种基于图像增强的地下管线 **GPR B-scan** 预处理方法

Author: 政一史[None]

Co-authors: 弘黄 [1]; 翰超马 [1]

[1] 清华大学安全科学学院

Corresponding Author: shizy21@mails.tsinghua.edu.cn

摘要:

探地雷达（GPR）已被证明是一种有效的无损检测地下管线的方法，然而，现有的自动化方法在从 B-scan 中分割目标双曲线方面表现不佳，尤其是在非理想野外条件下识别较细的管线时效果有限。本文提出了一种用于 B-scan 预处理的自动化算法流程。该流程包含三个核心步骤：地面反射条带消除算法（GRRA）、基于数据作用力的增强算法（DGFE），以及基于扩张的局部定阈和分割算法（DLTS）构成的全局–局部定阈方法。首先，算法利用基于快速傅里叶变换的频域滤波器和空间滤波器对原始 B-scan 进行处理，去除干扰性的地面反射条带。鉴于目标双曲线、多次

波和背景之间的强度差异较小，引入 DGFE 以增强双曲线的主体结构，使其从噪声中更可辨别。最后，采用一种混合定阈法从灰度图像中提取目标双曲线，主要使用 DLTS 方法，通过扩张和局部定阈完成双曲线的完整分割。实验表明，该模型在实地实验中获取的 B-scan 数据上实现了快速且有效的处理表现。

关键词:

探地雷达（GPR）；地下管线；图像增强；定阈；双曲线分割

Abstract:

Ground-penetrating radar (GPR) has been proven effective for detecting subsurface pipes in a nondestructive way, typically with manual processing and decision-making. However, existing automatic models for segmenting target hyperbolas from B-scans perform inadequately, particularly for thin pipes buried under suboptimal field conditions. In this paper, an automatic model for B-scan preprocessing is proposed to assist in interpreting B-scans with small-scale hyperbolas that attenuate along the time axis. The model includes a ground reflection removal algorithm (GRRA), the data gravitational force enhancement (DGFE) method, and a global–local thresholding technique consisting of dilation-based local thresholding and segmentation (DLTS). First, a frequency-domain filter based on the fast Fourier transform and a spatial filter are applied to the raw B-scan to remove obstructive ground reflection strips. Owing to the minimal intensity differences among the target hyperbola, multiples, and background, the DGFE enhancement approach is introduced to amplify the main body of the hyperbola, distinguishing it from the noise. Finally, the target hyperbola is extracted from the grayscale image by an integrated thresholding approach. The approach initially employs global thresholding to eliminate all information except part of the hyperbola, followed by DLTS, which uses a dilation operation with local thresholding to fully segment the hyperbola. The proposed model is demonstrated to be fast and effective through implementation on B-scans from a database acquired in a field experiment.

Keywords:

ground penetrating radar (GPR); underground pipes; image enhancement; thresholding; hyperbola segmentation

安全科学与技术 / **99**

基于设备可靠性预计的核电厂丧失厂用水系统始发事件频率定量化方法研究

Authors: 鹏程彭[1]; 军赵[2]; 节娟童[2]

[1] 清华大学核能与新能源技术研究院

[2] 清华大学

Corresponding Authors: tongjj@tsinghua.edu.cn, ppc23@mails.tsinghua.edu.cn, zhaojun@tsinghua.edu.cn

摘要:

风险监测器以核电厂运行阶段 PSA 模型为基础，已广泛应用于核电厂的在线风险监测，为运行与维修活动提供辅助决策支持。其中，以丧失厂用水系统为代表的支持系统始发事件是风险监测器中必不可少的一类始发事件。在风险监测器中需要根据特定的外部环境（如高温、风暴潮等）调整该类始发事件在特定环境下的发生频率，目前风险监测器中这类始发事件频率的修正主要基于专家判断，不能准确的体现核电厂的真实风险水平。本文基于机械设备可靠性预计方法，提出了一种根据关键环境影响因素对特定环境下丧失厂用水系统始发事件发生频率进行定量化和修正的方法。此方法包括关键环境因素的确定、关键因素参数与设备可靠性参数关系的拟合、厂用水系统关键能动设备可靠性参数的修正等，并通过蒙特卡洛抽样方法模拟厂用水系统运行状态，从而更为真实地对电厂始发事件频率进行在线修正，为风险监测器的应用提供支持。

关键词:

支持系统、始发事件频率、可靠性参数修正、核电厂风险监测器

Abstract:

To provide auxiliary decision-making support for operation and maintenance activities in nuclear power plants, the risk monitor is built on the probabilistic safety analysis (PSA) model of the operation phase, and has been widely used in online risk monitoring. It is an essential type of initiating event from support system represented by the loss of plant water system in risk monitors. And the frequency of such events should be revised according to specific external environments, say high temperature or storm surge. However, that correction in risk monitors is based on expert judgment at present and it cannot reflect the risk level of nuclear power plants on time and accurately. This paper proposes a novel method, based on the reliability prediction method of mechanical equipment, to quantify and correct the initial event frequency of loss of service water systems by selecting the key environmental influencing factors. This method is realized by steps of selecting key environmental factors, determining the relationship between those factors and equipment reliability parameters, and correcting the reliability parameters of key active equipment in the plant water system, then the operating state of this system is simulated through Monte Carlo sampling method. Compared to expert judgment, this method is more suitable and practical to support for the application of risk monitors.

Keywords:

Support system, initiating event frequency, reliability parameter correction, risk monitor of nuclear power plant

核技术与应用、医学物理与工程 / **74**

空间应用像素 **CdZnTe** 探测器的质子诱导辐射损伤研究

Authors: 昊常[1]; 煦韬郑[None]; 玉兰李[2]; 鸣曾[None]

[1] 清华大学

[2] *Tsinghua university*

Corresponding Authors: changh21@mails.tsinghua.edu.cn, yulanli@mail.tsinghua.edu.cn

摘要:

高性能 3 维位置灵敏的像素 CZT 探测器在康普顿成像望远镜中具有很大应用前景。我们提出在 MeV 天体物理光谱仪（MASS）中使用像素 CZT 探测器，这是一个大面积的康普顿望远镜。然而，空间中高能质子会导致像素 CZT 探测器的辐射损伤，导致探测器性能逐渐下降。利用非电离能量损失（NIEL）方法，提出了一种定量评估空间探测器辐射损伤的方法。为了验证该方法，本研究用 100 MeV 质子辐照了两个 2×2×1 cm^3 像素 CZT 探测器两种不同的偏压条件下。辐照累计通量范围为 3×10^7 p+/cm2 到 3×10^9 p+/cm2。当质子累计通量为 3×10^9p+/cm2 时，探测器的能量分辨率在 511keV（FWHM/E）时显著下降至 3.8%。最后，本研究为其在空间的应用提供了工程考虑。

关键词:

辐照损伤，像素 CZT，能量分辨率，空间伽马探测

Abstract:

High-performance pixelated CZT detectors that achieve 3D position sensitivity are promising candidates for use in Compton imaging telescopes. We proposed to use pixelated CZT detectors in the MeV Astrophysical Spectroscopic Surveyor(MASS), which is a large area Compton telescope. Nevertheless, the presence of high-energy protons in space can lead to radiation damage in pixelated CZT detectors, causing their performance to degrade gradually. Using non-ionizing energy loss (NIEL), this study develops a method that quantitatively evaluates the radiation damage of detectors in space. To verify the method, this study irradiated two 2 × 2 × 1 cm^3 pixelated CZT detectors with 100 MeV protons at fluences ranging from 3 × 10^7 p+/cm2 to 3 × 10^9 p+/cm2 under two bias sets. When the proton fluence reaches 3 × 10^9 p+/cm2, the energy resolution of the detectors significantly deteriorates to 3.8% at 511 keV (FWHM/E), even after post-correction. Finally, this study provides engineering considerations for their application in space.

Keywords:

Radiation damage, pixelated CZT, energy resolution, space gamma detection

核技术与应用、医学物理与工程 / **103**

基于级联激光尾波加速器的新型自由电子激光方案

Authors: 剑飞华[1]; 巍鲁[2]; 恒圆肖[1]; 飞李[1]

[1] 清华大学工程物理系

[2] 中国科学院高能物理研究所

Corresponding Author: xiaohy19@mails.tsinghua.edu.cn

摘要:

激光尾波加速（LWFA）具有超高加速梯度，具备实现紧凑型自由电子激光器 (FEL) 的重要潜力。当前 FEL 应用面临 X 射线、极紫外（EUV）及大带宽等多样化需求，但现有基于 LWFA 的 FEL 方案尚难以在单一系统中实现上述多模式兼容。在本报告中，我们提出一种新型基于级联 LWFA 的 FEL 方案解决这一问题，通过两级 LWFA 加速并配合磁压缩器（chicane）的综合调控，本方案可产生带宽与能量可调的高品质束团，满足不同的 FEL 应用需求。模拟表明，基于一个 35J 的激光器，可在一个总长 115m 的装置中通过不同的参数设置实现 X 射线、EUV 以及谱宽达 10% 的宽谱 FEL 三种模式的饱和出光。本研究为实现基于 LWFA 的紧凑型 FEL 的发展提供了可行的新途径。

关键词:

激光尾波加速，自由电子激光，级联加速，相空间操控

Abstract:

Laser wakefield acceleration (LWFA) possesses ultra-high acceleration gradients, demonstrating significant potential for realizing compact free-electron lasers (FELs). Current FEL applications face diverse requirements including X-ray generation, extreme ultraviolet (EUV) radiation, and broad bandwidth operation. However, existing LWFA-based FEL schemes struggle to achieve multi-mode compatibility within a single system. In this study, we propose a novel cascaded LWFA-based FEL scheme to address this challenge. By combining two-stage LWFA acceleration with comprehensive control through magnetic chicanes, this solution can generate high-quality electron beams with tunable bandwidth and energy to meet various FEL application needs. Simulation results demonstrate that using a 35J laser system, saturated FEL outputs can be achieved in three operational modes (X-ray, EUV, and broad-spectrum with 10% bandwidth) within a compact facility of 115 meters total length through different parameter configurations. This research provides a viable new pathway for developing compact LWFA-based FEL systems.

Keywords:

laser wakefield acceleration, free electron lasers, cascaded acceleration,phasespace manipulation

核技术与应用、医学物理与工程 / **17**

用于费托合成的铀单原子催化剂

Author: 家辉应[None]

Corresponding Author: ying-jh21@mails.tsinghua.edu.cn

摘要:

用简单的一步浸渍法，在碳纳米管上制备了负载型钴催化剂和负载在 Co 纳米颗粒上的铀单原子。用 XRD、XPS、AC-STEM、EXAFS 等多种表征手段确认了铀单原子的存在。用小型固定床反应器研究了铀单原子催化剂对费托合成的影响。结果表明，铀单原子的存在能够显著增加 CO 的转化率，同时保有很高的 C5+ 选择性与较低的甲烷选择性。电镜分析和 TPR 实验表明，铀单原子并

不是从促进粒径变化或是改变还原性质来促进费托合成反应的。进一步的放大实验证明了含铀单原子的催化剂在实际工业应用中的潜力。

关键词:

负载型 Co 催化剂；单原子催化剂；铀单原子；费托合成

Abstract:

Using a simple one-step impregnation method, supported cobalt catalysts and uranium single atoms loaded on cobalt nanoparticles were successfully synthesized. The presence of uranium single atoms was confirmed through multiple characterization techniques, including XRD, XPS, AC-STEM, and EXAFS. The influence of uranium single atom catalysts on Fischer-Tropsch synthesis was investigated using a small-scale fixed-bed reactor. Results indicated that the existence of uranium single atoms significantly enhanced CO conversion while maintaining high C5+ selectivity and low methane selectivity. Electron microscopy analysis and TPR experiments revealed that uranium single atoms do not promote the FT reaction by altering particle size distribution or reduction properties. Furthermore, scaled-up experiments demonstrated the potential of uranium single atom-containing catalysts for practical industrial applications.

Keywords:

Supported Co catalyst；Single-Atom Catalyst；Uranium Single Atom；Fischer-Tropsch Synthesis

核技术与应用、医学物理与工程 / **43**

基于康普顿散射的硬 X 射线辐射场调制方法

Authors: 梦凡张[1]; 定国来[2]; 启福徐[2]; 孟通邱[2]; 应超杜[1]

[1] 清华大学工程物理系

[2] 西北核技术研究所

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

Abstract:

The hard X-ray produced by the bremsstrahlung from low-energy electrons has a large emit angle, which makes a low utilization ratio of the radiation field in hard X-ray source. A modulation method based on Compton scattering to increase the utilization ratio of the radiation field is presented in this paper. Escaped photons are scattered into the detection region partially to increase the utilization ratio of radiation field by a Compton scattering layer with specific materials and structures. In addition, the average energy of the photon is reduced. The progress of Compton scattering of photons in materials at different energy and incident angles is studied. The effects of the materials and structures of Compton scattering layer on the radiation intensity and photon energy of X-ray are simulated. A Compton scattering layer is designed for the hard X-ray source, the array of cylindrical virtual cathode reflex triode, and an experimental study has been carried out. The experimental results show that the utilization ratio of the radial field is increased by 12% by the Compton scattering, which is an effective method to enhance the intensity of the radiation field.

Keywords:

Compton scattering, hard X-ray source, bremsstrahlung, Cylindrical Virtual Cathode Reflex Triode

关键词:

康普顿散射，硬 X 射线源，轫致辐射，同轴虚阴极反射三极管

摘要:

低能电子轫致辐射产生的硬 X 射线发射角度大，造成硬 X 射线源的辐射利用率低。本文介绍了一种采用康普顿散射提升硬 X 射线源辐射利用率的方法，通过设置特定材料和结构的康普顿散射层，将逃逸光子部分散射至探测区域，增大辐射利用效率；同时降低光子平均能量。研究了不

同能量和入射角度下光子在材料中发生康普顿散射的过程；模拟了康普顿散射层的材料和形状对 X 射线的辐射强度和光子能量的影响。针对同轴虚阴极反射三极管阵列型硬 X 射线源，优化设计了康普顿散射层并开展实验研究。结果表明：通过康普顿散射可将辐射利用率提升 12%，是提升辐射场强度的有效方法。

核技术与应用、医学物理与工程 / **54**

基于全图自相似的新非局部均值 **MRI** 去噪算法

Authors: 世奥李[None]; 嵩高[1]

Co-author: 飞王 [2]

[1] 北京大学

[2] 北京肿瘤医院

Corresponding Authors: gaoss@bjmu.edu.cn, fei.wang1225@outlook.com, 2311110784@stu.pku.edu.cn

Abstract:

Magnetic resonance imaging (MRI) is a non-invasive medical imaging technique that provides high-resolution 3D images and valuable insights into human tissue conditions. Even at present, the refinement of denoising methods for MRI remains a crucial concern for improving the quality of the images. This study aims to improve the prefiltered rotationally invariant non-local principal component analysis (PRI-NL-PCA) algorithm. We relaxed the original restrictions using particle swarm optimization to determine optimal parameters for the PCA part of the original algorithm. In addition, we adjusted the prefiltered rotationally invariant nonlocal mean (PRI-NLM) part by traversing the signal intensities of voxels instead of their spatial positions to reduce duplicate calculations and expand the search volume to the whole image when estimating voxels'signal intensities. The new method demonstrated superior denoising performance compared to the original approach. Moreover, in most cases, the new algorithm ran faster. Furthermore, our proposed method can also be applied to process Gaussian noise in natural images and has the potential to enhance other NLM-based denoising algorithms.

Keywords:

MRI; Denoising; Non-local mean; PRI-NL-PCA; PNLM-PCA; Self-similarity

摘要:

磁共振成像（MRI）是一种非侵入性的医学成像技术，能够提供高分辨率的 3D 图像，并为人体组织状况提供有价值的洞察。即使在当前，改进 MRI 去噪方法仍然是提升图像质量的一个关键问题。本研究旨在改进预滤波旋转不变非局部主成分分析（PRI-NL-PCA）算法。我们通过粒子群优化放松了原始限制，以确定原算法中 PCA 部分的最优参数。此外，我们通过遍历体素的信号强度而非其空间位置，调整了预滤波旋转不变非局部均值（PRI-NLM）部分，从而减少了重复计算，并在估计体素信号强度时将搜索范围扩展到整个图像。新方法相比原始方法表现出更优的去噪性能。此外，在大多数情况下，新算法运行速度更快。此外，我们提出的方法还可用于处理自然图像中的高斯噪声，并有潜力增强其他基于 NLM 的去噪算法。

关键词:

磁共振成像；去噪；非局部均值；主成分分析；自相似

核技术与应用、医学物理与工程 / **75**

基于聚乙烯的中子能谱探测组件研究设计

Author: 李展[1]

[1] 兰州大学

Corresponding Author: lizhan17@lzu.edu.cn

摘要:

自给能中子探测器（Self-Powered Neutron Detector, SPND）作为反应堆堆芯探测系统的核心设备，凭借其不需要外加电源、体积小等优势，长期承担堆芯中子通量监测任务。本研究针对现有 SPND 技术在中子能谱探测领域的局限性，提出一种基于慢化层结构的中子能谱探测方法。研究通过理论建模与数值模拟相结合的方法，系统阐述了自给能中子能谱探测组件的物理机制。设计了一种基于聚乙烯慢化层的中子能谱探测组件，其核心结构包含四个不同厚度慢化层的 SPND。采用蒙特卡洛模拟方法建立三维几何模型，计算能谱探测组件在中子能量 1×10-9 -10 MeV 范围内的响应函数矩阵，数值结果表明不同慢化层厚度探测器对特定能区中子具有显著选择性响应。为验证组件的能谱求解可行性，研究提出基于响应矩阵逆运算的能谱解析算法，并通过输入三类典型中子能谱（热中子谱、压水堆能谱、混合能谱）作为测试基准。结果显示：通过四通道电流信号反演计算获得的能谱分量占比与预设值最大相对偏差小于 3.5%，验证了探测组件结构设计及解谱算法的有效性。误差分析表明，误差主要来源于慢化层厚度优化不足及探测单元数量限制。本研究建立的 SPND 能谱探测方法为堆内实时能谱监测提供了新的技术路径。在后续工作中，可增加探测器的数量、使用耐高温慢化层材料，使用最小二乘算法等解谱方法，提高反演计算稳定性，实现更精准、分群更详细的能谱探测工作。

关键词:

中子探测；能谱探测；反应堆探测；蒙特卡洛方法；自给能中子探测器；

Abstract:

The Self-Powered Neutron Detector (SPND), as a core component of reactor core monitoring systems, has long been utilized for neutron flux measurement due to its advantages of requiring no external power supply and compact size. However, existing SPND technologies exhibit limitations in neutron spectrum detection. To address this, this study proposes a novel neutron spectrum detection method based on a moderated-layer structure. Combining theoretical modeling and numerical simulation, the physical mechanism of the self-powered neutron spectrum detection assembly was systematically analyzed. A polyethylene-moderated neutron spectrum detection module was designed, comprising four SPNDs with varying moderator thicknesses (0 cm, 2 cm, 5 cm, and 8 cm). A three-dimensional geometric model was established using the Monte Carlo simulation method to calculate the response function matrix of the detection assembly across the neutron energy range of 1×10^{-9}–10 MeV. Numerical results demonstrated that detectors with different moderator thicknesses exhibited selective sensitivity to neutrons in specific energy regions. To validate the feasibility of spectrum unfolding, an inversion algorithm based on the response matrix was developed and tested using three typical neutron spectra: a thermal neutron spectrum, a pressurized water reactor (PWR) spectrum, and a mixed spectrum. Simulation results showed that the maximum relative deviation between the unfolded spectrum components and preset values was less than 3.5%, confirming the effectiveness of both the detector design and the unfolding algorithm. Error analysis indicated that deviations primarily originated from suboptimal moderator thickness configurations and insufficient detector units. The proposed SPND-based spectrum detection method provides a new technical pathway for real-time in-core neutron spectrum monitoring. Future work should focus on increasing the number of detectors, employing high-temperature-resistant moderator materials, and implementing advanced unfolding algorithms to enhance computational stability and achieve higher-resolution spectrum detection.

Keywords:

neutron detection; spectrum measurement; reactor monitoring; Monte Carlo method; self-powered neutron detector (SPND)

核技术与应用、医学物理与工程 / **101**

高温气冷堆模拟机分相流蒸汽发生器模块开发及分析

Author: 浚麟方[1]

[1] 清华大学核研院 *103* 室

Corresponding Author: fangjl20@mails.tsinghua.edu.cn

摘要:

清华大学核研院针对模块式高温气冷堆开发了工程模拟机（HTR-ESS），已成功用于 HTR-PM 操纵员培训、运行特性分析、方案设计等工作。为拓展 HTR-ESS 模拟紧急停堆后蒸汽发生器内的气液分层现象以及再启动过程的能力，开发了分相流换热管模块 TFNet，并建立了高温气冷堆螺旋管直流蒸汽发生器的模型 TFNet-SG。通过多种节点划分方案的比较和分析，综合考虑计算精度与实时性，明确了 100 节点的模型。通过稳态工况分析确认了模型的合理性及准确性，并在此基础上模拟了紧急停堆过程，分析了不同操作对蒸汽发生器内部参数的影响。后续准备将 TFNet-SG 嵌入模拟机完整系统，开展正常运行、紧急停堆、再启动等全过程模拟。

关键词:

高温堆模拟机；直流螺旋管蒸汽发生器；紧急停堆；分相流流网

Abstract:

The Institute of Nuclear and New Energy Technology (INET) at Tsinghua University has developed an Engineering Simulator, HTR-ESS, specifically for Modular High-Temperature Gas-cooled Reactors (HTR), which has been successfully employed in operator training, operational characteristic analysis, and operational scheme design for the HTR-PM project. To expand the ability of HTR-ESS to simulate gas-liquid stratification phenomena and restart processes in the steam generator after the SCRAM, TFNet (Two-fluid Flow Network module) was established on the vPower platform. And TFNet-SG is specially developed from TFNet for helical tubes in HTR. Real-time thermal-hydraulic models of the steam generators have been established with various node division schemes. A nodes division scheme with 100 nodes has been selected for computational accuracy and real-time performance. The accuracy of the inlet and outlet parameters in steady-state conditions and the rationality of the internal parameter distribution have been confirmed by comparing the new steam generator models with the experimental data and design parameters. The results indicate that the difference between the calculated values, experimental data and design parameters of the steam generator model constructed by TFNet-SG is relatively small in 20%, 30%, 50%, 75% and 100% power conditions. And the variation trend of heat transfer coefficients and heat flux density calculated using TFNet-SG aligns more closely with actual physical processes compared to the original simulated steam generator module tools utilized in HTR-ESS. Furthermore, dynamic processes of the SCRAM have been simulated based on the 100% power steady-state condition with different operations of valves closure and flow flux reduction speed. The calculation results indicate that a shorter closing time interval between the main steam valve and the main feedwater valve will lead to a faster increase in internal pressure within the steam generator. Longer flow flux reduction time leads to extended heating time on the steam-water side and higher overall temperature of the steam generator. Future work will involve connecting TFNet-SG with other systems in the secondary loop of the simulator, coupling it with the primary loop for calculations, and conducting simulation analysis of the SCRAM to the restart process for the HTR-PM power plant.

Keywords:

HTR Simulator; Steam generator; SCRAM; Two-Fluid flow network

核技术与应用、医学物理与工程 / **10**

A SEMI-IMPLICIT CHORD LENGTH SAMPLING METHOD FOR DISPERSION FUEL ANALYSIS

Author: Zhe Chuan Tan[None]

Co-authors: 侃王; 曾国禹

Corresponding Authors: zeng-gy23@mails.tsinghua.edu.cn, chenzc24@mails.tsinghua.edu.cn, wangkan@mail.tsinghua.edu.cn

摘要:

随着随机几何在核反应堆中的应用，隐式建模方法在随机介质中粒子输运的精确模拟中发挥着越来越重要的作用。当前 RMC 中的隐式建模方法采用弦长抽样法（CLS）。然而，在模拟高散射、高吸收特性的材料时，尤其是当吸收干扰散射过程时，与显式建模方法相比，弦长抽样法存在显著误差，且在模拟非马尔可夫随机介质时尤其容易产生偏差。为此，本文提出了一种半隐式弦长

抽样法（SCLS），该方法通过记录中子及粒子的历史位置信息，并采用动态球来最大化计算精度，同时最小化计算开销。随后通过显式建模方法生成的粒子分布验证了该算法的准确性。结果表明，在模拟非马尔可夫弥散燃料时，与原始弦长抽样法相比，半隐式弦长抽样法能显著提升隐式建模的精度。

关键词:

RMC，弦长抽样法，随机介质，弥散燃料

Abstract:

With the advent of stochastic geometry in nuclear reactors, implicit modeling processes play an increasingly important role in the precise simulation of particle transport in random media. Current implicit modeling methods in RMC utilize Chord Length Sampling (CLS). However, the CLS method experiences significant inaccuracies compared to explicit modeling methods when simulating materials of high scattering and absorbing properties, particularly where absorption interferes with scattering, and is especially prone to errors when simulating non-Markovian stochastic media. A Semi-Implicit CLS (SCLS) method is proposed where previous neutron and particle positions are recorded, while an inclusion sphere is used to maximise the accuracy of the method whilst minimizing the computational expense incurred. The accuracy of the algorithm was then verified against particle distributions generated via explicit modeling methods. The results show that SCLS can significantly improve the accuracy of implicit modeling when simulating non-Markovian dispersion fuel compared to the original CLS method.

Keywords:

RMC, Chord Length Sampling, Stochastic Media, Dispersion Fuel

核技术与应用、医学物理与工程 / **109**

A newly developed multi-kilo-channel high-speed and high-precision waveform digitization system for Jinping Neutrino Experiment

Author: Haoyan Yang[1]

[1] *Tsinghua University*

Corresponding Author: hy-yang22@mails.tsinghua.edu.cn

摘要:

太阳中微子为研究恒星演化和中微子振荡提供了一种有效手段。位于中国锦屏地下实验室的锦屏中微子实验计划在 2026 年之前开发一个 500 吨的液体闪烁探测器来研究太阳中微子。这将成为全球第八个太阳中微子观测站。近年来，提出了一种基于波形读出的混合中微子探测方法。该方法有效地减小了各向同性背景信号，提高了碳-氮-氧中微子探测的灵敏度。然而，现有的太阳中微子实验只捕获电荷和时间信息，受到电子系统性能的限制。为此，本文提出了一种 4000 通道、高速、高精度的波形数字化系统。该系统基于 CPCI 协议设计，配备 1 个 GSPS/13 位 adc 和白兔节点。此外，使用 1 吨重的原型设计并验证了 30 通道波形数字化系统。
实验结果表明，在波形数字化系统中，信道间的最大参考时钟偏差为 85.6 ps。系统的最大可接受事件率为 193.5 kHz。实验结果表明，本文开发的波形数字化系统满足了 JNE 实验的物理要求，为 4000 通道电子系统的设计奠定了基础。

关键词:

CJPL, 电子学系统, 中微子实验

Abstract:

Solar neutrinos provide an effective means of studying stellar evolution and neutrino oscillation. The Jinping Neutrino Experiment, located at the China Jinping Underground Laboratory, plans to develop a 500-ton liquid scintillator detector to study solar neutrinos by 2026. This will become the eighth solar neutrino observatory globally.

Recently, a mixed neutrino detection method based on waveform readout has been proposed. This method effectively reduces isotropic background signals and enhances the sensitivity of Carbon-Nitrogen-Oxygen neutrino detection. However, existing solar neutrino experiments only capture charge and time information, limited by the performance of their electronic systems. Therefore, this paper proposes a 4000-channel, high-speed, high-precision waveform digitization system. The system is designed based on the CPCI protocol and is equipped with 1 GSPS/13-bit ADCs and White Rabbit nodes. Additionally, a 30-channel waveform digitization system was designed and validated using the 1-ton prototype. Experimental results indicate a maximum reference clock skew of 85.6 ps between channels in the waveform digitization system. The maximum acceptable event rate of the system is 193.5 kHz. These experimental results demonstrate that the waveform digitization system developed in this paper meets the JNE experiment's physical requirements and provides a foundation for the design of a 4000-channel electronics system.

Keywords:

CJPL, Electronics system, Neutrino Experiment

核技术与应用、医学物理与工程 / **114**

The signal quality improvement of laser-induced breakdown spectroscopy due to the microwave plasma torch modulation

Author: 炳玉魏[1]

[1] 兰州大学

Corresponding Author: 220220922381@lzu.edu.cn

摘要:

我们提出了一种新的方法，通过将微波等离子体炬（MPT）与激光诱导击穿光谱（LIBS）结合，称为 MPT-LIBS，有效解决了传统 LIBS 的局限性。使用低激光脉冲能量为 0.55 毫焦的铜样品对 MPT-LIBS 技术进行了评估。结果显示，Cu I 521.82 纳米线的增强因子超过 70，而 Cu I 324.75 纳米和 327.40 纳米线的增强因子超过了两个数量级。此外，所有铜谱线的相对标准偏差（RSD）均有所降低，特别是 Cu I 521.82 纳米线，从 11.48% 降低到 1.36%，这表明信号稳定性显著提高。利用共聚焦显微镜对测试样品进行表征发现，MPT-LIBS 的剥蚀区域仅为 LIBS 的 1.36 倍。Cu I 324.75 纳米线的检出限从 52.8 ppk 降低到 319 ppm。

关键词:

激光诱导击穿光谱；微波等离子体炬；低能激光检测

Abstract:

Here, we present a novel approach by integrating microwave plasma torch (MPT) with LIBS, referred to as MPT-LIBS, which effectively addresses the limitations associated with traditional LIBS. The MPT-LIBS technique is evaluated using Cu samples with a low laser pulse energy of 0.55 mJ. A remarkable enhancement factor of over 70 for Cu I 521.82 nm line is demonstrated, while that of Cu I 324.75 nm and 327.40 nm lines exceeding two orders of magnitude. Furthermore, the RSDs of all Cu spectral lines are reduced, especially for Cu I 521.82 nm, which is decreased from 11.48% to 1.36%. This indicates a significant improvement in signal stability. Characterization of the tested samples using con-focal microscopy reveals that the ablation area of MPT-LIBS is only 1.36 times of that of LIBS. The limit of detection of Cu I 324.75 nm line is reduced from 52.8 ppk to 319 ppm.

Keywords:

Laser-induced breakdown spectroscopy; Microwave plasma torch; Low laser energy detection

核能科学与工程 / **27**

基于 **RMC** 的接续面源功能开发验证

Authors: Yuanhao Gou[1]; Kan Wang[1]

[1] *Tsinghua University*

Corresponding Authors: wangkan@mail.tsinghua.edu.cn, gouyh23@mails.tsinghua.edu.cn

摘要:

在蒙卡模拟过程中，由于几何较大且复杂，在统计较远处位置信息时，会受到粒子数不够多而得不到足够精确结果的影响。一种可行的方法就是，采用接续面源。即在模拟时，记录穿过某个面或者某个栅元里面粒子的信息。然后在下一次计算当中，通过读取这些粒子径迹信息，即把这些信息作为源，然后通过对这些粒子进行分裂，偏倚等操作进行模拟，达到减少方差，得到较精确效果的手段。前在 MCNP 中有进行 MC-MC 耦合计算的功能，通过关键字 SSW(写面源卡) 记录穿过指定面的粒子信息，包括粒子能量，权重，位置，飞行方向等，然后形成了二进制文件 wssa, 提供给读面源 (SSR), 作为耦合接续计算的初始面源，然后可以对粒子进行分裂、偏倚等操作，达到减方差目的进而得到较为精确结果的手段。本研究基于清华大学工程物理系核能科学与工程管理所开发的堆用蒙特卡罗程序 RMC，实现了 RMC 中的接续面源功能。

关键词:

分段-衔接计算；面源记录；SSW/SSR；RMC

Abstract:

In the Monte Carlo simulation process, due to the large and complex geometry, when counting the information of distant positions, the number of particles is not enough and the results are not accurate enough. A feasible method is to use a continuous surface source. That is, during the simulation, record the information of particles passing through a certain surface or a certain grid element. Then in the next calculation, by reading these particle track information, that is, taking this information as the source, and then simulating these particles by splitting, biasing and other operations, the variance is reduced and a more accurate effect is obtained. There is a function for MC-MC coupling calculation in MCNP. The keyword SSW (write surface source card) is used to record the information of particles passing through the specified surface, including particle energy, weight, position, flight direction, etc., and then a binary file wssa is formed and provided to the read surface source (SSR) as the initial surface source for the coupled continuous calculation. Then the particles can be split, biased and other operations can be performed to reduce the variance and obtain more accurate results. This study is based on the reactor Monte Carlo program RMC (Wang et al., 2015) developed by the Institute of Nuclear Energy Science and Engineering Management, Department of Engineering Physics, Tsinghua University, and realizes the function of connecting surface sources in RMC.

Keywords:

Segment-connection calculation; surface source recording; SSW/SSR; RMC

核能科学与工程 / **9**

蒙卡程序 **RMC** 在聚变中子学中的应用研究

Author: 曾国禹[None]

Corresponding Author: zeng-gy23@mails.tsinghua.edu.cn

关键词:

RMC、蒙特卡洛、CFETR、聚变中子学

摘要:

本研究探讨了 Reactor Monte Carlo（RMC）代码在聚变中子学中的应用，并评估其在聚变反应堆分析中的关键能力。在模型适配方面面，为了满足现今大多以 MCNP 格式设计的聚变装置模型，能够转换成 RMC 格式，我们开发了 M2R 模型转换工具，并通过 CFETR 模型的转换验证了其准

确性。此外，本研究针对 CFETR 模型开展了全局中子通量分布计算，采用减密度方法生成权窗，并经过三次迭代获得完整的全局通量分布，验证了 RMC 在减方差和深穿透中子输运计算方面的可靠性。同时，为评估 RMC 的 CAD 几何输运能力，我们利用 Paramak 设计了一个半托卡马克模型，并分别在 RMC 和 OpenMC 中进行模拟，结果吻合良好。总体而言，本研究证明了 RMC 在复杂反应堆模型分析、深穿透中子输运计算及减方差方法应用方面的有效性和可靠性。

Abstract:

This study explores the application of the Reactor Monte Carlo (RMC) code in fusion neutronics and evaluates its key capabilities in fusion reactor analysis. In terms of model adaptation, to accommodate the prevalent use of MCNP-format models in fusion device design and enable their conversion to RMC format, we developed the M2R model conversion tool and validated its accuracy through the conversion of the CFETR model. Additionally, this study conducted global neutron flux distribution calculations for the CFETR model, employing a density reduction method for weight window generation. Through three iterations, a complete global flux distribution was obtained, verifying the reliability of RMC in variance reduction and deep-penetration neutron transport calculations. Furthermore, to assess RMC's CAD-based transport capabilities, we utilized Paramak to design a half-tokamak model and performed neutron transport simulations in both RMC and OpenMC, yielding consistent results. Overall, this study demonstrates the effectiveness and reliability of RMC in complex reactor model analysis, deep-penetration neutron transport calculations, and variance reduction applications.

Keywords:

RMC, Monte Carlo, CFETR, Fusion neutronics

核能科学与工程 / **15**

考虑接触角的两相格子玻尔兹曼模型：无界面速度滑移和非物理密度层

Author: Junren Hou[None]

Corresponding Author: hou_junren@163.com

摘要:

本文评估了各种作用力格式在运动条件下的适用性以及各种接触角格式的表现。研究发现，大多数作用力格式存在界面速度滑移问题，而其他格式则无法实现热力学一致性。此外，大多数接触角格式会在壁面附近产生非物理密度层，导致速度剖面出现显著偏差。为解决这些问题，本文提出了一种新型伪势模型，该模型结合了新的伪势力和改进的接触角格式。新的伪势力确保了热力学一致性，同时消除了界面速度滑移；改进的接触角格式有效去除了非物理密度层，并可在很大范围内灵活调整接触角。使用所提出的伪势模型模拟了方腔和圆管中的毛细提升现象。模拟结果与解析解吻合良好，准确捕捉了毛细提升的稳态和动态行为。这些结果体现了该模型在模拟毛细现象方面的巨大潜力。

关键词:

格子玻尔兹曼方法；两相流；接触角；毛细提升

Abstract:

The applicability of various force schemes under moving conditions is evaluated using two-phase Poiseuille flow simulations. Most force schemes are found to suffer from interfacial velocity slip, while others fail to achieve thermodynamic consistency. Additionally, the performance of various contact angle schemes is as-sessed. It is observed that most contact angle schemes produce unphysical density layers near the wall, lead-ing to significant errors in velocity profiles. To address these challenges, we propose a novel pseudopotential model incorporating a new pseudopotential force and an improved contact angle scheme. The new pseudopo-tential force ensures thermodynamic consistency while eliminating interfacial velocity slip. Furthermore, the improved contact angle scheme effectively removes the unphysical density layer and allows for flexible ad-justment of contact angles across a wide range. The proposed pseudopotential model is applied to simulate capillary rise in cavities and tubes. The simulation results show excellent agreement with analytical solutions, accurately capturing both the steady-state and dynamic behaviors of capillary rise. These findings highlight the significant potential of our model for

simulating capillary phenomena.

Keywords:

Lattice Boltzmann method, Two-phase flow, Contact angle, Capillary rise.

核能科学与工程 / **44**

基于 **CFD** 的球形燃料元件气力抽吸行为数值研究

Authors: 云梦穆[1]; 彬吴[1]

[1] 清华大学核研院

Corresponding Authors: wu-bin@tsinghua.edu.cn, mym21@mails.tsinghua.edu.cn

摘要:

球形燃料元件装入贮罐后，如需要从贮罐内取出，需要通过乏燃料气力输送子系统，用负压抽吸的方式，通过抽吸软管将元件从贮罐内抽吸取出，输送到下游的输球管道。本文采用计算流体力学（CFD）方法，针对球形元件在不同初始位置下的可抽吸性进行了数值模拟，界定了在最高抽吸流速（300 m3/h）条件下的有效抽吸区域，并分析了相应的流场特征。结果表明，球形元件在抽吸过程中所受的曳力与其位置密切相关。随着元件进入抽吸口，其受到非对称的流场作用，呈现向抽吸管轴线趋近的运动趋势，有利于后续稳定输送。在上升阶段，元件所受曳力虽存在小幅波动，但始终大于其重力，确保了持续的输送能力。总体而言，当球形元件位于 45° 斜角管嘴外约 15 mm 范围内时，可实现稳定抽吸。本研究结果不仅可为乏燃料输送系统的设计与优化提供参考，也可为其他领域中球形物体的气力抽吸问题提供理论支持。

关键词:

数值模拟；气力输送；抽吸；球形燃料元件

Abstract:

After spherical fuel elements are loaded into the storage tank, they must be extracted via the spent fuel pneumatic conveying subsystem when needed. This process relies on negative pressure suction, where the elements are drawn out of the tank through a suction hose and transported to the downstream conveying pipeline. In this study, computational fluid dynamics (CFD) simulations are conducted to investigate the suction feasibility of spherical elements positioned at various initial locations. The effective suction region under a maximum airflow rate of 300 m^3/h is identified, and the associated flow field characteristics are analyzed. The results indicate that the drag force acting on the spherical element during suction is closely related to its position. As the element approaches the suction inlet, it experiences an asymmetric flow field, resulting in a movement trend toward the central axis of the suction pipe, which facilitates subsequent stable transport. During the ascent, although the drag force exhibits slight fluctuations, it consistently exceeds the gravitational force of the element, ensuring continuous transport. Overall, stable suction can be achieved when the spherical element is located within approximately 15 mm outside the 45° inclined suction nozzle. These findings provide valuable guidance for the design and optimization of spent fuel conveying systems and offer theoretical support for pneumatic suction of spherical objects in other engineering applications.

Keywords:

Numerical simulation; Pneumatic conveying; Suction; Spherical fuel element

核能科学与工程 / **52**

颗粒床反应堆流动不稳定研究及缓解措施分析

Author: 友纯陈[1]

[1] 清华大学核研院

Corresponding Author: 1442186363@qq.com

摘要:

颗粒床反应堆（PBR）具有功率密度高和堆芯压降低的优点，在核热推进（NTP）中具有很大的应用潜力。PBR 中氢气的流动路径不固定，物性变化剧烈，容易导致流动不稳定，使反应堆温度更加不均匀，甚至干涸。考虑到 NTP 的安全性，有必要对流动不稳定性及其缓解措施进行详细分析。本文采用计算流体力学方法分析了简化的二维颗粒床多孔介质模型的流动不稳定性，并通过证明不稳定性的存在，验证了该模型的适用性。计算了稳定边界，并与经典的水堆两相不稳定进行了比较，总结了流动不稳定的特征。此外，在颗粒床入口加入冷孔板，分析了不同情况下界面反向导热对缓解能力的影响。

关键词:

颗粒床反应堆；流动不稳定性；缓解措施；反向导热

Abstract:

With the advantages of high-power density and low reactor pressure drop, Particle Bed Reactor (PBR) has great application potential in Nuclear Thermal Propulsion (NTP). Flow path in PBR is no fixed and the physical properties of hydrogen change dramatically, so it is easy to lead to flow instability, causing the reactor temperature more uneven and even dry up. Considering the safety of NTP, it is necessary to conduct a detailed analysis of flow instability and its mitigations. In this paper, computational fluid dynamics method is used to analyze the flow instability in the simplified two-dimensional porous media model of particle bed, whose applicability is verified by proving the existence of instability. The stability boundary is calculated and the characteristics of flow instability are summarized by comparing with classical two-phase instability in water reactor. Besides, a cold frit is added to the inlet of particle bed to analyze the influence of the interface back conduction on the mitigation at different cases.

Keywords:

Particle Bed Reactor; Flow Instability; Mitigation; Back conduction

核能科学与工程 / **55**

烧结作用对高温堆石墨粉尘重悬浮行为的影响

Author: 淑苗赵[1]

[1] 清华大学

Corresponding Author: zhaosm23@mails.tsinghua.edu.cn

摘要:

高温气冷堆的石墨粉尘重悬浮特性对其源项估计意义重大。颗粒的重悬浮行为与颗粒-颗粒和颗粒-壁面的相互作用密切相关。反应堆内高温高压的环境会促使已沉积的石墨颗粒发生烧结，显著影响颗粒与颗粒间及颗粒与壁面间的粘附力，但是这种效应在已有的研究中很少被考虑。忽视高温烧结历史的影响可能会导致高估事故中石墨粉尘的重悬浮率，也会影响重悬浮颗粒的特性。本文对沉积石墨颗粒经不同温度和时长烧结后的重悬浮特性进行了实验研究，并结合 Rock 'n' Roll（R 'n' R）重悬浮模型开展了理论分析。同时，用高速摄像机记录重悬浮过程。结果表明，与未烧结的颗粒相比，烧结颗粒在重悬浮时表现出更高的摩擦速度阈值，烧结温度和持续时间的增加会放大这种效应，尤其是对于较大的颗粒。烧结 9 小时后，摩擦速度明显增加（达约 80%）。通过调整等效表面能，新的重悬浮曲线仍可与 Rock'n'Roll 模型相匹配，等效表面能与烧结温度呈阿伦尼乌斯型关系。这项初步研究表明，纳入烧结效应可以显著降低高温堆气溶胶源项的估算值。

关键词:

高温气冷堆；石墨粉尘；烧结；重悬浮；R 'n' R 模型

Abstract:

The resuspension of deposited graphite particles in high-temperature gas-cooled reactors (HTGRs) under specific accident conditions has attracted considerable attention due to its critical connection with source terms. However, nearly all related studies have overlooked the effects of long-term high-temperature sintering after particle deposition, which could have a significant impact by changing the strength of particle-particle and particle-wall connections and lead to an overestimation of graphite dust resuspension in accident scenarios. In this work, we conduct an experimental study to quantitatively evaluate the effect of sintering on the resuspension behavior of graphite particles, and combined with the Rock 'n' Roll (R 'n' R) model for theoretical analysis. Meanwhile, the resuspension process is recorded with a high-speed camera. The results show that sintered particles exhibit a higher friction velocity threshold for resuspension compared to their un-sintered counterparts, with the effect amplified by increased sintering temperature and duration, particularly for larger particles. The friction velocity significantly increases (up to ~80%) after 9 h sintering. The new resuspension curve can still be fitted to Rock'n'Roll model by adjusting the effective surface energy which shows an Arrhenius-type dependence on the sintering temperature. This preliminary study suggests that incorporating the sintering effect could significantly lower the estimated aerosol source term for HTGRs.

Keywords:

High-temperature gas-cooled reactor; Graphite dust; Sintering; Resuspension; Rock 'n' Roll model

核能科学与工程 / **57**

基于张量操作和梯度下降的 **SIMPLE** 算法计算效率优化

Author: 烨冰张[None]

Co-author: 纹珲刘 [1]

[1] 清华大学核研院

Corresponding Authors: liu-wh24@mails.tsinghua.edu.cn, yb-zhang24@mails.tsinghua.edu.cn

摘要:

本研究针对传统 SIMPLE 算法压力修正过程计算效率低、稳定性受限的瓶颈问题，通过算法架构重构与数值方法创新，提出系统性优化方案。首先，采用张量操作替代传统的循环嵌套编程结构。在 51x51 网格和 0.3 压力松弛因子的测试算例中，计算时间从 265.5 秒显著降低至 80 秒，速度提升约 231%。其次，构建基于自动微分和动态松弛因子的智能梯度解析体系，实现不同网格位置的压力松弛因子自适应调整，减少迭代次数以实现加速计算。此外，考虑到直接求解压力修正值的效率瓶颈，采用梯度下降的优化方法替代传统的求解方式，进一步减少计算时间并提高求解精度。经标准算例验证，优化后的算法在维持高精度前提下，显著增强了复杂流动模拟的实时性与鲁棒性，为工程流体仿真提供了高效可靠的新范式。

关键词:

SIMPLE 算法；张量操作；自适应压力松弛；梯度下降

Abstract:

This study addresses the computational inefficiency and stability limitations of the traditional SIMPLE algorithm's pressure correction process through systematic optimization via algorithmic architecture reconstruction and numerical method innovation. The proposed solution involves three key strategies: Firstly, replacing traditional nested-loop programming structures with tensor operations. In a benchmark test case with a 51×51 grid and a pressure relaxation factor of 0.3, the computation time was dramatically reduced from 265.5 seconds to 80 seconds, achieving a speed improvement of approximately 231%. Secondly, an intelligent gradient analysis system was developed using automatic differentiation and dynamic relaxation factors, enabling adaptive adjustment of pressure relaxation factors across grid locations to reduce iteration counts and accelerate computations. Additionally, to overcome the efficiency bottleneck in direct pressure correction value solving, a gradient descent optimization

method was employed as an alternative to traditional solvers, further decreasing computational time while enhancing solution accuracy. Validated through standard benchmark cases, the optimized algorithm maintains high precision while significantly improving real-time performance and robustness in complex flow simulations, establishing an efficient and reliable new paradigm for engineering fluid dynamics applications.

Keywords:

SIMPLE Algorithm; Tensor Operations; Adaptive Pressure Relaxation; Gradient Descent

核能科学与工程 / **58**

圆管内组分热扩散对氦氙流动换热的影响研究

Author: 思钧单[1]

Co-authors: 俊孙 [1]; 玉良孙 [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的热扩散影响下的混合均匀性分布以及对流动换热的影响开展研究。结果表明在 Taylor 的工况下，热扩散对氦氙流动换热的影响并不明显。进一步分别针对不同加热段热流密度、入口混合均匀性，探究截面上氦氙分布变化以及对氦氙流动换热的影响。结果表明热流密度越高、加热段长度较短的情况下，热扩散对氦氙混合均匀性及流动换热带来的影响越大。

关键词:

氦氙混合气体；流动换热；组分输运；热扩散

Abstract:

Helium-xenon gas mixture is used as the coolant of space nuclear power plants. Under the influence of temperature gradient, thermal diffusion will lead to uneven mixture of helium-xenon. Current studies on helium-xenon flow and heat transfer regard helium-xenon as pure gas, without considering the problem of uneven mixing. However, the properties of helium and xenon are very different, and the non-uniform mixing may have a great influence on the characteristics of flow and heat transfer. In this paper, based on Taylor's experiment, the mixing uniformity distribution of helium-xenon and the flow and heat transfer characteristics in a circular tube under the influence of thermal diffusion are studied based on Fluent. The results show that the influence of thermal diffusion on helium-xenon flow heat transfer is not obvious in Taylor's working condition. Further, the variation of helium-xenon distribution and its influence on helium-xenon flow and heat transfer are investigated according to the different heat flux and inlet mixing uniformity respectively. The results show that the higher the heat flux and the shorter the length of the heating section, the greater the influence of thermal diffusion on the mixing uniformity and flow and heat transfer characteristics of helium-xenon gas mixture.

Keywords:

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

核能科学与工程 / **64**

HTR-PM 正常工况一回路典型核素化学形态和化学反应研究

Author: 静霓郭[1]

Co-author: 锋谢 [2]

[1] 北京市清华大学核能与新能源技术研究院

[2] 清华大学

Corresponding Authors: fxie@tsinghua.edu.cn, guojn21@mails.tsinghua.edu.cn

摘要:

核素的化学状态会极大地影响其在多组分和多相系统中的行为，包括吸附、解吸、沉积、扩散、迁移和化学反应。根据世界上第一个鹅卵石床模块化高温气冷堆示范电站（HTR-PM）的设计和运行参数，在热力学框架和新开发的二维投影相图下，研究了 HTR-PM 正常运行条件下一次回路中 14 种典型核素的化学状态和潜在反应。利用相关矩阵定量分析了影响化学态的因素，包括温度、压力和杂质元素（C、H、O 和 N）的数量。结果表明，温度对核素化学态的影响最大，而压力和 N 含量的影响可以忽略不计。在 C 和 O 对典型核素化学态的影响之间发现了一种镜像对称关系。这种对称性所导致的相界在很大程度上受到次要元素化合物的化学状态和含量的影响。该研究系统地提供了典型核素在 HTR-PM 一次回路中的化学状态和反应，对研究先进核能系统中裂变产物的行为具有重要意义。所开发的技术和方法也广泛适用于多组分和多相化学系统。

关键词:

HTR-PM 化学形态化学反应吉布斯自由能二维投影相图相关性分析

Abstract:

The chemical states of nuclides significantly affect their behaviors in multicomponent and multiphase systems, including adsorption, desorption, deposition, diffusion, migration, and chemical reactions. Based on the design and operating parameters of the world's first pebble-bed modular high-temperature gas-cooled reactor demonstration power plant (HTR-PM), the chemical states and potential reactions of 14 typical nuclides in the primary circuit under normal operating conditions of HTR-PM were investigated under a thermodynamic framework and a newly developed two-dimensional projected phase diagram. A correlation matrix was used to quantitatively analyze the factors influencing the chemical states, including the temperature, pressure, and amount of impurity elements (C, H, O, and N). The results showed that the temperature had the greatest effect on the chemical states of the nuclides, while the pressure and N content had negligible effects. A mirror-symmetry relationship was discovered between the effects of C and O on the chemical states of typical nuclides. The phase boundary caused by this symmetry was largely influenced by the chemical states and contents of the compounds of minor elements. This study systematically provides the chemical states and reactions for typical nuclides in the primary circuit of HTR-PM, which is of great significance for research into the behaviors of fission products in advanced nuclear energy systems. The developed technologies and methods are also widely applicable to multicomponent and multiphase chemical systems.

Keywords:

HTR-PM, Primary circuit, Chemical states and reactions, 2D projected phase diagram, Correlation analysis, Mirror symmetry relationship

核能科学与工程 / **67**

球床颗粒尺度接触导热的建模及运用

Author: Yiyang Luo[1]

[1] *Tsinghua University*

Corresponding Author: yiyangluo.thu@gmail.com

摘要:

本文基于热力比拟的思路提出了一种新型颗粒间接触导热热阻模型，通过假设热通量在接触表面上的分布类似于应力的分布，消除了传统热阻模型在接触边缘处温度奇异性的问题。该模型在基本堆积方式和实际堆积方式下与现有的理论公式和实验进行比较，验证了使用该热阻模型预测颗粒材料导热系数的可行性。将该热阻模型运用到热离散单元法中，分析了高温试验装置内卵石床的温度和有效导热系数分布。由热传导方式得到的平均有效导热系数在 20 kW 和 82 kW 功率输入时分别为 2.99 和 2.61 W/m·K。对于该空心圆柱构成的球床，当外壁温度从 200 ℃ 增加到 1000 ℃ 时，有效热扩散系数大约增加了 20%。

关键词:

热力比拟，接触热阻模型，热离散单元法，有效导热系数，有效热扩散率

Abstract:

This study introduces a novel particle-to-particle contact thermal resistance model, which is developed based on the concept of analogical correspondence between force dynamics and heat transfer phenomena. By presuming a likeness between the distribution of heat flux across the contact surface and the distribution of stress, the issue of temperature singularity at the contact edge is effectively mitigated. The proposed model undergoes rigorous validation against existing theoretical frameworks and experimental data, exhibiting commendable concurrence. Furthermore, the combined utilization of this model alongside the thermal discrete element method is employed to scrutinize the temperature profiles and effective thermal conductivity distributions within a pebble bed confined within a high-temperature test unit. The computed average effective thermal conductivity values, derived from thermal conduction analyses, stand at 2.99 W/m·K and 2.61 W/m·K for power inputs of 20 kW and 82 kW, respectively. Remarkably, a notable approximately 20% augmentation in effective thermal diffusivity is observed as the outer wall temperature ascends from 200 ℃ to 1000 ℃.

Keywords:

thermal analogy, contact thermal resistance model, thermal discrete element method, effective thermal conductivity, effective thermal diffusivity

核能科学与工程 / **68**

槽道内氦氙混合气体 **RANS** 模拟的计算模型适用性研究

Authors: 舜琦王[1]; 宇吉[1]; 俊孙[1]; 玉良孙[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:

小型气冷核反应堆系统多以氦氙混合气体为循环工质及堆芯冷却剂。在推荐混合比下，其普朗特数（Pr）可低至 0.2。雷诺时均模拟（RANS）方法依赖湍流模型与湍流普朗特数（Prt）模型，已有研究重点关注 Prt 模型对氦氙换热的影响，对湍流模型适用性的讨论还不深入。本文采用 RANS 方法研究槽道内氦氙气体流动换热，并与直接数值模拟（DNS）结果对比，依次开展湍流模型与 Prt 模型适用性研究，阐明湍流模型和 Prt 模型对 RANS 结果的影响。结果表明，SST k-ω 模型是槽道流的优选湍流模型，当前的 Prt 模型仍需改进才能更好满足氦氙的换热计算。建议针对氦氙流动换热的 RANS 分析中应同时考虑湍流模型和 Prt 模型的组合。

关键词:

雷诺时均模拟；DNS 标准数据；RANS 计算模型

Abstract:

Small gas-cooled nuclear reactor systems almost regard the helium-xenon mixture (He-Xe) as the cycling working fluid and reactor core coolant. With the recommended mixing ratio, the Prandtl number (Pr) of He-Xe is as low as 0.2. The RANS method is the main method on the CFD computation of nuclear engineering, which needs the turbulence model and Prt model. Previous studies have focused on the effect of Prt model on He-Xe heat transfer, but the applicability of turbulence model has not been deeply

discussed. In this paper, the RANS method is used to study the flow and heat transfer of He-Xe in a parallel channel, and the applicability of turbulence model and Prt model is studied in order to clarify the influence on the heat transfer simulation. The results show that the SST k-ω model is the preferred turbulence model for the channel flow, and existing Prt models still need to be improved to satisfy the heat transfer simulation of He-Xe. It is proposed that the combination of turbulence model and Prt model should be considered in RANS analysis of He-Xe flow and heat transfer.

Keywords:

Reynolds-Averaged Numerical Simulation; DNS standard Data; RANS Models

核能科学与工程 / **73**

基于栅格法的球床内流道六面体网格生成算法

Author: 赖桂桦[None]

Co-author: 王宏

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

摘要:

高温气冷堆是第四代先进核能系统的优选堆型，其中关于球床堆芯内部的流动与传热研究不仅是高温气冷堆技术攻关的重要难题, 也是学术研究的前沿热点。然而，球床堆芯中大量燃料元件的无序堆积形成了高度复杂的孔隙结构，这使得在计算流体力学（Computational Fluid Dynamics, CFD）模拟中难以生成高质量的网格。传统的四面体网格虽然能够较好地适应复杂的几何形状，但需要大量的网格单元，导致计算成本显著增加；而六面体网格不仅能够提供更高的数值精度，还能显著减少网格数量，从而降低计算资源消耗。目前，鲜有针对球床内流道的高质量六面体网格自动生成算法，因此，本研究旨在开发一种有效的全六面体网格生成算法，以解决任意堆积球床中的网格生成难题，为高精度 CFD 模拟提供可靠的技术支持。

本研究提出了一种系统性的网格生成算法，该方法通过多个关键步骤确保网格质量。首先基于栅格法在计算域内生成初始的六面体核心网格。在这一步骤中，根据节点与几何边界的空间位置关系，将网格单元分类为内部单元、外部单元和边界单元，并移除位于计算域外部的外部单元和边界单元。然后，根据网格面与几何的位置关系，将几何边界映射到网格面上。最后，根据映射关系将网格面投影到几何边界的位置，形成新的网格，以实现计算域与流道几何域的完全一致。

由于核心网格的解析度有限，无法完全反映球床内流道所有几何特征。因此需要提出一种网格重构算法，以修复由堆积球床中存在的大量狭缝结构导致的网格失真问题。本研究基于 Paving 的面网格生成算法，对于颗粒-颗粒接触采用对称切平面网格划分策略，对于颗粒-壁面接触则采用了非对称椭球面网格划分方法，成功重构了狭缝结构内部的网格。该方法有效解决了传统算法在接触区域容易产生低质量网格的问题。

为了进一步提升网格质量，本研究在核心网格与边界层网格间添加了过渡层网格。该技术通过计算相邻面法向量的加权和来确定每个边界节点的最优投影方向，同时根据节点到几何边界的最短距离动态调整投影长度，从而在几何边界处形成高质量的过渡层网格。

在网格优化方面，本研究采用了结合拉普拉斯平滑和基于雅可比矩阵优化的混合平滑算法。拉普拉斯平滑通过调整节点坐标来改善网格均匀性，而基于雅可比矩阵的优化则重点关注消除负体积单元，采用缩放雅可比（Scaled Jacobian）和形状度量（Shape Metric）等指标来评价优化过程。

通过系统的测试验证，本研究所提出的算法展现出较好的结果。在包含 25 种不同接触方向的测试案例中，生成的网格均未出现负体积单元，最差网格质量保持在 0.1 以上，平均网格质量均达到 0.85 以上。针对包含 10 个球体的实际应用案例，算法成功生成了约 60 万个高质量的六面体网格单元。与现有的 tet-to-hex 转换方法 [1,2] 相比，本算法在保持相同精度的前提下，将网格数量减少了约 30%，显著提高了计算效率。此外，算法还表现出良好的适应性，能够处理不同管径比和不同堆积密度的复杂情况。

本研究针对球床内流道开发了基于栅格法的六面体网格生成算法，结合核心网格与过渡层网格生成技术、接触处理策略和网格优化方法，成功解决了随机堆积球床中的网格生成难题。相比传统方法，该算法在网格质量、计算效率和适应性等方面都具有明显优势。实际测试表明，算法生成的网格可满足高精度 CFD 模拟的要求，为球床反应堆的热工水力分析提供了可靠的技术支持。未来研究将重点优化算法的并行计算性能，以适应更大规模的工程应用需求，同时将进一步发展自适应网格加密技术，以更好地捕捉边界层等关键流动特征。

关键词:

计算流体动力学；球床堆芯；六面体网格生成算法；网格优化算法；

Abstract:

无

Keywords:

无

核能科学与工程 / **72**

杭州湾区域氚的迁移扩散行为模拟

Author: 政哲屈[1]

Co-author: 锋谢 [2]

[1] 核研院

[2] 清华大学

Corresponding Authors: 1605896599@qq.com, fxie@tsinghua.edu.cn

摘要:

杭州湾是世界知名的潮汐河口，一直是研究热点区域。本研究以秦山核电站为研究对象，采用二维数值模拟方法，研究放射性核素在水环境中的迁移行为。基于 MIKE 模型，构建了杭州湾二维水动力模型，用以模拟受纳水体的流场及在不同时间假设事故情景下氚的迁移过程。本文评估了在不同季节潮汐作用下，杭州湾中放射性核素的分布特征。研究结果表明，所模拟的流场在很大程度上能够反映杭州湾区域的实际情况对于不同排放速率的事故情景，氚的浓度场呈现出相似的分布模式，但峰值浓度存在显著差异。同时，潮汐作用将放射性核素带往外海，能够降低厂址附近的氚浓度。

关键词:

氚，核素迁移，释放速率，数值模拟

Abstract:

Hangzhou Bay is a world-renowned tidal estuary and has long been a hot topic of research. This study focuses on the Qinshan Nuclear Power Plant and adopts a 2D numerical simulation approach to investigate the transport behavior of radionuclides in the aquatic environment. Based on the MIKE model, a two-dimensional hydrodynamic model of Hangzhou Bay was constructed to simulate the flow field of the receiving water body and the transport of tritium under hypothetical accident scenarios at different times. This paper assesses the distribution characteristics of radionuclides in Hangzhou Bay under the influence of tidal forces in different seasons. The results show that the simulated flow field largely reflects the actual conditions in the Hangzhou Bay area. For accident scenarios with different release rates, the concentration fields of tritium exhibit similar distribution patterns, but there are significant differences in peak concentrations. At the same time, tidal forces carry radionuclides to the open sea, which can reduce the tritium concentration near the plant site.

Keywords:

Tritium, Radionuclide transport, Release rate, Numerical simulation

核能科学与工程 / **95**

局部高空泡板型燃料压水堆高保真核热耦合计算方法

Authors: 国栋刘[1]; 颖何[1]; 郡任侯[1]; 善仿黄[1]; 侃王[1]

[1] 清华大学工物系

Corresponding Authors: wangkan@mail.tsinghua.edu.cn, he-y22@mails.tsinghua.edu.cn, lgd18@mails.tsinghua.edu.cn, hou_junren@163.com, sfhuang@mail.tsinghua.edu.cn

摘要:

由于具有高传热效率与高功率密度，板式燃料元件已在研究堆和特殊应用领域获得广泛应用。随着对更高反应堆堆芯功率密度的追求不断推进，即便在压水堆中，也会出现局部高空泡现象。此时，堆芯内部存在紧密耦合的多物理过程，如中子学与两相流热工水力等。仅使用中子学或热工水力单独计算，难以得到最准确的评价结果。然而，目前尚无可同时考虑上述复杂耦合机制的反应堆堆芯耦合计算程序，这限制了板式燃料元件进一步提升功率密度。为了解决这一问题，本论文基于蒙卡程序 RMC 和商业 CFD 软件 ANSYS Fluent，建立了适用于高功率密度 PWR 堆芯且考虑局部高空泡份额的精细化稳态核热耦合计算方法。本文选取由中国核动力研究设计院提出的 COPHP（Coupling calculation Of plate-type PWR based on High Parameters）基准题，分析了所提出耦合计算方法的数值收敛特性，结果显示耦合计算在单相与两相工况下均在五步迭代内收敛。对从 0% 到 100% 满功率的 6 种不同功率水平进行了计算与分析。结果表明，在满功率工况（HFP）下，流道内最大出口汽泡份额可达 0.48，远高于传统压水堆。在功率水平变化的过程中，堆芯经历从单相工况到两相工况的转变。在 HFP 条件下，包壳表面的最大局部热流密度高达 918.49 kW/m²，为堆芯平均热流密度的 2.33 倍。本文提出的耦合计算方法对高功率密度板式 PWR 的堆芯设计与安全分析具有指导意义。

关键词:

高功率密度压水堆；局部高空泡；蒙卡；两相流；核热耦合

Abstract:

Due to the high heat transfer efficiency and power density, plate-type fuel elements have been widely applied in research reactors and special application scenarios. As the pursuit of higher reactor core power density continues, even in PWR, high local void fraction phenomena will occur. At this point, there is a tight multi-physics coupling within the reactor core, such as neutronics and two-phase flow thermohydraulics, making it impossible to obtain the most accurate evaluation results with standalone neutronic or thermohydraulic calculations. However, currently, no reactor coupling calculation code considers the complex coupling mechanisms mentioned above. Thus, this limits the further increase in power density of plate-type reactors. To address this issue, this paper establishes a refined steady-state Neutronic-Thermohydraulic (N-TH) coupling calculation method suitable for the core of high-power density PWRs based on the RMC and the commercial CFD software ANSYS Fluent. Coupling calculation Of plate-type PWR based on High Parameters (COPHP) problem pro-posed by Nuclear Power Institute of China (NPIC) is selected to show the numerical convergence characteristics of the coupling calculation method. It achieves convergence within five iterations under both single-phase and two-phase operating conditions. Calculations and analyses were carried out for 6 different power levels ranging from 0% to 100%. The results show that under the Hot Full Power (HFP) condition, the maximum outlet void fraction in sub-channels reached 0.48, significant-ly higher than that of traditional PWRs. As the power level changes, there is a transition from single-phase operating mode to two-phase operating mode. Under HFP condition, the maximum local heat flux on the cladding surface reached 918.49 kW/m2, which is 2.33 times that of the average heat flux of the core. The coupled calculation code developed in this paper has guiding significance for the design and safety analysis of high-power density plate-type PWRs.

Keywords:

High-power density reactor; High local void fraction; Monte Carlo; Two-phase flow; N-TH coupling calculation

核能科学与工程 / **47**

玻璃金属封接中冷却诱发应力的起源及演变

Authors: Keqian Gong[None]; Yong Zhang[None]; Zifeng Song[1]

[1] 清华大学核研院

Corresponding Author: szf23@mails.tsinghua.edu.cn

摘要:

玻璃-金属（GTM）密封中的残余应力是决定其机械性能的关键因素。本研究主要关注冷却诱导应力的形成和演化。K 型热电偶和光纤布拉格光栅（FBG）传感器用于获取 GTM 密封在冷却过程中的原位温度和应力数据。同时，还建立了该过程的热力耦合有限元分析（FEA）模型。研究发现，玻璃的内部温度分布呈"水煮蛋"形状。这是由于导热系数低，导致中心出现延时效应。分析其应力形成曲线，当温度降至 200℃ 以下时，观察到应力反弹，这在有限元分析中已被证实是由热膨胀系数（CTE）的差异决定的。冷却速率直接决定了应力形成速率。本研究加深了对 GTM 密封件冷却过程中应力形成和演变的理解，并强调了不同冷却速率对应力形成的影响。它为优化工艺和定制应力分布提供了理论指导。

关键词:

玻璃-金属封接；应力分布；有限元分析

Abstract:

The residual stress in the Glass-to-Metal (GTM) seal is a key factor determining its mechanical performance. This study focuses on the cooling-induced stress formation and evolution. K-type thermocouples and fiber Bragg grating (FBG) sensors were used to obtain the in situ temperature and stress data of the GTM seal during the cooling process. At the same time, a thermo-mechanical coupling finite element analysis (FEA) model for this process has also been established. It was found that the internal temperature distribution of the glass exhibits a "soft-boiled egg" shape. This is due to the low thermal conductivity, which causes a time-delay effect at the center. Analyzing its stress formation curve, stress rebound was observed when the temperature dropped below 200℃, which has been confirmed in the FEA to be determined by the difference in thermal expansion coefficients (CTE)s. The cooling rate directly determines the rate of stress formation. This study enhances the understanding of the stress formation and evolution during the cooling process of GTM seals and emphasizes the impact of different cooling rates on stress formation. It provides theoretical guidance for optimizing the process and tailoring stress distribution.

Keywords:

Glass-to-metal seal; stress distribution; finite element analysis

核能科学与工程 / **110**

高温气冷堆反应堆压力容器在几种典型瞬态条件下的概率断裂力学分析

Authors: 李博文[1]; 王海涛[1]; 彭恒[1]

[1] 核能与新能源技术研究院

Corresponding Author: bw-li21@mails.tsinghua.edu.cn

摘要:

概率断裂力学（PFM）在轻水堆压力容器结构完整性评价中的应用越来越广泛。对于高温气冷堆（HTGR）来说，其压力容器的工作负荷在温度、压力、瞬态和快中子通量等方面都与轻水堆不同。此外，与压力容器相关的安全要求也存在差异。本文对 290MW 球床模块式高温堆的压力容器进行了几种典型瞬态工况下的概率断裂力学分析。为了模拟不同 ASME 规范下压力容器的制造条件，假设不同制造质量水平的压力容器具有不同的沿壁厚的缺陷分布。此外，还研究了压力容器中不同类型和不同区域的缺陷对条件启裂概率（CPI）和条件失效概率（CPF）的贡献。计算结果表明，即使在缺陷尺寸的保守假设下，由于快中子通量水平低和瞬态发展缓慢，高温气冷堆压力容器的失效概率也非常低。

关键词:

高温气冷堆；反应堆压力容器；概率断裂力学

Abstract:

Probabilistic fracture mechanics (PFM) has been increasingly used in the structural integrity evaluation of reactor pressure vessels (RPVs) in light water reactors (LWRs). For high temperature gas-cooled reactor (HTGR), the working load of its RPV is different from that of LWR in terms of temperature, pressure, transient and fast neutron fluence. In addition, there are differences in the safety requirements associated with RPV. In this paper, PFM analysis of RPV of a 290MWth pebble-bed modular HTGR under several typical transient conditions is carried out. To simulate the manufacturing conditions of RPVs under different ASME rules, it is assumed that the flaw information of RPV along the wall thickness has different levels of manufacturing quality. In addition, the contribution of different types and regions of flaws in RPV to the conditional probability of initiation (CPI) and the conditional probability of failure (CPF) is investigated. Numerical results indicate that due to the low level of fast neutron fluence and slow transient development, the CPF of the RPV of HTGR is extremely low even under conservative assumptions of flaw size.

Keywords:

High temperature gas-cooled reactor; Reactor pressure vessel; Probabilistic fracture mechanics

核能科学与工程 / **82**

环境温度和压力容器温度对 **HTR-PM** 反应堆舱室冷却系统运行性能的影响研究

Author: 新生徐[1]

Co-authors: 毅杨叶 [1]; 艳华郑 [1]

[1] 北京市海淀区清华大学核能与新能源技术研究院

Corresponding Author: xuxs22@mails.tsinghua.edu.cn

摘要:

高温气冷堆（HTGR）是第四代先进核反应堆，可以实现固有安全，防止堆芯熔化事故的发生。清华大学核与新能源技术研究所（INET）开发了一个商业规模的 200 MWe 模块式高温气冷堆，该项目于 2023 年 12 月 6 日投入商业运行。非能动反应堆舱室冷却系统（RCCS）专为 HTR-PM 设计，在正常运行和事故条件下从反应堆腔中输出热量，保持反应堆压力容器（RPV）和反应堆舱室的安全。HTR-PM 的 RCCS 被设计为三套独立的机组，两套 RCCS 工作可以保证 RRV 和反应堆舱室活动的安全。舱室中热辐射和自然对流产生的热量可以通过水和空气的自然循环传递到大气中。CAVCO 代码由 INET 开发，用于模拟 RCCS 的行为。本文分析了不同的 RPV 温度和不同的环境温度，以及 RCCS 系统全部或部分工作对系统运行特性的影响，CAVCO 对 RCCS 的性能进行了研究，以评估其运行可靠性，为进一步优化提供参考。分析结果表明，即使在可想象的极高 RPV 温度下，两套 RCCS 也可以有效导出堆芯热量，而不会导致水沸腾或系统故障。然而，在冬季环境温度较低的情况下，特别是当反应堆在较低的 RPV 温度下运行时，需要更加注意系统的运行安全。需要避免循环水冻结和水冷管冻裂造成的系统故障。根据压力容器和环境温度的不同，在较冷天气下为了防止管道冻结，3 套 RCCS 系统中的部分或全部需要退出运行。此外，只有两套 RCCS 正常工作的系统最大载热能力超过了 1.2MW 的设计要求。当环境温度急剧变化时，可以考虑增加 RCCS 机组的数量，以避免冷却水温度急剧变化对管道热应力的影响。

关键词:

高温气冷堆、舱室冷却系统、CAVCO、安全

Abstract:

High Temperature Gas-cooled Reactor (HTGR) is the Generation IV advanced nuclear reactor, which can realize inherent safety and prevent the occurrence of core melting accidents. Institute of Nuclear and New Energy Technology (INET) of Tsinghua University has developed a commercial scale 200 MWe High Temperature gas-cooled Reactor Pebble bed Module project (HTR-PM), which entered commercial operation on December 6, 2023. A passive Reactor Cavity Cooling System (RCCS) is designed for HTR-PM to export heat from the reactor cavity in normal operation and also in accident condition, keeping the safety of the reactor pressure vessel (RPV) and reactor cavity. RCCS of HTR-PM has been designed

as three independent sets, two sets of RCCS work can guarantee the safety of the PRV and reactor activity. The heat from the RPV through thermal radiation and natural convection can be transmitted to the final heat sink, atmosphere, through the natural circulation of water and air. The CAVCO code has been developed by INET to simulate the behavior of RCCS. In this paper, assuming different RPV temperatures and different ambient temperatures, as well assuming all or parts of the RCCS sets work, the performances of RCCS are studied by CAVCO to evaluate its operational reliability, so as to provide reference for further optimization. The analysis results indicate that even at conceivable extremely high RPV temperatures, two sets of RCCS could effectively carry out the heat, without resulting in the boiling of the water or failure of the system. However, in the case of low ambient temperatures in winter, especially when reactor operates at lower RPV temperature, more attention needs to be paid to the operation safety of the system. System failure caused by freezing of the circulating water and freezing crack of the water-cooling pipe need to be avoided. Parts or all of the 3 sets need to be quit operation depending on the reactor status and environmental conditions. Besides, the maximum heat carrying capacity of the RCCS with only two sets working exceeds the design requirement of 1.2MW. When the ambient temperature changes dramatically, it can be considered to increase the number of RCCS sets to avoid the impact of drastic changes in cooling water temperature on pipeline thermal stress.

Keywords:

HTGR, reactor cavity cooling system (RCCS), CAVCO, safety

核能科学与工程 / **88**

共振计算的子群法与广义 **Stamm'ler** 方法的对比研究

Author: 叶凡侯[1]

[1] 清华大学

Corresponding Author: hou-yf21@mails.tsinghua.edu.cn

摘要:

子群法和广义 Stamm'ler 方法是两种经典的共振自屏计算方法，已被广泛用于共振处理，显示出很好的计算精度与几何处理能力。最近，基于高温气冷堆栅格物理程序 XPZ，开发了两种方法，用于双重非均匀性系统的共振处理。本文通过理论与数值分析表明，两种方法在单共振区系统以及考虑分布式自屏效应的多共振区系统中是等价的，在双重非均匀性系统中仍然有效。基于高温气冷堆燃料颗粒与燃料球的数值验证表明两种方法计算有效多群截面与有效增殖因子的一致性，进一步证明了理论结论。

关键词:

共振自屏计算；子群法；广义 Stamm'ler 方法

Abstract:

The subgroup method and the generalized Stamm'ler method are two classical methods for resonance self-shielding calculation, which have been used in resonant self-shielding calculation and shown good accuracy and geometric adaptability. Recently, the two methods have been implemented in XPZ code for resonance treatment with double heterogeneous geometry in high temperature gas cooled reactors (HTGRs). This paper presents a comparison study on the two methods in both theoretical and numerical analyses. It is found that the two methods have equivalent accuracy in case of single resonance region or distributed multi-resonance region, regardless of double heterogeneous system. Numerical results are presented for HTGR fuel particle and element, which demonstrate the consistency of the two methods in effective multi-group cross sections and multiplication factors

Keywords:

resonance self-shielding;subgroup method;generalized Stamm'ler method

核能科学与工程 / **92**

基于 **SABCM** 转捩模型的管内圆球绕流数值模拟

Author: 马安祥[1]

Co-authors: 穆云梦 [1]; 吴彬 [1]

[1] 核能与新能源技术研究院

Corresponding Authors: maax24@mails.tsinghua.edu.cn, wu-bin@tsinghua.edu.cn, mym21@mails.tsinghua.edu.cn

摘要:

高温气冷堆采用气力输送实现不停堆换料。然而输送过程中气流雷诺数很高，若要进一步提高输送效率，可能面临阻力危机现象。气力输运过程可看做圆管内圆球绕流流动，存在边界层分离和漩涡脱落等复杂特征。当圆球直径与管内直径之比（阻塞比）较大时，管壁会影响圆球绕流流动。目前很少有针对大阻塞比下管内圆球绕流阻力危机的数值模拟研究。本文基于 OpenFOAM 植入 Spalart-Allmaras BCM 转捩模型（SABCM 转捩模型），采用零压力梯度平板算例验证植入代码的正确性，选取四种湍流模型模拟管内圆球绕流流动模拟。数值结果表明：在所选模型中，SABCM 转捩模型的预测结果与实验值吻合最好，且所需的计算资源最少。因此，可考虑将 SABCM 转捩模型用于研究阻力危机现象。

关键词:

圆球绕流、阻力危机、转捩模型

Abstract:

In High-Temperature Gas-Cooled Reactors (HTGRs), pneumatic conveying is used to achieve continuous refueling without shutdown. However, the conveying process operates at high Reynolds number, further efficiency enhancement may induce drag crisis. The pneumatic conveying process can be modeled as the flow past a sphere in a pipe, exhibiting complex flow features such as boundary layer separation and vortex shedding. When the ratio of the sphere diameter to the pipe diameter (blockage ratio) is large, the pipe wall will significantly influence the flow past a sphere. Currently, there are few numerical simulation studies on the drag crisis of flow past a sphere in a pipe under high blockage ratios. In this study, the Spalart-Allmaras BCM transition model (SABCM transition model) is implemented in OpenFOAM. The validation of SABCM transition model code is performed using two zero-pressure-gradient flat plate cases. Four turbulence models are selected to simulate the flow past a sphere in a pipe. Among the four turbulence models, the simulation results of SABCM transition model agree best with the experimental data while requiring the least computational resources. Therefore, the SABCM transition model is capable to predict the drag crisis phenomenon.

Keywords:

flow past a sphere, drag crisis, transition model

核能科学与工程 / **131**

高通量反应堆中锎**-252** 辐照生产特性初步研究

Author: 博亦于[1]

[1] 核研院

Corresponding Author: 2385489965@qq.com

摘要:

锎-252（^{252}Cf）是一种强大的自发裂变中子源，具有体积小、强度高、连续释放裂变中子及低热释放的特点。作为重要的放射性同位素，^{252}Cf 广泛应用于反应堆启动中子源及瞬发 γ-中子探测中。^{252}Cf 的制备途径包括反应堆辐照、加速器法以及地下热核爆炸，其中高通量反应堆辐照是实

现大规模生产最重要且最有效的方法。本研究采用详细的燃耗分析程序与蒙特卡罗模拟相结合的方法，对 ^{252}Cf 的生产过程进行评估，分析在不同中子通量水平和能谱条件下典型靶核材料的产量和效率差异，探讨了不同靶核素的转化特性，并提出适用于高通量反应堆的 ^{252}Cf 优化辐照方案。研究进一步分析了反应堆中 ^{252}Cf 生产的主要损耗链及关键中间核素。结果表明，辐照通道中的中子能谱对 ^{252}Cf 的产量有显著影响，其中（n, γ）反应是限制生产效率的主要因素。通过优化能谱以增强瓶颈核素的（n, γ）反应截面，有望显著提升 ^{252}Cf 的生产能力。本研究也为高通量反应堆中 ^{252}Cf 生产过程中的辐照方案、靶结构设计及靶材布置优化提供了理论基础。

关键词:

高通量堆；锎-252；辐照生产；转换特性

Abstract:

252Cf is a powerful spontaneous fission neutron source, characterized by its compact size, high intensity, continuous neutron fission, and low heat emission. It is an important radioisotope, used as a neutron source for the reactor startup and prompt γ-neutron detection. Possible pathways for preparation of 252Cf include reactor irradiation, accelerators, or underground thermonuclear explosions, with high flux reactor irradiation being the most important and effective approach for large-scale production. This paper employs a detailed burnup analysis program coupled with Monte Carlo simulations to evaluate the 252Cf production process, analyzing differences in production yield and efficiency under various neutron flux levels and energy spectra for typical target nuclei. The conversion characteristics of different target nuclei are discussed, and optimized irradiation schemes for 252Cf production in high flux reactors are proposed. This study examines the primary depletion chain in the reactor-based production of 252Cf and analyzes main intermediate nuclides. The findings reveal that the neutron spectrum in the irradiation channel significantly influences 252Cf yield, with the (n, γ) reaction being the primary factor affecting production efficiency. Enhancing the (n, γ) reaction cross-section of bottleneck nuclides through energy spectrum optimization can significantly improve productivity. This research also lays the foundation for optimizing irradiation schemes, target structures, and target arrangements in high flux reactors for 252Cf production.

Keywords:

252Cf, High flux reactor, Irradiation production, Conversion characteristics.

核能科学与工程 / **106**

基于 **Newton-Krylov** 方法联立求解核能供热的碘硫循环制氢系统

Authors: Xinru Peng[None]; 富李[None]; 汉张[None]

Corresponding Author: pxr22@mails.tsinghua.edu.cn

摘要:

高温气冷堆（HTR）是先进的第四代核电堆型之一，利用高温堆产生的高温氦气，通过热化学循环来生产氢气，被认为是能充分发挥高温气冷堆特性优势的下一步研究方向，其中碘硫（IS）循环被认为是能实现工业大规模制氢的先进工艺之一。传统方法或者程序在求解高温堆制氢耦合系统时，往往采用 Picard 迭代，将各个子系统甚至子物理场解耦并分别求解，再传递边界条件进行耦合，该方法只有线性收敛率并且稳定性较差。采用 Newton-Krylov（NK）方法直接联立求解这样的非线性耦合系统具有计算效率和稳定性的优势。本研究运用 NK 方法求解了基于清华大学 INET 制氢流程的简化 IS 循环制氢回路系统，分别求得了稳态下系统内部的物质组成分布，和堆芯出口氦气参数变化引起的制氢回路的动态响应过程，及其对堆芯的温度影响，相关计算结果对于进一步研究高温气冷堆氢电热联供系统的全耦合联立求解具有借鉴意义。

关键词:

高温气冷堆；碘硫循环；核能制氢；Newton-Krylov 方法

Abstract:

High-temperature gas-cooled reactor (HTR) is one of the advanced fourth-generation nuclear power reactor types. Using the high-temperature helium generated from HTR to produce hydrogen through ther-

mochemical cycles is considered to be the next research direction that can fully utilize the advantages of the characteristics of high-temperature gas-cooled reactors. The iodine-sulfur (IS) cycle is considered to be one of the advanced processes that can realize industrial large-scale hydrogen production. The traditional method or program for solving the high-temperature reactor hydrogen production coupled system often adopts Picard iteration, decoupling each subsystem or sub-physical field and solving them separately, and then transferring the boundary conditions for coupling, which has only linear convergence rate and poor stability. Using the Newton-Krylov (NK) method to directly solve such nonlinear coupled systems has the advantages of computational efficiency and stability. In this study, a simplified IS cycle hydrogen loop system based on the INET hydrogen production process at Tsinghua University is solved by the NK method. The composition distribution of the system in the steady state and the dynamic response of the hydrogen loop due to the change of the helium parameter at the core outlet are obtained, as well as its effect on the temperature of the core. The numerical results of the calculations are of great significance for the further study of the fully coupled solution of the hydrogen-electricity-heat supply system of high-temperature gas-cooled reactor.

Keywords:

High-temperature gas-cooled reactors; Iodine-sulfur cycle; Nuclear energy for Hydrogen production; Newton-Krylov method

海报展示 / **5**

Projection Embedded Schrödinger Bridge for CT Sparse View Reconstruction

Authors: Li Zhang[1]; Yuang Wang[1]; Zhiqiang Chen[1]

[1] 清华大学工程物理系

Corresponding Authors: wangya22@mails.tsinghua.edu.cn, zli@mail.tsinghua.edu.cn, czq@mail.tsinghua.edu.cn

摘要:

在这项工作中，我们提出了投影嵌入薛定谔桥（Projection Embedded Schrödinger Bridge, PESB）用于 CT 稀疏视图重建。PESB 在滤波反投影（Filtered Back-Projection, FBP）重建图像的分布与基于测量投影的干净图像分布之间构建了薛定谔桥。通过将投影嵌入到边际条件中，数据一致性被自然地整合到生成过程中。实验结果验证了 PESB 的有效性，证明了其在 CT 稀疏视图重建中优于多种基于扩散模型的性能。

关键词:

CT 稀疏角重建，扩散模型，薛定谔桥

Abstract:

In this work, we proposed the Projection Embedded Schrödinger Bridge (PESB) for CT sparse view reconstruction. PESB constructs Schrödinger Bridges between the distribution of Filtered Back-Projection (FBP) reconstructed images and the distribution of clean images conditioned on measured projections. By embedding projections into the marginal conditions, data consistency is inherently incorporated into the generative process. Experimental results validate the effectiveness of PESB, demonstrating its superior performance in CT sparse view reconstruction compared to several diffusion-based models.

Keywords:

CT sparse view reconstruction, diffusion model, schrodinger bridge

海报展示 / **6**

基于高纯锗探测器的反应堆中微子 **CEνNS** 探测实验

Author: 梁艺帆[1]

[1] 清华大学

Corresponding Author: liangyf20@mails.tsinghua.edu.cn

摘要:

中微子-原子核相干弹性散射 (CEνNS) 是标准模型中一种基本的中微子-物质相互作用。在该相互作用中，原子核作为一个整体与中微子发生弹性散射。CEνNS 探测实验将帮助研究人员检验标准模型和研究超越标准模型的新物理。CEνNS 探测还可能成为实时监测反应堆功率和探测太阳与超新星中微子的新方法。此外，CEνNS 将会成为下一代暗物质直接探测实验的重要本底来源。因此，CEνNS 探测已成为近年来中微子物理领域的一个重要前沿课题，国际上有大量的 CEνNS 探测实验正在运行或建设中。但是，CEνNS 极低的截面对 CEνNS 探测器的阈值和本底提出了极高的要求。中国的 CDEX-RECODE 实验是一个基于高纯锗探测器的反应堆中微子 CEνNS 探测实验，实验将在中国浙江三门核电站进行。CDEX-RECODE 实验预计将拥有大约 160eVee (1keVnr) 的能量阈值、小于 2cpkkd 的低能区本底和极好的长时间稳定性，在同类型实验中拥有较大的优势。本文对 CDEX-RECODE 实验进行了介绍，并对该实验的未来进行了展望。

关键词:

中微子-原子核相干弹性散射；反应堆中微子；CDEX-RECODE 实验；高纯锗探测器

Abstract:

Coherent elastic neutrino-nucleus scattering (CEνNS) is a fundamental neutrino-matter interaction predicted by the Standard Model, in which neutrinos elastically scatter off entire atomic nuclei. Detection of CEνNS not only enables researchers to verify the Standard Model but also provides opportunities to explore physics beyond it. Furthermore, CEνNS measurements could potentially offer new approaches for real-time reactor monitoring and detection of solar and supernova neutrinos. CEνNS will also emerge as a significant background source for next-generation dark matter direct detection experiments. Given its importance, CEνNS detection has become a frontier topic in neutrino physics, with numerous detection experiments currently operating or under development worldwide. However, the extremely low cross section of CEνNS poses significant challenges for detector threshold and background requirements. The CDEX RECODE experiment, a reactor neutrino CEνNS detection experiment utilizing high purity germanium detectors, is scheduled to operate at the Sanmen Nuclear Power Plant in Zhejiang, China. With its projected energy threshold of approximately 160 eVee (1 keVnr), the low-energy background of less than 2 cpkkd, and exceptional long-term stability, CDEX-RECODE holds significant advantages among similar experiments. This paper introduces the CDEX-RECODE experiment and discusses the future prospects of this experiment.

Keywords:

coherent elastic neutrino-nucleus scattering; reactor neutrinos; CDEX-RECODE experiment; high purity germanium detector

海报展示 / **8**

基于大语言模型的动态高精度场景驱动人因可靠性数据采集方法研究

Authors: 海涛王[None]; 金刚梁[None]; 倩倩贾[None]; 节娟童[None]; 星宇萧[1]

[1] 清华大学

Corresponding Author: xxy23@mails.tsinghua.edu.cn

Abstract:

Human reliability data is critical for advancing reliability analysis methodologies. However, existing data collection methods lack dynamic features and suffer from coarse granularity, with a heavy reliance on expert knowledge, making the process time-consuming and labor-intensive. To address these challenges, this paper proposes a scenario-driven, automated human reliability data collection paradigm based on large language models (LLMs). Our approach focuses on the workload indicators behind human errors. First, we collected operator workload data in a high-temperature gas-cooled reactor (HTGR) control room environment, using the NASA-TLX questionnaire under different scenarios. Subsequently, we fine-tuned the large language model Qwen-7B based on the collected real-world data. Experimental results demonstrate that the proposed method can simulate the cognitive workload of operators in real-time within the explored scenarios. Compared to traditional HUNTER methods, our approach offers significant advantages and outperforms existing commercial large language models in prediction accuracy, providing more accurate, flexible, and scalable workload estimates.

Keywords:

Automated Human Reliability Data Collection; Large Language Models; Dynamic Load Prediction; High-Temperature Gas-Cooled Reactor (HTGR)

摘要:

人因数据对于推进可靠性分析方法具有重要意义。然而，现有的数据收集方法缺乏动态特征，且颗粒度较粗糙，大量依赖专家知识，过程费时费力。为了解决这些挑战，本文提出了一种基于大语言模型的场景驱动的自动化人因可靠性数据收集研究范式。我们的方法聚焦于人因失误背后的工作负荷指标，首先，我们基于 NASA-TLX 问卷，在高温气冷堆 1：1 主控室环境收集了操作员在不同场景下的工作负荷。接着，基于所收集的真实数据微调大语言模型 qwen-7B。实验结果表明，所提出的方法能够实时模拟在探讨场景下的操作员的认知负荷，相比于传统的 HUNTER 方法具有使用优势，且预测精度优于现有的商业大语言模型，能够提供更加准确、灵活和可扩展的工作负荷估计。

关键词:

人因可靠性数据自动收集；大语言模型；动态负荷预测；高温气冷堆

海报展示 / **12**

基于 **M** 型电极的离子引出过程二维粒子模拟研究

Authors: 梦龙张[1]; 晟鲁[1]; 耀庭汪[1]; 鑫礼孙[1]; 岚月罗[1]; 和平李[1]; 东君姜[1]; 明胜周[1]

[1] 清华大学工程物理系

Corresponding Author: zml23@mails.tsinghua.edu.cn

摘要:

改进电极结构是提高原子蒸气激光同位素分离离子引出效率的有效手段。本研究基于一维平行板电极离子引出过程解析模型，采用二维粒子模拟软件（EDIPIC-2D），对 M 型电极结构下的离子引出过程进行了理论分析和数值模拟。在此基础上，研究了不同引出区结构参数对离子引出特性的影响规律。
一方面，在 M 型电极结构下，数值模拟结果观察到了电子振荡、朗缪尔鞘层的形成与扩张、离子稀疏波的传播等过程。但与一维平行板电极不同的是，M 型电极下的离子稀疏波会在两个方向上产生并传播，二者共同对等离子体主体区的离子密度产生影响。另一方面，在保持其他参数不变的条件下，当阳极插入深度和宽度足够大时，等离子体主体区及附近区域的电势会达到与阳极相近的水平，该区域被称为虚拟阳极；阳极插入深度和宽度的增大均会导致等离子体主体区电势的上升和引出时间的缩短；等离子体边界和阴极间距离对引出时间没有明显的影响。
上述研究工作对于实际应用中离子引出装置结构参数的选择具有一定的理论指导意义。

关键词:

原子蒸气激光同位素分离（AVLIS）；离子引出；M 型电极；粒子模拟（PIC）；朗缪尔鞘层

Abstract:

Improving the electrode configuration has been proved to be effective to improve the ion extraction efficiency of atomic vapor laser isotope separation.
In this study, based on the analytical model of the ion extraction process of the one-dimensional parallel plate electrode, the theoretical analysis and numerical simulation of the ion extraction process under the M-type electrode structure were carried out by using the two-dimensional particle simulation software (EDIPIC-2D).
On the one hand, the particle-in-cell (PIC) modeling results show that, for the M-type electrode configuration, the physical processes such as electron oscillations, Langmuir sheath formation and expansion, and ion rarefaction wave (IRW) propagation can be observed during the ion extraction process. However, different from the 1-D ion extraction process, the IRW propagation occurs in both directions within the M-type electrode, both of which affect the ion density distributions.
On the other hand, if the insertion depth or width of the anode is large enough, the potential of the main plasma region will reach the level of the anode, forming a virtual anode. And with other parameters being unchanged, increasing in the insertion depth and width of the anode can effectively improve the potential of the main plasma region and shorten the ion extraction time; the insertion depth of the anode has a more significant influence on the ion extraction features, and simultaneously, the potential value of the anode also limits that of the main plasma region. In addition, the gap spacing between the plasma and cathode surface has no significant impacts on the overall extraction time.
The above research work has a certain theoretical guiding significance for the selection of structural parameters of ion extraction devices in practical applications.

Keywords:

Atomic vapor laser isotope separation (AVLIS); Ion extraction; M-type electrode configuration; Particle simulation (PIC); Langmuir sheath

海报展示 / **14**

CJPL 中宇宙线缪子通量和缪致中子产额测量

Author: 彬张[None]

Corresponding Author: zhangb20@mails.tsinghua.edu.cn

Keywords:

CJPL, Cosmic-ray muon, Muon-induced neutron, Liquid scintillator detector

摘要:

中国锦屏地下实验室（CJPL）是开展 MeV 尺度中微子实验和寻找无中微子双 β 衰变的理想场所。为了理解宇宙线本底，我们分析了一吨原型探测器 820.28 天的数据，测得宇宙线 μ 子通量为 (3.61±0.19stat.±0.10sys.)×10−10cm−2s−1。从探测到的宇宙线 μ 子事件中,我们还测量了液体闪烁体中 μ 子诱发的中子产额,在 μ 子平均能量为 340 GeV 时,其值为 (3.44±1.86stat.±0.76sys.)×10−4□−1g−1cm2。此外，我们对全球不同实验室位置的 μ 子通量进行了研究，包括位于山下的实验室和矿井中的实验室。在相同的垂直覆盖层深度下，由于从山体侧面的泄漏，前者的 μ 子通量通常是后者的 (4±2) 倍。基于锦屏山的地形和 CJPL-I 的测量结果，我们预测了 CJPL-II 四个厅的宇宙线 μ 子能量、角度分布和通量。我们发现 C 厅和 D 厅的通量分别约为 2.3×10−10cm−2s−1 和 2.5×10−10cm−2s−1。

关键词:

中国锦屏地下实验室，宇宙线缪子，缪致中子，液体闪烁体探测器

Abstract:

China Jinping Underground Laboratory (CJPL) is ideal for carrying out MeV-scale neutrino experiments and searching for neutrinoless double-beta-decay. To understand the cosmogenic background, we analyzed 820.28 days of the dataset from a one-ton prototype detector and measured the cosmic-ray muon flux to be (3.61±0.19stat.±0.10sys.)×10−10cm−2s−1. From the detected cosmic-ray muon events, we also measured the muon-induced neutron yield in liquid scintillation, which is (3.44±1.86stat.±0.76sys.)×10−4□−1g−1cm2 at 340 GeV average energy of muons. In addition, we performed a survey of muon fluxes at different laboratory locations globally, considering both those situated under mountains and those down mine shafts. Under the same vertical overburden, the former is generally (4±2) times the latter due to the leakage through the mountain. Based on Jinping Mountain's terrain and the measurement in CJPL-I,

we predicted cosmic-ray muons' energy and angle distributions and fluxes for the four halls at CJPL-II. We found the fluxes of Hall C and Hall D were about 2.3×10−10cm−2s−1 and 2.5×10−10cm−2s−1 respectively.

海报展示 / **20**

Spectrum estimation from transmission measurements of Inverse Compton Scattering gamma rays based on a modified Expectation Maximization method

Author: 锦林[None]

Corresponding Author: linj21@mails.tsinghua.edu.cn

摘要:

逆康普顿散射（ICS）光源的能谱测量既是评估系统运行状态的关键指标，也是后续应用研究的基础。基于最大期望值（EM）算法的衰减法能谱重建方法已广泛应用于 X 射线或韧致辐射能谱测量。然而，针对 ICS 源的准单能 γ 射线能谱，由于材料衰减系数变化率较低，传统 EM 算法收敛速度过慢而难以实现有效重建。本研究提出改进的 EM 算法，显著提升了收敛速度。通过蒙特卡洛模拟获得 ICS 源的 γ 能谱后，采用数值模拟验证了该方法在不同测量误差条件下对平均能量 530keV（能散 1.1%）和 2853keV（能散 1.28%）准单能 γ 射线的重建效果。结果表明，改进算法能以更少迭代次数获得优于传统方法的能谱估计，但要求透射测量精度分别达到 10^(-4) 和 10^(-5) 量级。

关键词:

逆康普顿散射；能谱测量；最大期望值法

Abstract:

The energy spectrum estimation of an inverse Compton scattering (ICS) source is not only a key indicator for assessing whether the system is operating normally, but also serves as the foundation for further application studies. Spectrum estimation from transmission measurements using the expectation maximization (EM) method has been widely applied for X-ray spectra or Bremsstrahlung spectra. However, for quasi-monochromatic gamma ray spectra of ICS sources, the low rate of change in the attenuation coefficients of materials causes the traditional EM method to converge too slowly, making it ineffective for spectrum reconstruction. We proposed a modified EM method that significantly accelerated the convergence rate. The energy spectra of an ICS gamma ray source were obtained using Monte Carlo simulations. Numerical simulations were carried out to test the feasibility of estimating quasi-monochromatic spectra with mean energies of 530 keV (energy spread of 1.1%), and 2853 keV (energy spread of 1.28%) under various measurement error conditions. The results demonstrated that the modified EM method can provide better approximations of quasi-monochromatic gamma ray spectra with fewer iterations than the traditional EM method, but the transmission measurement accuracy were required to reach 10^(-4), and 10^(-5) respectively.

Keywords:

Inverse Compton Scattering；spectrum estimation；Expectation Maximization method

海报展示 / **97**

局部 **RF-KO** 方法降低同步环低能慢引出束流能散

Author: Yang Xiong[1]

Co-authors: Hongjuan Yao ; Shuxin Zheng ; Zejiang Wang

[1] *Tsinghua University*

Corresponding Author: xiongy21@tsinghua.org.cn

摘要:

紧凑型质子同步加速器是常用的空间辐射模装置，三阶共振慢引出技术是该类装置最常用的引出方法。但是该方法在低能量区间（一般小于 60 MeV）因为纵向发射度大会导致引出束流能散大，从而降低引出效率；此外，受强空间荷效应影响，束流发射度增长激励困难，且会出现质心振荡，从而导致引出束流不稳定等。为此，我们提出一种局部横向射频踢脚（RF-KO）激励方法，可以有效减弱上述效应的影响。本研究聚焦于使用局部 RF-KO 激励降低引出束流的能散，通过模拟计算验证了该方法的有效性。

关键词:

质子同步加速器、低能慢引出、RF-KO 激励、动量分散

Abstract:

For space radiation simulation applications, low-energy slow extraction from proton synchrotron suffers from strong space charge effect. Using high-order harmonic excitation and extraction below resonance can solve this. Based on above, we studied local RF-KO method to reduce energy spread of extracted beam and the effectiveness is demonstrated through simulation.

Keywords:

Proton Synchrotron, low-energy slow extraction, RF-KO excitation, energy spread

海报展示 / **21**

基于逆康普顿散射源的高能相衬成像研究

Author: Jiayi Sun[1]

[1] *Tsinghua university*

Corresponding Author: sjy22@mails.tsinghua.edu.cn

Abstract:

This study presents a hybrid simulation method for gamma-ray phase contrast imaging of metallic materials, called the Directional Macro Wavefront (DMWF) method. Combining Monte Carlo simulation and wave optics propagation techniques, the method aims to improve both the computational efficiency and accuracy of high-energy gamma-ray phase contrast imaging. A series of simulations were conducted to validate the effectiveness of the DMWF method, which demonstrated excellent energy adaptability across a wide range of energy levels and a significant improvement in computational efficiency, especially under high-energy radiation conditions. The results show that the DMWF method can effectively reduce computational complexity and storage requirements while providing high-quality simulation. This method holds great potential for applications, particularly in industrial inspection and medical imaging.

Keywords:

Phase Contrast Imaging; Inverse Compton Scattering Source; Monte Carlo Method; Wave Optics; Directional Macro Wavefront Method

摘要:

本研究提出了一种基于伽马射线相衬成像的金属材料混合仿真方法——定向宏波前（DMWF）方法。该方法结合了蒙特卡罗模拟和波光学传播技术，旨在提高高能伽马射线成像的计算效率与精度。通过一系列仿真实验验证，DMWF 方法在不同能量范围内表现出优良的能量适应性，并显著提高了计算效率，尤其在高能辐射条件下。实验表明，DMWF 方法能够有效地减少计算复杂度和存储需求，同时高质量模拟的相位对比成像，具有广泛的应用前景，尤其在工业检测和医学成像领域。

关键词:

相衬成像；逆康普顿散射源；蒙特卡罗方法；波动光学；定向宏波前方法

海报展示 / **22**

Operation optimization strategy of a BIPV-battery storage hybrid system

Authors: 双寿李[1]; 欣欣郭[1]; 琦张[1]; 琪孙[1]; 蔚然林[1]; 鸣锋钟[1]

[1] 清华大学

Corresponding Author: 997533507@qq.com

摘要:

建筑光伏一体化（BIPV）系统具有环保、节约土地资源等优点，越来越受到研究者的关注，将蓄电池与 BIPV 相结合可以提高整个系统的灵活性，对于分布式可再生能源应用具有广阔前景。然而，如何根据建筑负荷最优调度光伏板、储能电池和电网的每小时能量流动至关重要，但研究较少。本文建立了一个多约束条件下的非线性优化模型，用于在晴天不同建筑负荷下 BIPV-电池储能混合系统。该优化模型通过 MATLAB 代码中的 fmincon 函数求解。在优化过程中，考虑了包括混合系统的设施成本、电价和碳价在内的总体最低日成本作为目标函数，以获得光伏、电池和电网每日电力分配的最佳运行策略，满足日常建筑需求。研究结果表明，当办公楼负荷较重时，系统对电网的高度依赖性增加；而随着电力需求减少，这种依赖性降低。在满载居民建筑场景下，当系统电池成本为 800 元/kW 时。当电压达到或超过某个水平时，光伏（PV）产生的多余绿色电力会实时售电给电网以赚取额外利润，同时绿色电力会在储能电池中累积，因为储能电池的成本正在下降。此外，采用 BIPV 电池储能混合系统的住宅建筑在白天对电网的依赖减少，可以实现自给自足。在所有情况下，高昂的储能电池成本限制了储能电池的容量。而随着 BIPV 电池储能混合系统的采用，二氧化碳排放量也得到了减少。

关键词:

建筑光伏一体化储能系统；优化策略；办公楼负载；居民楼负载

Abstract:

Building integrated photovoltaic (BIPV) system attracts increasing attention of researchers due to environmentally friendly and saving land resource. Combining storage battery with BIPV can improve the flexibility of the entire system, which is promising for distributed renewable energy application. However, how to optimally dispatch the hourly energy flow of PV panel, storage battery and power grid based on a building load is crucial and less investigated. In the paper, a multi-restricted condition nonlinear optimization model is established for a BIPV-battery storage hybrid system under different building loads at a clear day. The optimization model was solved by fmincon function through MATLAB code. In the optimization, overall minimum daily cost including facility cost of the hybrid system, electric price and carbon price were considered as objective function to obtain optimal operation strategy of hourly power distributions of PV, battery and grid for daily building consumption. The key finding indicates that the system has high dependence on power gird when the office building load is heavy, while reduces the depending of power grid as the electrical demand is decreased. Under full-load resident building scenario, when the system with battery cost of 800 Yuan/kW·h or higher, the redundant green power generated by photovoltaic (PV) is sold to power grid in real time to earn extra profit, while the green power is accumulated in the storage batteries as storage battery cost is declined. Moreover, the resident building with BIPV-battery storage hybrid system has less dependence on power gird during day time, realizing self-sufficiency. Under all the scenarios, high storage battery cost limits the capacity of storage battery. And the CO2 emission is reduced as the BIPV-battery storage hybrid system is adopted.

Keywords:

BIPV-battery storage system; optimization strategy; office building load; resident building load

海报展示 / **25**

关于风电场的风功率时序预测研究

Author: 雨轩韩[None]

Co-author: 井泉刘 [1]

[1] 清华大学工程物理系

Corresponding Author: 1841524010@qq.com

摘要:

随着能源危机、环境污染等问题的日益加重，可再生能源的开发已经引起了全世界的广泛关注。由于风能是一种清洁、绿色的能源，具有成本低、可再生等优点，风力发电技术近年来发展迅速。但是由于风能具有随机性、波动性等特点，使得风能发电的输出功率具有不稳定性，对电力系统的正常运行和调度有较大的影响。本文利用深度学习算法来进行风功率的时序预测，以历史风功率数据作为输入，建立风力发电功率预测模型，实现对未来一定时间的风力发电功率预测。本文利用多种方式对模型进行调试，最终得出预测误差和预测趋势拟合度均较高的模型。

关键词:

时序预测；深度学习；风功率预测；LSTM；FNN

Abstract:

With the growing severity of issues such as the energy crisis and environmental pollution, the development of renewable energy has attracted widespread global attention. Wind energy, being a clean, green energy source with advantages such as low cost and renewability, has witnessed rapid growth in wind power generation technology in recent years. However, due to the inherent randomness and variability of wind energy, wind-generated power output remains unstable, significantly affecting the normal operation and scheduling of power systems. In this paper, we utilize deep learning algorithms to perform time-series forecasting of wind power. Using historical wind power data as inputs, we establish a predictive model for wind power generation to forecast wind power outputs over future time horizons. Through multiple approaches for model tuning, we ultimately achieve a model exhibiting high accuracy in prediction error and strong alignment with observed trends.

Keywords:

Time Series Forecasting; Deep Learning; Wind Power Prediction; LSTM; FNN

海报展示 / **32**

电磁轴承故障仿真系统研究与开发

Author: 世锬张[1]

[1] 清华大学

Corresponding Author: zst23@mails.tsinghua.edu.cn

摘要:

本文针对一套电磁轴承-转子系统，开发仿真程序来模拟各种工况下系统的响应情况。根据电磁轴承使用的磁极建立了十六极磁极电磁力模型；建立了 5 自由度转子模型；建立了包括碰摩、不平衡的故障模型；建立了 5 自由度分散 PID 控制的控制器模型。根据建立的各个理论模型，在 Matlab/Simulink 中使用 Simscape 工具箱，建立各个部分对应的仿真模型，并进行模块化。之后进行各个模块之间的装配，完成整体仿真系统的搭建。对各种正常工况以及故障工况进行仿真模拟，测试仿真系统工作的准确性。对故障工况进行简单分析，寻找故障产生的原因，以及各类故障对转子行为的影响。

关键词:

电磁轴承；故障仿真；碰摩；不平衡响应

Abstract:

In this paper, a simulation program is developed for an AMB-rotor system to simulate the response under various operating conditions. A sixteen-pole pole electromagnetic force model is developed based on the magnetic poles used in the AMB; a 5 DOF rotor model is developed; a fault model including rub-impact and unbalance is developed; and a controller model with 5 DOF decentralized PID control is developed. According to each theoretical model established, the simulation model corresponding to each part is established and modularized in Matlab/Simulink using Simscape toolbox. After that, the assembly between each module is carried out to complete the construction of the overall simulation system. Simulation of various normal and fault conditions is carried out to test the accuracy of the simulation system. A simple analysis of the fault conditions is carried out to find the causes of the faults and the effects of each type of fault on the rotor behavior.

Keywords:

Active magnetic bearing; Fault simulation; Rub-impact; Unbalance response

海报展示 / **34**

Quantifying Indirect Economic Losses from Extreme Events to Inform Global and Local Adaptation Strategies

Authors: 一贺[1]; 博文王[1]; 文昊吴[2]; 飞滕[1]

[1] 清华大学

[2] 北京师范大学

Corresponding Author: wbw23@mails.tsinghua.edu.cn

摘要:

气候变化增加了极端天气气候事件发生的范围、频率和强度，带来巨大的经济损失。现有极端事件归因研究主要侧重于对人员和实物资产造成的直接经济损失，往往忽略了波及整个供应链的更广泛的间接损失。本文将灾害数据与归因研究相结合，并采用全球多区域混合投入产出模型来评估人类活动引起的气候变化造成的直接和间接经济损失。研究结果显示，全球干旱、洪涝、风暴事件每年可归因直接损失为 668.9 亿美元，可归因间接损失为 827.7 亿美元，约占灾害损失的 47%。国际贸易和产业关联放大了国外极端事件对国内的影响，中国总归因损失的 15% 源于国外灾害。本研究确定了最需要气候适应投资的风险脆弱行业和地区。研究还表明，对海外适应措施的投资可以间接减轻当地的影响，强调了全球经济应对气候变化的相互关联性。

关键词:

极端天气气候事件；经济影响；影响归因；气候变化适应；多区域投入产出分析

Abstract:

Extreme weather events, increasingly influenced by anthropogenic climate change, are inflicting substantial economic impacts globally. Existing research on climate change attribution for extreme events has primarily focused on direct economic losses to people and physical assets, often neglecting the broader indirect losses that ripple through the entire supply chain. Here, we combined disaster data with attribution studies and employ a global multi-regional hybrid input-output model to assess both direct and indirect economic losses attributable to anthropogenic climate change. Our findings reveal annual direct attributable losses of $66.89 billion and indirect losses of $82.77 billion, together accounting for approximately 47% of the total losses. International trade and industry linkages significantly amplify the domestic impact of international extreme events, with 15% of China's total attributable losses stemming from disasters abroad. Our assessment identifies risk-vulnerable sectors and regions where climate adaptation investments are most needed. Our study also suggests the investments in overseas adaptation measures can indirectly mitigate local impacts, emphasizing the interconnected nature of global economic resilience against climate change.

Keywords:

Extreme weather events; Economic impact; Impact attribution; Climate adaptation; Multi-regional input-output analysis

海报展示 / **35**

Applying Mn-Sb/SnO2 anode-based electrochemical induced iodide recycle for continuous and efficient ozone resource utilization in VOCs removal

Author: 嘉鸿廖[1]

[1] 浙江大学化学工程与生物工程学院

Corresponding Author: liaojh@zju.edu.cn

摘要:

开发高效、连续的臭氧资源利用技术对于实现环境可持续发展至关重要。本研究利用 Mn-Sb/SnO2 阳极构建了一个碘化物电循环系统，该系统既能高效去除臭氧，又能利用臭氧降解挥发性有机化合物（VOC），两者的去除率均达到 100%。在该系统中，臭氧和 I- 之间的自发氧化还原反应促进了 IO3- 的生成，同时确保了臭氧的完全去除。在随后的 IO3- 氧化反应（IO3OR）中，Mn-Sb/SnO2 电极表现出卓越的 IO3OR 性能，法拉第效率高达 96.2%。随后，IO3OR 反应中生成的 IO4- 被进一步活化，生成 IO3·和·OH 自由基，从而有效地矿化了各种挥发性有机化合物，矿化率高达 76%。此外，系统中的碘化物可以循环使用，从而确保系统能够持续稳定地运行。这种创新方法为高效、可持续地利用臭氧资源提供了一种前景广阔的解决方案。

关键词:

Mn-Sb-SnO2 、臭氧、挥发性有机化合物、IO3·and ·OH 、碘化物

Abstract:

The development of efficient and continuous ozone resource utilization technology is crucial for achieving environmentally sustainable development. In this study, an iodide electro-cycling system using the Mn-Sb/SnO2 anode was constructed, achieving both efficient ozone removal and its utilization for the degradation of volatile organic compounds (VOCs), with the removal of both reaching 100%. Within this system, the spontaneous redox reaction between ozone and I- facilitated the generation of IO3- while ensuring complete ozone removal. For the subsequent IO3- oxidation reaction (IO3OR), the Mn-Sb/SnO2 electrode exhibited exceptional performance of IO3OR, with a Faraday efficiency of 96.2%. Afterward, the IO4- generated during the IO3OR is further activated to generate IO3·and ·OH free radicals, enabling the effective mineralization of various VOCs with a mineralization rate reaching up to 76%. Moreover, the iodide in the system can be recycled, which ensures the system can operate continuously and stably. This innovative approach offers a promising solution for the efficient and sustainable resource utilization of ozone.

Keywords:

Mn-Sb-SnO2, Ozone, VOCs, IO3·and ·OH, Iodide

海报展示 / **36**

犯罪侦查决策支持模型

Author: 维曦王[None]

Corresponding Author: wwx21@mails.tsinghua.edu.cn

摘要:

人工智能和大数据技术已成功应用于众多领域的科学问题分析中，其中也包括犯罪分析领域。犯罪案件侦查一直是犯罪分析工作的重点和难点。犯罪案件在侦查阶段，主要包括证据收集和证据推理等工作。证据的全面高效收集对案件推理和快速侦破具有重要意义。与此同时，不同证据在案件中的重要程度不同，如果具有高重要度的证据在侦查早期阶段被收集，可有助于提高案件侦破效率。然而，现有的人工智能方法应用于犯罪侦查决策支持的研究较少。鉴于此，该文提出了一种基于加权信息熵的证据重要度的计算方法，并在此基础上构建了基于 Bayes 网络的犯罪侦查决策支持模型，然后利用 420 例犯罪案例对模型的准确率进行了验证，并用一例实际案例的分析过程对模型应用进行了阐述。分析结果表明：提出的模型能够输出有效的侦查建议，为侦查阶段的证据收集和推理工作提供决策支持。

关键词:

社会安全；犯罪侦查；证据重要度；Bayes 网络；决策支持

Abstract:

[Objective] Artificial intelligence and big data technologies have been used to solve many scientific problems, including crime analysis. The investigation of criminal cases has always been a critical and difficult point in the domain of crime analysis. The investigation stage of criminal cases primarily consists of evidence collection and evidence reasoning, and comprehensive and efficient collection and reasoning of evidence are critical to the rapid detection of cases. Simultaneously, the significance of the various pieces of evidence in the case varies. Evidence of high importance gathered during the investigation stage is critical for the accurate and efficient resolution of crime cases. However, existing research lacks the application of artificial intelligence methods to crime investigation decision support. Aiming at the problem of crime investigation, this research proposes a decision support model based on the Bayes Network to help domain experts determine the direction of the investigation and reasoning the criminal facts. [Methods] First, the Bayes Network is used to reason the hypothesis of criminal facts. Second, the weighted information entropy method was used to calculate the importance of criminal evidence. Four different types of weighted information entropy methods are employed to test the efficiency of the calculation method. The two methodologies are then combined to create the decision support model for crime investigation. Finally, the proposed model is applied to 420 crime cases to verify its accuracy, and the proposed model is also applied to a real case analysis to illustrate the application process of the model. [Results] The analysis of 420 crime cases revealed that calculations based on weighted information entropy are the best of all four methods. The top 3, 5, and 10 evidence provided with the weighted information entropy method all have the highest coverage of importance, given any arbitrary evidence missing ratio. Meanwhile, when 50% of the evidence is missing, the output result's coverage of the top 3, 5, and 10 important pieces of evidence are greater than 50%, 65%, and 80%, respectively; when 90% of the evidence is missing, coverage of the top 3, 5, and 10 is greater than 40%, 60%, 75% respectively. These suggest that the model's detection recommendations are effective and can be used to assist in crime detection. Furthermore, the analysis of a real-world case also shows that the proposed model can generate effective investigation suggestions and provide decision support for evidence collection and reasoning during the investigation stage. [Conclusions]Finally, the proposed decision support model for crime investigation can analyze available case information and generate effective investigation suggestions and reasoning conclusions. However, it should be noted that the model developed in this study does not completely replace the role of professionals in the field of criminal investigations but rather provides analysis results to scientifically support the investigation's subsequent investigators'decisions in the initial stages of the investigation. Furthermore, this study focuses on the research of evidence collection and reasoning during the investigation stage of criminal cases but pays limited attention to the "evidence standard"involved in the process of evidence collection. Therefore, we can continue to investigate this aspect in the future to aid intelligence and standardization of evidence collected during the investigation stage.

Keywords:

Social Security; Crime Investigation; Evidence Importance; Bayes Network; Decision Support

海报展示 / **37**

Tapering enhanced high efficiency THz waveguide oscillator

Author: 一宁杨[1]

[1] 清华大学

Corresponding Author: yang-yn21@mails.tsinghua.edu.cn

摘要:

在 taper 的 THz 自由电子激光（THz-FEL）中插入波导能够显著提升单通的能量提取效率。文章介绍了采用 FEL 振荡器的方式，进一步在较高的单通能量提取效率基础上提升提取效率。该设计特别为高重复频率热阴极电子枪设计，能够产生高平均功率的 THz 辐射。

关键词:

THz，自由电子激光，振荡器，波导

Abstract:

Using a waveguide in a THz Free electron laser (FEL) has been validated experimentally to enable efficient single-pass energy extraction through a tapered helical undulator. An oscillator configuration can further boost energy extraction above the single pass limits and open the door towards very high average power THz sources with the help of high repetition rate electron sources

Keywords:

THz， FEL, oscillator, waveguide

海报展示 / **38**

高速永磁同步电机反电动势优化设计研究

Author: 恩池刘[1]

[1] 工程物理系

Corresponding Author: lec22@mails.tsinghua.edu.cn

Keywords:

uranium enrichment cascade; compressor; high-speed permanent magnet synchronous motor design; back-EMF; RMxprt; finite element calculation

摘要:

压缩机作为铀浓缩级联中的重要设备，在整个分离过程中承担着气体高效传输和压缩的关键任务，清华大学工程物理系技术物理所自主研发的磁悬浮离心式压缩机已成功应用于国内多处铀浓缩级联工厂。永磁同步电机因其高效率、低损耗和显著的节能效果，是具有更高能效的压缩机用高速电机，其中反电动势与额定电压的匹配关系是电机整体性能的关键，基于此开展了高速永磁同步电机优化设计。首先，文章对电机的关键因素进行了详细分析，发现反电动势的大小与永磁体设计、定子绕组匝数和气隙长度等因素密切相关。其次，文章采用了电磁设计计算和电磁场模拟相结合的方法对一款永磁同步电机进行了性能校核。最后，针对该案例提出了一种优化方案，在软件拟合层面降低了电机的反电动势。该研究在设计层面对高速永磁同步电机反电动势进行了分析与优化，为高速永磁同步电机在压缩机领域的应用提供了参考。

关键词:

铀浓缩级联；压缩机；高速永磁同步电机设计；反电动势；RMxprt；有限元计算

Abstract:

As a crucial component in uranium enrichment cascades, compressors play a key role in the efficient transportation and compression of gases throughout the separation process. The magnetic suspension centrifugal compressor, independently developed by the Institute of Technical Physics at the Department of Engineering Physics, Tsinghua University, has been successfully applied in several domestic

uranium enrichment cascade plants. Permanent magnet synchronous motors (PMSM) are favored for high-speed applications due to their high efficiency, low losses, and significant energy-saving effects. The matching of back-EMF with rated voltage is critical to motor performance. This paper analyzes key factors influencing back-EMF, such as magnet design, winding turns, and air gap length. Through a combination of electromagnetic design and simulations, a PMSM's performance was verified, and an optimization plan to reduce back-EMF was proposed. This research offers analysis and optimization of the back-EMF of high-speed PMSMs from a design perspective, providing a reference for the application of high-speed PMSMs in compressors.

海报展示 / **39**

利用太赫兹高次谐波补偿产生阿秒超短电子束

Author: 王翼安[1]

[1] 清华大学工程物理系

Corresponding Author: wya20@mails.tsinghua.edu.cn

摘要:

获得超短电子束是超快科学研究的关键，然而二次及更高阶的非线性限制了束团的压缩极限，目前在不进行非线性补偿情况下，电子束仅能压缩到几飞秒的水平。传统射频高次谐波补偿方法可以将束长优化到亚飞秒尺度，但同时会带来无法忽略的能量损耗和射频抖动。本研究通过介质加载波导，利用太赫兹脉冲进行二次非线性补偿。模拟表明，通过高次谐波补偿，10fC 电荷、MeV 能量范围的电子束的长度可以被压缩到亚飞秒，同时，横向束流尺寸也可以优化至小于 20 微米。此类方法可应用于超快电子衍射（UED）、超快电子显微镜（UEM）和其他超快、时间分辨装置中，以实现更高的时间分辨率。

关键词:

束团压缩，超快电子衍射，太赫兹

Keywords:

beam compression, ultrafast electron diffraction, terahertz

Abstract:

Obtaining ultrashort electron bunches is the key to the studies of ultrafast science, yet second and higher order nonlinearities limits the bunch length to a few femtoseconds after compression. Traditional regulation methods using rf higher order harmonics have already optimized the bunch length to sub-fs scale, yet the energy loss and rf jitter are not negligible. In this paper we demonstrate the second order regulation with THz pulses through a dielectric-loaded waveguide. Simulations suggest that with higher order regulations, the MeV electron bunches with tens of fC charges can be compressed to sub-fs rms and the second order distortion can be compensated. The transverse beam size is also optimized to less than 20um rms. This scheme is feasible for a wide range of electron charges. The relatively short bunch length is expected to find a better time resolution in UED, UEM and other ultrafast, time-resolved studies.

海报展示 / **42**

激光诱导荧光测量横掠管束流动标量混合系数

Author: 罗昀昊[1]

Co-authors: 吴莘馨 [1]; 李晓伟 [1]; 谢箫阳 [1]

[1] 清华大学

Corresponding Authors: xinxin@tsinghua.edu.cn, lixiaowei@tsinghua.edu.cn, luoyh22@mails.tsinghua.edu.cn, xiexy22@mails.tsinghua.edu.cn

摘要:

螺旋管式换热器通常被选用作高温气冷堆（HTGRs）的主要换热器。为了提高热效率，设计者追求尽可能高的运行温度，这几乎接近镍基合金的极限温度。管束中的温度峰值会使部分传热管的工作温度高于设计值，并可能在管头处引起较大的热应力。湍流脉动、流束分离和再汇以及管后尾迹摆动等现象有助于管束内温度峰值的混合和展平。佩克莱数（Pe）可以描述管束内温度分布的有效混合效果。在本研究中，通过在水洞中测量罗丹明 6G 的浓度场，研究了横流过管束的标量混合过程。通过比较不同流向位置的拟合曲线得到 Pe。测试的管束为管间距与直径比（P/D）为 1.58 的直管束。雷诺数（Re）范围为 10000～40000。当 Re 从 10000 增加到 40000 时，Pe 先下降，然后保持稳定。

关键词:

横掠管束、标量混合、激光诱导荧光

Abstract:

Helical tube bundles are usually used for the main heat exchangers of High Temperature Gas-cooled Reactors (HTGRs). In order to improve the thermal efficiency, the designers pursue as high as possible operating temperature, which almost reaches the limited temperature of nickel based alloys. Temperature peaks in tube bundles will additionally make some of the tubes work at temperature higher than the design value, and may induce large thermal stress in the tube header. The phenomenon of turbulence fluctuation, splitting-rejoining flow and swinging wakes can help mixing and flattening the temperature peaks in tube bundles. Peclet number (Pe) can describe the effective mixing effect on temperature distribution in tube bundles. In the current investigation, the concentration field of Rhodamine 6G is measured to investigate scalar mixing process in cross flow over a tube bundle in a water tunnel. Pe is obtained by comparing fitting curves at different streamwise locations. The tested tube bundle is a straight tube bundle with tube pitch to diameter ratio (P/D) of 1.58. The Reynolds number (Re) range is 10000 ~ 40000. Pe first declines and then maintains stable when increasing Re from 10000 to 40000.

Keywords:

cross flow over tube bundle, scalar mixing, laser induced flourence

海报展示 / **45**

基于蒙特卡罗的背散射多次散射校正算法

Authors: 常荣石[None]; 永顺肖[1]

[1] 清华大学工程物理系

Corresponding Author: scr20@mails.tsinghua.edu.cn

摘要:

在康普顿背散射成像过程中，探测器捕获的光子不仅包括一次散射光子，还包含大量多次散射光子。如何区分和提取一次散射信号，有效降低多次散射信号对重建的不利影响，是提高重建图像的信噪比和缺陷识别能力的重要因素。本文提出了基于蒙特卡罗的康普顿背散射多次散射校正重建算法，通过两次蒙特卡罗模拟判断缺陷位置并补偿缺陷导致的散射信号变化。该方法根据实际无损检测应用场景的特点，将材料属性作为先验知识，获取材料的线性衰减系数。算法首先假设物体内部没有缺陷，得到初次粗略校正的一次散射数据。然后，使用图像分割技术区分材料与空气缺陷，并利用两次蒙特卡罗模拟精确估计原始数据中的一次散射数。通过建立连续能谱 X 射线管和康普顿背散射成像系统的数学模型，对系统矩阵进行精确建模，并使用 MLEM 算法得到信噪比更高的重建图像。为了降低蒙特卡罗模拟的噪声以改善重建效果，还提出了一种基于统计的降噪算法来减少多次散射数据中的噪声。对不同材料组成的物体以及不同尺寸缺陷的模拟结果和真实验结果显示，所提出方法可以有效提高图像的 CNR 和 SSIM，并提供更准确的物体电子密度信息，以实现更加准确的缺陷图像分割。与直接从原始数据重建相比，该方法有效改善了重

建图像的信噪比。该成果在大型物体的无损检测中具有一定的实用价值。

关键词:

康普顿背散射成; 蒙特卡罗; 多次散射校正

Abstract:

During the process of Compton backscattering imaging, detectors capture not only single-scattered photons but also a large number of multiple-scattered photons. Distinguishing and extracting the single-scatter signals while effectively reducing the adverse impact of multiple-scatter signals on reconstruction is crucial for improving the signal-to-noise ratio (SNR) and defect identification capability of reconstructed images. This paper proposes a Monte Carlo-based correction and reconstruction algorithm for multiple scattering in Compton backscattering, which judges the defect locations and compensates for the changes in scatter signals caused by defects through two rounds of Monte Carlo simulations. The method incorporates material properties as prior knowledge to obtain the linear attenuation coefficient of the materials according to the characteristics of practical non-destructive testing applications. Initially, the algorithm assumes there are no defects inside the object to get a rough initial correction of single-scatter data. Then, image segmentation techniques are used to differentiate between material and air defects, and two rounds of Monte Carlo simulations are employed to precisely estimate the single-scatter counts in the original data. By establishing mathematical models of both continuous spectrum X-ray tubes and Compton backscatter imaging systems, the system matrix is accurately modeled, and higher SNR reconstructed images are obtained using the MLEM algorithm. To reduce noise from Monte Carlo simulations and improve reconstruction quality, a statistics-based denoising algorithm is proposed to decrease noise in multiple-scatter data. Simulation results on objects composed of different materials and with various defect sizes, as well as real experiments, show that the proposed method can effectively enhance the contrast-to-noise ratio (CNR) and structural similarity index measure (SSIM) of images, providing more accurate information about the electronic density of objects for achieving more precise defect image segmentation. Compared to direct reconstruction from raw data, this method significantly improves the SNR of reconstructed images. The findings hold practical value for non-destructive testing of large objects.

Keywords:

Compton backscatter imaging; Monte Carlo; Multiple scattering correction

海报展示 / **46**

基于动态时空网络的操作员异常认知状态多步预测模型

Author: 妍张[1]

[1] 清华大学

Corresponding Author: zhang-y21@mails.tsinghua.edu.cn

摘要:

环境因素，尤其是热不适，会显著损害认知和执行功能，导致人因失误，进而引发严重的系统事故。目前已有各种基于生理监测的深度学习模型被开发，以评估认知状态并识别不安全行为。然而，大多数研究侧重于实时评估，而非预测，且通常忽略生理信号中的丰富动态时空信息。为了应对这些挑战，本文提出了一种新型的时空模型 DCATT（扩散卷积注意力模型），用于在热应激下预测操作员的异常认知状态。该模型引入神经科学领域知识，基于动态前额叶脑血氧网络和心电时频特征进行建模，有效利用了脑网络的时空信息。DCATT 通过扩散图卷积捕捉空间依赖关系，模拟动态脑网络，从而增强短期预测能力。通过多头自注意机制建模时序关系，聚合历史信息，提升长期预测性能。并引入时序映射模块，利用带位置编码的多头交叉注意力机制将生理时空嵌入直接映射为未来认知状态表示，最终获得多步预测分类。实验结果表明，DCATT 在准确率、AUC 和 F1 评分上均优于经典的基于 TCN、RNN 和注意力的时空模型，准确率为 0.7222，AUC 为 0.7243，F1 评分为 0.6741。这种方法为应急情况下操作员异常认知状态的早期预警提供了一种有前景的解决方案，增强了人机系统在工业 5.0 时代的可靠性和生产力。

关键词:

认知状态预测；时空模型；扩散图卷积；

Abstract:

Environmental factors, especially thermal discomfort, significantly impair cognitive and executive functions, leading to human errors that may result in severe system accidents. Various deep-learning models driven by physiological monitoring have been developed to assess cognitive states and recognize unsafe behaviors. However, most studies focus on real-time evaluation rather than forecasting and often ignore the rich dynamic spatiotemporal information in physiological signals. To address these challenges, this paper proposed DCATT (diffusion convolutional attention model), a novel spatial-temporal model to provide multistep predictions of operators' abnormal cognitive state under heat stress. Leveraging fNIRS dynamic graphs and ECG time-frequency features extracted via neuroscience analysis, DCATT effectively utilizes spatiotemporal information. The model captures spatial dependencies via diffusion graph convolution to simulate dynamic brain networks, enhancing short-term forecasting. It further models temporal relationships by a multi-head self-attention mechanism to aggregate historical information, improving long-term prediction. Additionally, a temporal projection module, a multi-head cross-attention mechanism with position encoding, is applied to the physiological embeddings to directly generate latent future cognitive representations. DCATT outperformed classic TCN, RNN, and attention-based spatial-temporal models, achieving an accuracy of 0.7222, an AUC of 0.7243, and an F1 score of 0.6741. This approach provides a promising solution for early warning of abnormal cognitive states in emergency scenarios, enhancing the reliability and productivity of human-cybernetic systems in the Industry 5.0 era.

Keywords:

cognitive state prediction; spatial-temporal model; graph diffusion convolution;

海报展示 / **59**

Multi-scale spatio-temporal features fusion method for fault diagnosis of NPPs under high noise

Author: 玉顺王[None]

Corresponding Author: 735034777@qq.com

摘要:

核能对于优化能源结构和促进可持续发展至关重要而核电站的准确故障诊断对安全至关重要因为操作人员依赖经验和知识可能在压力下导致错误当前不依赖经验或先验知识的数据驱动故障诊断方法被认为是最有前景的方法之一该方法对原始数据要求较高而核电站常受到电磁干扰或背景噪声影响这些干扰可能掩盖早期故障的细微特征导致误诊或漏诊可能引发严重事故为解决这个问题我们提出基于多尺度学习和时空特征融合的方法通过使用 CNN 构建多尺度学习框架并将其与 LSTM 结合进行时空特征融合为验证该方法有效性我们在模拟数据中测试了三种典型场景：故障类型诊断、故障严重程度诊断以及多故障并发条件下的故障诊断并将我们的方法与 CNN、LSTM、WDCNN 和 MBSCNN 等模型进行对比结果表明在信噪比-100 的高噪声环境下我们提出的模型故障诊断准确率超过 99% 优于基准模型。

关键词:

故障诊断，时空特征融合，多尺度特征提取

Abstract:

Nuclear energy is vital for optimizing the energy mix and promoting sustainable development, and accurate fault diagnosis in NPPs is crucial for safety, as operators' reliance on experience and knowledge may lead to errors under pressure. Currently, the data-driven fault diagnosis approach that does not rely on experience or prior knowledge is considered one of the most promising methods. This method has high requirements for raw data, while NPPs often experience interference from electromagnetic disturbances or background noise, which can obscure the subtle features of early faults, leading to misdiagnosis or missed diagnosis, potentially resulting in severe accidents. To address this issue, we propose a method based on multi-scale learning and spatiotemporal feature fusion. We have constructed a multi-scale learning framework using CNNs and integrated it with LSTM for spatiotemporal feature fusion. To

validate the effectiveness of the proposed method, we tested it in three typical scenarios on simulated data: fault type diagnosis, fault severity diagnosis, and fault diagnosis under multiple fault concurrent conditions. We compared our method with models such as CNN, LSTM, WDCNN, and MBSCNN. The results demonstrate that our proposed model achieves a fault diagnosis accuracy of over 99\% under high noise conditions with an SNR of -100, outperforming the baseline models.

Keywords:

Fault diagnosis , Spatio-temporal features fusion, Multi-scale learning

海报展示 / **60**

Fast front-end readout design for NICA-MPD shashlik electromagnetic calorimeter

Author: 冉鑫驰[1]

[1] 清华大学工程物理系

Corresponding Author: 941189729@qq.com

摘要:

硅光电倍增器（SiPMs）因其出色的光响应和高增益特性而备受青睐，但其在快速定时应用中的使用常受到其高端接电容（通常超过 300 pF）的限制。 在电磁量热器中，亚纳秒级的时间测量使这些探测器能够作为辅助的飞行时间设备使用，特别是在 NICA-MPD 实验中，目标时间分辨率为 150 皮秒。

为应对这些挑战，本研究提出了一种新颖的前端读出电子学设计，采用两级共基极跨阻前置放大器和一个 12 位、200 MS/s 的流水线逐次逼近寄存器（SAR）模数转换器（ADC）。利用 Hamamatsu S13360-6025 作为输入源进行的大量 SPICE 仿真显示，该前置放大器具有快速的上升时间和良好的线性度。 激光测试的实验结果证实，该快速前置放大器设计实现了优于 20 皮秒的卓越时间分辨率。

ADC 电路采用 TSMC 65nm 低功耗工艺设计，采用两级流水线 SAR 结构，并引入了两步转换技术（6 位 +7 位），在第二步中包含冗余设计。 在 160 MHz 采样率和 80 MHz 输入条件下进行的测试显示，在 Vpk = -1dBFS 时，ADC 的 FFT 频谱分析得到了 9.34 的有效位数（ENOB）和 73.8 dBc 的无杂散动态范围（SFDR）。

在 200 MHz 采样率下进行的初步系统级时间评估表明，对于上升时间为 15 至 20 纳秒的波形，在上升沿具有 3 至 4 个采样点的情况下，时间分辨率约为 20 皮秒。

关键词:

快速前置放大器，前端读出电子学，时间分辨率

Abstract:

Silicon photomultipliers (SiPMs) are highly valued for their excellent light response and high gain characteristics, yet their application in fast timing scenarios is often limited by their high terminal capacitance, typically over 300 pF. In electromagnetic calorimeters, sub-nanosecond time measurements allow these detectors to function as supplementary time-of-flight devices, specifically aiming for a time resolution of 150 ps in the NICA-MPD. To address these challenges, this study proposes a novel front-end readout electronics design featuring a two-stage common-base transimpedance preamplifier and a 12-bit 200 MS/s pipelined successive-approximation-register (SAR) analog-to-digital converter (ADC). Extensive SPICE simulations, using the Hamamatsu S13360-6025 as the input source, demonstrate the preamplifier's rapid rise time and good linearity. Experimental results from laser testing confirm that this fast preamplifier design achieves a remarkable time resolution of better than 20 ps. The ADC circuit, designed using the TSMC65nmLP process, employs a two-stage pipelined SAR structure with a two-step conversion technique (6-bit + 7-bit), incorporating redundancy in the second step. Testing at a 160MHz sampling rate with an 80MHz input condition showed that, at Vpk = -1dBFS, the ADC's FFT spectrum analysis yielded an effective number of bits (ENOB) of 9.34 and a spurious-free dynamic range (SFDR)

of 73.8 dBc. Preliminary System-level timing assessments under a 200 MHz sampling rate revealed that waveforms with 3 to 4 sampling points on the rising edge, with a rise time of 15 to 20 ns, achieved a time resolution of approximately 20 ps.

Keywords:

fast pre-amplifier, front-end readout, time resolution

海报展示 / **62**

New iterative method based on the Q-iteration method for robust and rapid determination of concentration distribution in multi-component separation cascades

Author: 瑞南唔[None]

Corresponding Author: wrnthu@163.com

摘要:

同位素分离级联的浓度分布计算是级联设计与优化的关键，直接影响分离效率与成本。传统 Q 迭代法因其简洁性和快速收敛性被广泛采用，但存在三大缺陷：松弛因子需手动调整且无法自适应级联特性，迭代方向缺乏全局优化易导致震荡，以及在强分离或临界参数下收敛速度极低甚至停滞。

本文提出最小残差 Q 迭代法（MR Q 迭代法），结合传统 Q 迭代与改进的 Q 迭代策略。新方法分两阶段：首先通过 Q 迭代生成近似解，随后切换至 Q 迭代，利用梯度信息动态优化迭代方向与步长，将非线性问题转化为线性求解。该方法通过自适应调整松弛因子与全局梯度引导，有效平衡收敛速度与稳定性，避免局部震荡。

实验表明，MR Q 迭代法显著减少迭代次数与计算耗时，在传统 Q 迭代失效的场景中仍稳健收敛。其自适应机制与全局优化能力提升了复杂级联场景的适用性，为同位素分离的高效优化提供新思路，未来可拓展至瞬态过程与多目标优化领域。

关键词:

多组分同位素混合物；分离级联；迭代法；Q 迭代法；牛顿法

Abstract:

The determination of concentration distributions in isotope separation cascades is crucial for design and optimization, directly impacting efficiency and costs. While the conventional Q-iteration method is widely used for its simplicity and rapid convergence, it suffers from three limitations: manual tuning of the relaxation factor without adaptability, suboptimal update directions leading to oscillations, and extremely slow or stalled convergence under strong separation or critical parameters.

This study proposes the Minimal Residuals Q-iteration (MR Q-iteration), integrating traditional Q-iteration with an enhanced Q-iteration strategy. The method operates in two phases: generating an initial approximation via Q-iteration, then switching to Q-iteration to optimize update directions and step sizes using gradient information, transforming nonlinear problems into linear solutions. By adaptively adjusting the relaxation factor and leveraging global gradients, the method balances convergence speed with stability while avoiding local oscillations.

Experiments demonstrate that MR Q-iteration significantly reduces iterations and computational time, achieving robust convergence even in scenarios where conventional Q-iteration fails. Its adaptive mechanisms and global optimization capabilities enhance applicability to complex cascades, offering a novel approach for efficient isotope separation. Future extensions may address transient processes and multi-objective optimization.

Keywords:

multi-component isotope mixture; separation cascades; iterative method; Q-iteration method; Newton–Raphson method

海报展示 / **77**

Innovative Stacking Method for Enhanced Data Fusion in Pollutant Population Risk Evaluation

Author: Yudie Jianyao[1]

Co-author: Xiaole Zhang [1]

[1] *School of Safety Science*

Corresponding Author: jyyd23@mails.tsinghua.edu.cn

摘要:

近年来，空气污染，尤其是颗粒物 (PM) 污染，日益成为全球公共卫生领域的重大问题。PM10 和 PM2.5 是关注的重点，由于它们对健康具有重大影响，因此在研究中至关重要。PM2.5 的粒径相对较小，因此更容易进入血液循环，对人体健康造成不利影响，因此风险更高。因此，以高精度和时空分辨率评估 PM2.5 和 PM10 暴露至关重要，这是评估健康影响的基础数据。机器学习方法是实现这一目标的有力候选方法。在本研究中，我们开发了多种机器学习方法，通过对化学迁移模型的结果进行降尺度处理，以高时空分辨率估算 PM 的分布，并比较了这些方法的性能。一项重要发现是，就计算性能和运行效率而言，Stacking 方法在预测准确度和精确度方面与深度学习方法相当甚至更胜一筹。此外，Stacking 方法显著缩短了计算时间。该研究利用堆叠模型对污染物数据进行降尺度处理，成功生成了详细的污染分布图，便于将 PM2.5 和 PM10 污染物分布与人口分布图进行比较分析，最终绘制出一幅全面的环境污染人口风险图。这一观察结果强调了人口规模对污染水平的深远影响，表明人类居住密度与空气质量恶化之间存在直接关联。此外，该研究还探讨了不同人口统计学特征（例如年龄和性别）与其 PM 暴露水平之间的关系。研究发现，老年人口尤其容易受到污染的影响，这表明风险状况存在人口统计学偏差。此外，研究还强调了不同地理环境（包括城市、农村和工业区）中污染物暴露水平的显著差异，并考虑了土地利用模式。这些差异揭示了不同土地利用和城市规划对环境的影响。总而言之，本研究的结果对于制定有效的环境和健康政策具有重要意义。通过加强对颗粒物污染、人口分布和人口统计特征之间关系的理解，这项研究为政策制定者制定有针对性的策略以减轻空气污染对公众健康的影响（特别是在人口稠密和高风险地区）提供了重要见解。

关键词:

颗粒物（PM）污染、机器学习技术、叠加方法、人群健康风险分析

Abstract:

Air pollution, with a particular emphasis on particulate matter (PM) pollution, has increasingly become a critical global public health concern in recent years. The primary focus of this concern lies in PM10 and PM2.5, which are crucial in research due to their significant health impact. PM2.5, with its relatively smaller particle size, poses a greater risk as it is more likely to penetrate the blood circulation and adversely affect human health. Consequently, it is imperative to assess PM2.5 and PM10 exposure with high accuracy and spatial-temporal resolutions, which is the fundamental data for evaluating health effects. Machine learning methods are promising candidates for this purpose. In this study, we developed various machine learning methods to estimate the distribution of PM with high spatial and temporal resolutions by downscaling results from chemical transport models and compared the performance of the methods. A key finding is that the Stacking method, when considered for computational performance and operational efficiency, aligns with or surpasses deep learning methods regarding prediction accuracy and precision. Moreover, the Stacking method significantly reduced computational time. Utilizing the Stacking model for downscaling pollutant data, the study successfully generated detailed pollution distribution maps, which facilitate comparative and analytical assessment of PM2.5 and PM10 pollutant distributions alongside population distribution maps, ultimately leading to a comprehensive population risk map due to environmental pollution. This observation underscores the profound impact of population size on pollution levels, demonstrating a direct correlation between human habitation density and air quality deterioration. Furthermore, the study investigated the relationship between different demographic characteristics, e.g., age and gender, and their respective PM exposure levels. It was found that the elderly population is particularly vulnerable to pollution, indicating a demographic skew in the risk profile. Additionally, the research highlights significant variations in pollutant exposure levels across different geographical settings, including urban, rural, and industrial areas, with a consideration of land

usage patterns. These disparities shed light on the environmental impacts influenced by varying land use and urban planning. In conclusion, the findings of this study are invaluable in informing the development of effective environmental and health policies. By enhancing understanding of the relationship between particulate matter pollution, population distribution, and demographic characteristics, this research offers critical insights for policymakers to devise targeted strategies to mitigate air pollution's impact on public health, especially in densely populated and high-risk areas.

Keywords:

Particulate Matter (PM) Pollution, Machine Learning Techniques, Stacking Method, Population Health Risk Analysis

海报展示 / **71**

托克马克中相对论性粒子导心轨道分类

Author: 董晨超[None]

Co-author: 龙曾

Corresponding Author: dongcc23@mails.tsinghua.edu.cn

摘要:

本工作研究了托克马克中相对论性粒子导心轨道的分类问题，分析了相对论效应对高能电子轨道动力学的影响。通过比较非相对论和相对论情况下的拉格朗日量，发现相对论效应对轨道分类的影响主要体现在能量项的变化上，而非轨道类型的存在性。研究表明，相对论修正会导致相图上分界线的平移或形变，为理解高能电子在低密度等离子体或破裂阶段的共振过程提供了理论支持。

关键词:

逃逸电子、托克马克、导心运动

Abstract:

In this work, the classification of relativistic particle guide orbits in tokamak is studied, and the influence of relativistic effect on the dynamics of high-energy electron orbits is analyzed. By comparing the Lagrangian quantities in non-relativistic and relativistic cases, it is found that the influence of relativistic effect on orbital classification is mainly reflected in the change of energy term, rather than the existence of orbital type. The study shows that the relativistic correction will lead to the translation or deformation of the boundary on the phase diagram, which provides theoretical support for understanding the resonance process of high-energy electrons in low-density plasma or disruption stage.

Keywords:

runaway electron, tokamak, guiding-center motion

海报展示 / **79**

HTR-PM600 新燃料贮存容器内球床力学行为模拟研究

Authors: 梦瑶王[None]; 悦李[None]; 金华王[None]

Corresponding Authors: lyue@tsinghua.edu.cn, wmy23@mails.tsinghua.edu.cn, wangjinhua@tsinghua.edu.cn

摘要:

本文采用基于赫兹接触的 FEM 耦合 DEM 方法，对 HTR-PM600 新燃料贮存容器内规则排列球床在 15m 跌落工况下的冲击破坏行为展开研究，通过试验对数值计算准确性进行验证。结果表明

对法向赫兹接触曲线进行线性化处理可以在提高计算效率的同时，使计算精度处于可接受范围。以往的研究中，一般认为跌落工况下球床受力从容器底部到顶部依次减小，碎球主要集中在容器底部。然而，本研究的试验和模拟均发现了球床受力的离散性、分层性和链式传递特性，表明受力分布具有显著的非均匀性。本研究不仅深化了对规则排列球床破坏机制的理解，还为工程设计和安全评估提供了新的理论依据，为后续优化燃料容器性能奠定了重要基础。

关键词:

赫兹接触；离散单元法；链式传递；离散性；规则排列球床

Abstract:

This article uses a combination of the Discrete Element Method (DEM) and the Finite Element Method (FEM) based on Hertz contact theory to study the impact failure behavior of the regularly arranged pebble-bed in the HTR-PM600 fresh fuel storage canister under 15m drop conditions. The accuracy of numerical calculations is verified through experiments. Linearizing the normal Hertz contact curve can improve computational efficiency while maintaining acceptable accuracy. In previous studies, it was generally believed that the force within a canister decreases sequentially from the bottom to the top under drop conditions, and the broken pebbles were mainly concentrated at the bottom of the container. However, both the experiments and simulations in this study discover the discreteness, layering, and chain transmission characteristics of the force on the pebble-bed, indicating significant non-uniformity in the force distribution. This study not only deepens the understanding of the failure mechanism of regularly arranged pebble-bed, but also provides new theoretical basis for engineering design and safety assessment as well as important foundation for optimizing the performance of fuel canisters in the future.

Keywords:

Hertz contact; discrete element method; chain transfer, discreteness; regularly arranged pebble-bed

海报展示 / **80**

一种基于多层涂硼圆筒的 γ 补偿中子探测器的仿真研究

Authors: 鹏唐[1]; 嘉豪常[1]; 朝阳朱[1]; 新程向[1]

[1] 清华大学

Corresponding Authors: changjh23@mails.tsinghua.edu.cn, inetxxc@tsinghua.edu.cn, tp22@mails.tsinghua.edu.cn, zhucy20@mails.tsinghua.edu.cn

摘要:

硼涂层电离室因其强大的辐射耐受性、长寿命、耐高温高湿度以及可靠的性能，被广泛应用于反应堆外部核仪表系统中的中子探测。这些电离室在核能、辐射防护和放射医学中有着广泛的应用。硼涂层电离室中的电信号主要由伽马射线和中子产生，通过补偿技术可以显著降低伽马噪声。然而，由于可能存在补偿误差，伽马噪声仍可能影响中子信号。在低中子通量和高伽马噪声条件下，传统的硼涂层电离室信噪比较低，导致中子信号被伽马噪声掩盖，难以准确测量中子通量。为了提高硼涂层电离室的中子探测效率和灵敏度，本研究提出了一种基于平行板伽马补偿电离室的多层硼涂层圆柱体结构的新设计。这种新结构显著增加了单位体积内的有效硼涂层体积，取代了传统仅在电极表面涂覆硼化合物的方法，从而提高了中子探测效率。通过结合 Geant4、Garfield++ 和 SRIM 的联合模拟，优化了电离室的结构参数，并计算了改进前后的中子探测效率。模拟结果表明，改进后的硼涂层电离室中子探测效率显著提高，为实际中子探测应用提供了一种有前景且可靠的解决方案。

关键词:

关键词：硼涂电离室；中子探测器；伽马补偿；蒙特卡洛仿真

Abstract:

The boron-coated ionization chamber is widely used in neutron detection for reactor external nuclear instrumentation systems due to its strong radiation resistance, long service life, high-temperature and

humidity tolerance, and reliable performance. These ionization chambers find extensive applications in nuclear energy, radiation protection, and radiological medicine. The electrical signals in boron-coated ionization chambers are primarily generated by gamma rays and neutrons, with gamma noise significantly reduced through compensation techniques. However, due to potential compensation errors, gamma noise may still affect the neutron signal. Under low neutron flux and high gamma noise conditions, traditional boron-coated ionization chambers exhibit a low signal-to-noise ratio, leading to neutron signals being obscured by gamma noise, making accurate neutron flux measurements difficult. To enhance the neutron detection efficiency and sensitivity of boron-coated ionization chambers, this study proposes a novel design that incorporates a multilayer boron-coated cylindrical structure based on a parallel-plate gamma compensation ionization chamber. The new structure significantly increases the effective boron-coated volume per unit volume, replacing the traditional method of coating boron compounds only on electrode surfaces, thereby improving neutron detection efficiency. Using combined simulations with Geant4, Garfield++, and SRIM, the structural parameters of the ionization chamber were optimized, and the neutron detection efficiency before and after improvement was calculated. Simulation results demonstrate a significant enhancement in neutron detection efficiency with the improved boron-coated ionization chamber, providing a promising and reliable solution for practical neutron detection applications.

Keywords:

Key words: boron coated ionization chamber; Neutron detector; Gamma compensation; Monte Carlo simulation

海报展示 / **83**

Beam Shaping Based on Axisymmetric Aspheric Mirrors

Author: 陈志浩[1]

[1] 清华大学工程物理系

Corresponding Author: zh-chen23@mails.tsinghua.edu.cn

摘要:

平顶光束因其能够在照射区域内提供均匀的光强分布，广泛应用于科学研究与工业领域。本研究提出一种基于两片轴对称非球面反射镜（axisymmetric aspheric mirrors, AAMs）、偏振分光器及两片四分之一波片的反射式激光光束整形方法，用以将高斯光束转换为平顶光束。与其他光束整形方法相比，基于 AAMs 的整形方案在能量利用效率和输出平行光束的能力方面具有显著优势。

关键词:

光束整形；非球面反射镜；高斯光束；平顶光束

Abstract:

Flat-top beam, known for its ability to generate a consistently even irradiation area, holds vast utility in many fields of scientific and industrial applications. In this paper, a reflective laser beam shaping method based on two axisymmetric aspheric mirrors (AAMs), a polarizing beam splitter (PBS) and two quarter wave plates (QWPs) is proposed to transform Gaussian beam into flat-top beam. Compared to alternative beam shaping methods, the method using AAMs demonstrates distinct advantages on notably high energy efficiency and unique capability to generate parallel beams. Thanks to its relative simplicities of design, manufacture and tunability, AAMs-shaping further enhances its appeal in applied research scenarios.

Keywords:

beam shaping; aspheric mirror; Gaussian beam; flat-top beam

海报展示 / **87**

不确定性感知卷积自编码器在核电厂异常检测中的应用

Author: 豪王[1]

Co-author: 金岑马 [1]

[1] 清华大学工程物理系

Corresponding Author: 1391904724@qq.com

摘要:

作为预测与健康管理的关键组成部分，异常检测对于确保核电厂的稳定运行和安全至关重要。随着人工智能技术的快速发展，深度学习在异常检测方面取得了重大进展。然而，关于核电厂深度学习中不确定性量化的研究仍然有限。本文提出了一种不确定性感知卷积自编码器（UAC-AE），用于核电厂时间序列数据的无监督异常检测。该方法结合了卷积神经网络在特征提取方面的优势以及贝叶斯神经网络提供的不确定性估计。核心思想是在自编码器中引入基于蒙特卡洛丢弃的变分推理，这允许在有效重建输入数据的同时，在重建过程中评估认知不确定性和偶然不确定性。实验结果表明，UAC-AE 在异常检测方面优于传统的自编码器方法，特别是在有噪声的背景条件下。该模型不仅提高了异常检测的准确性，还提供了有价值的不确定性信息。这项研究强调了在异常检测中考虑不确定性的重要性和优势，为提高实际核电厂的可靠性和安全性提供了一种有效的解决方案。

关键词:

核电厂，异常检测，卷积自编码器，不确定性感知

Abstract:

As a critical component of Prognostics and Health Management, anomaly detection (AD) is crucial for ensuring the stable operation and safety of nuclear power plants (NPPs). With the rapid development of artificial intelligence technologies, deep learning has made significant strides in AD. However, research on uncertainty quantification in deep learning for NPPs remains limited. This paper proposes an Uncertainty-Aware Convolutional Autoencoder (UAC-AE) for unsupervised AD in time-series data from nuclear power plants. This approach combines the strengths of Convolutional Neural Networks in feature extraction with the uncertainty estimation offered by Bayesian Neural Networks. The core idea is to introduce the Monte Carlo Dropout-based variational inference in the autoencoder, which allows for effective reconstruction of the input data while evaluating both epistemic and aleatoric uncertainty in the reconstruction process. Experimental results demonstrate that UAC-AE outperforms traditional autoencoder methods in AD, particularly in noisy background conditions. The model not only improves the accuracy of AD but also provides valuable uncertainty information. This study highlights the importance and advantages of considering uncertainty in AD, offering an effective solution to enhance the reliability and safety of actual NPPs.

Keywords:

Nuclear Power Plants, Anomaly Detection, Convolutional Autoencoder, Uncertainty Aware.

海报展示 / **94**

锂诱导的共价有机框架材料增强吸附热用于高效储氢

Author: 茁卓汤[1]

[1] 清华大学核能与新能源技术研究院

Corresponding Author: tangzz21@mails.tsinghua.edu.cn

摘要:

共价有机框架材料（COFs）具有高比表面积和可调节的孔结构，是极具潜力的氢气物理吸附材料。1 然而，其与氢气分子之间的相互作用过于微弱，无法充分发挥 COFs 材料的高孔隙率优势。本研究首次报道了一种通过金属掺杂增强氢气物理吸附性能的 COFs 材料。借助 TPB-DMTP-COF 材料出色的稳定性，我们在锂（Li）掺杂后成功保留了 COF 材料的孔结构，其比表面积达到 1350 m2/g。由于锂掺杂提高了材料对氢气的吸附热，材料在 77 K、80 bar 条件下的总氢气吸附量从 4.98 wt% 提升至 6.91 wt%。锂掺杂引起的增强效应不涉及化学吸附，且材料表现出优异的循环性能：在 30 bar 条件下循环 10 次后容量保持率达 99%。研究结果表明，通过后修饰调控氢气的吸附热是充分开发多孔材料潜力、实现高效氢气储存的有效策略。

关键词:

共价有机框架材料；氢气存储；锂掺杂；气体吸附；吸附热

Abstract:

Covalent organic frameworks (COFs) possess high surface areas and tunable pore structures and are promising candidates for H2 physisorption materials. However, their interaction with H2 molecules is too weak to take advantage of the high porosity of the COFs. Here, we report the first example of metal-doped enhanced H2- physisorption COF. By leveraging the superior stability of TPB-DMTP-COF, we can well preserve the porosity of the COF after lithium (Li) doping, yielding a surface area of 1350 m2/g. Due to the Li-doping-enhanced H2 isosteric heat, the material's total H2 uptake increased from 4.98 to 6.91 wt % at 77 K and 80 bar. The Li-doping-induced enhancement effect does not involve chemisorption, and the material shows excellent cycling performance: 10 cycles at 30 bar with a capacity retention of 99%. Our results reveal that tuning H2 adsorption heat by postmodification is a promising strategy to exploit the potential of porous materials for efficient H2 storage.

Keywords:

Covalent Organic Frameworks; H2 storage; Lithium Doping; Gas adsorption; Sorption heat

海报展示 / **100**

位置灵敏 **3He** 管探测器读出电子学研究

Author: 南华[1]

[1] 清华大学工程物理系

Corresponding Author: huan20@mails.tsinghua.edu.cn

摘要:

无

关键词:

数字信号处理、中子探测器、3He 探测器、位置分辨率、读出电子学

Abstract:

无

Keywords:

无

海报展示 / **102**

高海拔公路隧道紧急停车带火灾烟气控制研究

Author: 冉辰皓[1]

Co-authors: 吴乐 [1]; 李峰 [2]; 袁东 [3]; 钟茂华 [1]

[1] 清华大学安全科学学院

[2] 城关区消防救援局

[3] 中交二公局第四工程有限公司

Corresponding Author: 310320257@qq.com

摘要:

本研究通过全尺寸实验和数值模拟，研究了不同气压下应急停车场火灾烟雾的控制。当烟气在应急停车场边缘遇到横截面积变化时，部分烟雾向上游扩散，而部分烟气沉降后再循环。气压的降低会加速烟气的扩散，使烟气控制变得困难。为了通过纵向通风在火源侧紧急停车时控制火灾烟气，所需的控制速度比普通隧道中高 30-60%。当考虑通过纵向通风控制紧急停车带中的烟气时，应急响应的时间增加，但所需的控制速度没有显著降低，这表明紧急停车带结构不利于烟气控制，会导致火灾风险增加。

关键词:

紧急停车带；火灾烟气；环境压强；控制风速

Abstract:

This study investigates the control of fire smoke in emergency lay-bys under different air pressures through full-scale experiments and numerical simulations. When smoke encounters a change in cross-sectional area at the edge of the emergency lay-by, part of the smoke diffuses upstream, while some smoke recirculates. A decrease in air pressure accelerates the diffusion of smoke, making smoke control more challenging. To control the fire smoke in the emergency lay-by on the fire source side through longitudinal ventilation, the required control velocity is 30-60% higher than that in a regular tunnel. When considering the control of smoke in the emergency lay-by via longitudinal ventilation, the response time increases, but the required control velocity does not significantly decrease, indicating that the emergency lay-by structure is unfavorable for smoke control and increases the fire risk.

Keywords:

emergency lay-by; fire smoke; ambient pressure; control velocity

海报展示 / **104**

Calculation of response matrices for GRID CubeSat gamma-ray detectors

Author: 潘晓凡[None]

Co-authors: 刘奇泽 [1]; 杨紫瑞 [1]; 高怀众 [1]; 李红 [1]; 曾鸣 [1]; 冯骅 [2]; 曾志 [1]; 王奇东 [1]; 李龙昊 [1]

[1] 清华大学

[2] 中国科学院高能物理研究所

Corresponding Authors: pxf21@mails.tsinghua.edu.cn, zengming@tsinghua.edu.cn

摘要:

空间分布式伽马射线暴探测网（天格计划）是一个旨在监测空间高能瞬变源的项目，该项目使用紧凑型的伽马射线探测器作为微纳卫星的有效载荷，用多个卫星组网进行观测。为了从探测器测得的能量信息重建出所观测到的瞬变源的能谱，我们需要详细了解探测器的响应特性，该响应特性是通过响应矩阵描述的。为此，我们计算了已发射的天格计划探测器的响应矩阵，并使用在轨观测数据验证了它们的准确性。我们首先使用 Geant4 进行蒙特卡罗模拟，计算了不同条件下伽马射线光子在探测器中的能量沉积，然后根据地面标定得到的能量分辨率对模拟结果进行校正，以最终得到响应矩阵。此外，我们还建立了一个用于插值的响应矩阵数据库，以便于快速生成对

应于任何入射方向的响应矩阵。我们通过对天格计划探测器在轨观测到的伽马射线暴进行能谱拟合，验证了响应矩阵的正确性。基于上述计算方法，我们在发布天格计划科学数据的同时提供响应矩阵生成工具，从而有效提高对天格计划观测数据开展科学分析的效率。

关键词:

空间仪器；伽马射线探测器；能谱响应

Abstract:

The Gamma-Ray Integrated Detectors (GRID) mission aims to monitor high energy transients in space with multiple CubeSats carrying compact gamma-ray detectors as payloads. Reconstructing the energy spectra of detected bursts from the measured detector output energies requires detailed knowledge of the detector response characteristics, which are represented by response matrices. We calculate the response matrices for each GRID detector that has been launched and verify their accuracy using in-orbit data. In this work, Monte Carlo simulations with Geant4 are employed to calculate the energy deposition of gamma-ray photons in the detectors under various conditions. The response matrices are then generated by adjusting the simulation results based on the energy resolution obtained from on-ground calibrations. In addition, we establish a database of response matrices designed for interpolation, enabling efficient generation of matrices for any incident direction. The generated response matrices are verified through spectra fittings of gamma-ray bursts (GRBs) observed by GRID detectors in orbit. Building on the calculation method described above, we provide a response matrix generation tool alongside the release of GRID scientific data, enabling convenient scientific analysis for the GRID mission.

Keywords:

space instrumentation, gamma detectors, spectral responses

海报展示 / **107**

Application and Prospects of Multimodal Data Fusion UAV Systems for Landmine Detection

Author: 煌唐[None]

Co-author: 自然赵

Corresponding Author: tang-h24@mails.tsinghua.edu.cn

摘要:

当前国际形势纷繁复杂，局部冲突和动荡频发，地雷探测面临日益严峻的挑战，特别是在俄乌冲突、巴以冲突等局部冲突中，地雷的大量使用，使地区安全风险直线上升。传统以基于人工为主的地雷探测方法，效率和准确性都满足不了需求，无人机正在成为地雷探测关注的热点。无人机配上各种传感器，通过整合光学、红外、雷达、磁力计等这些传感器的数据，可以有效克服单一传感器所带来的局限性，从而显著增强地雷探测的精确度和可靠性。本文详细分析了多模态数据融合无人机地雷探测的架构，并讨论了数据融合在地雷探测数据处理中的重要作用。最后，论文探讨了无人机地雷探测技术当前研究的热点和主要挑战，及可能的未来发展趋势。

关键词:

地雷探测，多模态，数据融合，无人机

Abstract:

The current international situation is complex, with frequent local conflicts and turmoil, which bring huge and increasing challenges to landmine detection. Especially in some local conflicts, such as the Russia-Ukraine and Israel-Palestine conflicts, the extensive use of landmines sharply increases regional security risks. Traditional landmine detection methods mainly rely on manpower and cannot meet the demands for efficiency and accuracy. Currently, UAVs are becoming a new method for landmine detection. With equipped multifarious sensors, UAVs integrate data from optical, infrared, radar, and magnetometer sensors, which effectively overcomes the limitations of a single sensor, thereby significantly improving the precision and reliability of landmine detection. This paper presents a comprehensive study of the architecture of a multimodal data-fusion UAV system for landmine detection and discusses

the critical role of data fusion in processing landmine-detection data. In addition, we discuss current research hotspots, major challenges, and potential future development trends in UAV landmine detection technology. The present review attempts to serve as a reference for research and practice in the field of landmine detection and believes that multimodal UAV technology will be increasingly integrated into global demining.

Keywords:

landmine detection, multimodal, data fusion, UAVs

海报展示 / **115**

Energy and timing resolution boost with waveform analysis

Author: 宇逸王[None]

Corresponding Author: wangyy21@mails.tsinghua.edu.cn

摘要:

在中微子或暗物质实验中，为了在液闪探测器中重建事例的能量和时间，我们需要分析 PMT 读出的波形。快速随机匹配追踪（FSMP）可以对每个波形从光电子（PE）时间序列的后验分布采样。它在 GPU 上得以加速，最终在液闪探测器中提升能量和时间分辨率。能量的分辨率的提升为降低 12% 的相对分辨率。

关键词:

波形分析, 重建, GPU 加速

Abstract:

To reconstruct the energy and time of events in the liquid scintillator detector, in a neutrino or dark matter experiment, we need to analyze the waveforms from photomultiplier tubes (PMTs). Fast Stochastic Matching Pursuit (FSMP) samples the posterior of PE time sequence for each waveform. It gains acceleration on GPU, and improves the energy and time resolution of LS detectors. The energy resolution is improved by decreasing 12% of relative resolution.

Keywords:

waveform analysis, reconstruction, GPU acceleration

海报展示 / **118**

Online Detection of Early Thermal Runaway Gas Characteristics: A Comparative Study of Two Types of Lithium Batteries

Author: 钰珧曹[None]

Co-authors: 亚彭 [1]; 振翔陶 [1]; 锐杨 [2]; 辉张 [2]

[1] 中国矿业大学（北京）

[2] 清华大学

Corresponding Author: caoyy21@mails.tsinghua.edu.cn

摘要:

锂离子电池热失控过程中产生的气体会严重影响储能系统的安全性，因此需要探索气体检测技术，以了解气体的产生机制并增强安全预警技术。本研究提出了一种新型气体监测方法，该方法

将传统气体传感器与可调谐二极管激光吸收光谱 (TDLAS) 相结合，用于检测热失控前甚至首次排气阶段的气体排放。测试了两种类型的电池：磷酸铁锂圆柱电池和新鲜的三元圆柱电池。这些电池置于受控过热条件下，以模拟逐渐发生的热失控过程，从而可以充分监测早期气体的产生。研究了电池类型对排气气体变化的影响，包括临界热失控阶段、气体浓度和检测响应时间。特别是，通过 TDLAS 实时测量的甲烷变化曲线揭示了磷酸铁锂电池初始排气事件之前甲烷浓度值便有上升趋势，有效实现了早期检测，而这些是传统传感器在热失控极端情况下无法实现的。这凸显了光学方法在监测早期气体排放特性的巨大潜力。此外，我们还对比了各种气体传感器的响应时间序列，这对于在预警系统中建立实际响应阈值至关重要。

关键词:

储能电站安全，锂离子电池，原位检测，TDLAS

Abstract:

The emission of gases during the thermal runaway of lithium-ion batteries (LIBs) significantly impacts energy storage system safety, prompting exploration into gas detection technologies to understand gas generation mechanisms and enhance safety warning technologies. In this study, we present a novel gas monitoring approach that integrates traditional gas sensors with Tunable Diode Laser Absorption Spectroscopy (TDLAS), to detect gas venting before thermal runaway and even the first venting period. Two types of LIBs were tested: fresh LFP 26650 cells and fresh NCM 18650 cells. These cells were subjected to controlled overheating conditions to simulate a gradual thermal runaway process, where the early gas generation can be monitored sufficiently. The effects of the LIB type on venting gas variation were studied, including critical thermal runaway phase, gas concentration and detection response time. In particular, the real-time CH4 change curves via TDLAS reveal distinct concentration values and early detection of CH4 before the initial venting event in LFP cells, which the sensor cannot realize without disturbance. This highlights the strong potential for verification of early gas venting characteristics through optical methods. Additionally, we delineate the response time sequence of various gas sensors, crucial for establishing practical response thresholds in warning systems.

Keywords:

Energy storage station safety, Lithium-ion battery, In-situ detection, TDLAS

海报展示 / **40**

实现能量低于 **3 MeV** 且具有低能散的强流质子束横向均匀分布

Author: 李文亮[None]

Co-authors: 毕崇博; 杜畅通; 胡闯; 汪星辰; 吴锦鹏; 严肃; 张化一; 邢庆子; 郑曙昕; 关遐令; 王学武

Corresponding Author: 1213109904@qq.com

摘要:

基于质子辐照的载流子寿命控制可以提升二极管和绝缘栅双极晶体管等功率半导体器件性能，如降低漏电流、减小反向恢复损耗等，其典型辐照能量低于 3 MeV。基于清华大学电机系功率半导体辐照需求，在清华大学微型脉冲强子源 13 MeV 强流质子直线加速器基础上，通过衰减掉进入到 DTL 加速器中的微波功率，在 DTL 出口获得能量为 3 MeV 的质子束流，并通过铝降能片进一步降能，能够保证质子束流能散低于 0.2 MeV。通过非线性磁铁法与扩束法相结合的方式获得直径 149 mm 辐照范围内的束流不均匀性为 9.8%，并通过靶片旋转的方式进一步降低束流不均匀性到 4% 以下。

关键词:

质子辐照，束流均匀化，微型脉冲强子源

Abstract:

Carrier lifetime control through proton irradiation has proven effective in enhancing the performance of power semiconductor devices such as diodes and insulated gate bipolar transistors (IGBTs), offering advantages including reduced leakage currents and suppressed reverse recovery losses, with typical

irradiation energies below 3 MeV. To fulfill the proton irradiation demands for power semiconductor research at Tsinghua University's Department of Electrical Engineering, a tailored irradiation system was developed based on the existing 13 MeV high-current proton linear accelerator at the Compact Pulsed Hadron Source (CPHS). By attenuating the microwave power fed into the Drift Tube Linac (DTL), a 3 MeV proton beam was extracted at the DTL exit, followed by energy reduction using aluminum degraders while maintaining a beam energy spread below 0.2 MeV. To achieve uniform irradiation across a 149 mm diameter area, beam uniformity was optimized through a synergistic approach integrating beam expansion and nonlinear magnet method, yielding an initial beam nonuniformity of 9.8%. This uniformity was further improved to below 4% by implementing dynamic target rotation during irradiation.

Keywords:

Proton irradiation, Uniform distribution, CPHS

海报展示 / **108**

非极端相对论的阻抗壁尾场计算

Author: JIAZHEN TANG[1]

[1] *Tsinghua University*

Corresponding Author: tjz21@mails.tsinghua.edu.cn

摘要:

非相对论尾场函数理论不仅适用于质子或重离子加速器，而且随着新的加速器物理理论的出现，人们发现它同样适用于诸如稳态微聚束（SSMB）储存环之类的电子加速器。然而，现有的研究成果距离实际应用仍有很大差距。在本文中，我们在前人工作的基础上，进一步将之前的点源模型推广为更具普遍性的环模型。当考虑非相对论极限情况时，我们发现了一种全新的最低阶横向尾场，并估计在某些情况下其强度可与偶极场相当。此外，通过分离空间电荷分量，我们提出了一种能够更高效计算电阻壁场的数值算法。最后，作为简单应用，我们利用稳态微聚束（SSMB）的参数计算了寄生损耗和踢角。

关键词:

阻抗壁尾场非极端相对论

Abstract:

The Non-Ultrarelativistic Wake Function theory is not only applicable to proton or heavy ion accelerators. But with the emergence of new accelerator physics, it has been found to be equally applicable to electron accelerators such as the Steady State Micro Bunching (SSMB) storage rings.
However, existing results are still far from practical applications. In this paper, building on previous work, we further generalize the previous point source model into a more universal ring model.
When considering the non-ultrarelativistic limit, we discover a completely new lowest-order transverse wake field and estimate its intensity to be comparable to the dipole field on certain circumstance.
Moreover, by separating the space charge component, we propose a numerical algorithm that can compute the Resistive Wall field more efficiently.
Finally, we calculate the Parasitic Loss and Kick Angle using SSMB's parameters as simple applications.

Keywords:

resistive wall, wakefield, non-ultrarelativistic

海报展示 / **119**

中国女性乳腺系列精细面元模型的建立及研究

Author: 青云李[1]

[1] 工程物理系

Corresponding Author: 1354070327@qq.com

摘要:

乳腺癌以成为世界第一大癌症，乳腺对 DM 等外照射辐射极为敏感，因此需要通过精细且可变性的方式对乳腺外照射剂量进行准确的评估。然而国际通用模型大多采用高加索人的乳房特征进行建模，这并不符合中国女性乳房特征，影响剂量评估的准确性，因此亟需建立一套符合我国女性乳房结构的面元模型。本文采用中国女性内衣数据，采用数学方法生成了一套精细的符合中国女性乳房特征的系列乳房模型，模型中建立了腺体内脂肪组织、输乳管及 TDLU 腺小叶等多种精细结构，且该系列包含了 AA、A、B、C、D 五种尺寸的乳房模型，同时每类乳房模型中又分别建立腺体含量分别为 25%、50% 和 75% 的三组乳腺模型。同时通过蒙塔卡罗模拟计算并绘制了 AP 几何照射场景中不同模型参数下腺体剂量转换系数随不同能量光子照射的变化曲线，探究了影响乳腺腺体剂量转换系数的因素。

关键词:

面元模型；剂量转换系数；中国女性特征

Abstract:

Breast cancer has become the most prevalent cancer worldwide. Given the high radiosensitivity of breast tissue to external radiation such as diagnostic mammography (DM), accurate assessment of the external radiation dose to the breast is critically important. However, most internationally used models are based on the anatomical characteristics of Caucasian women, which do not adequately represent the breast morphology of Chinese women, thus affecting the accuracy of dose assessment. Therefore, there is an urgent need to develop a mesh-based breast model that reflects the anatomical features of Chinese women. In this study, we constructed a series of high-resolution breast models based on anthropometric data derived from Chinese women's underwear sizes. The models incorporate detailed anatomical structures, including adipose tissue within the glandular region, milk ducts, and terminal duct lobular units (TDLUs). The series includes five cup sizes—AA, A, B, C, and D—each further subdivided into three glandular content levels: 25%, 50%, and 75%. Monte Carlo simulations were performed to calculate and visualize the variations in glandular dose conversion coefficients under anterior-posterior (AP) irradiation scenarios across different photon energies. The study also explores key factors influencing glandular dose conversion, providing critical insights for improving the accuracy of breast dose assessments in Chinese women.

Keywords:

mesh-based model; dose conversion coefficient; anatomical characteristics of Chinese women

海报展示 / **125**

Intelligent Building Fire Evacuation Indication System Based on Edge Computing Devices

Author: 佩王[1]

Co-authors: 亚彭; 嘉明柳; 辉张

[1] 安全学院

Corresponding Author: wp20@mails.tsinghua.edu.cn

摘要:

近年来，城市建筑呈现出数量多、规模大、内部结构复杂等特点，这些特征给建筑安防和消防安全带来了重大挑战。特别是在火灾事故中，人员伤亡已成为主要的安全隐患。及时有效的疏散引

导能显著降低火灾造成的危害。针对这一问题，本文提出建立一种基于边缘计算设备、运用人工智能算法的集成式火灾报警与疏散引导系统，兼具安防与消防双重功能。该系统在正常情况下主要发挥安防作用，实时检测并追踪行人；当火灾发生时，可根据检测到的人员数量和火源位置提供火灾预警并计算最优疏散路径。通过实际部署测试，验证了该系统的可行性。最后，本文讨论了系统当前存在的问题并展望了未来工作方向。

关键词:

建筑安全；火灾预警；火灾疏散；行人检测与追踪

Abstract:

In recent years, urban buildings have exhibited characteristics such as a high quantity, large scale, and complex internal structures. These features pose significant challenges for both building security and fire safety. Particularly concerning fire incidents, casualties have become a major safety concern. Timely and effective evacuation guidance can significantly reduce the harm caused by fires. Addressing this issue, this paper proposes the establishment of an integrated fire alarm and evacuation guidance system based on edge computing devices and utilizing artificial intelligence algorithms for both security and fire safety purposes. This system primarily functions as a security measure during normal circumstances, detecting and tracking pedestrians in real-time. In the event of a fire, it can provide fire warnings and calculate the optimal evacuation routes based on the detected number of pedestrians and the location of the fire source. Through empirical testing, the feasibility of this system has been demonstrated. Finally, this paper discusses the current issues with the system and outlines future work.

Keywords:

Building safety；Fire warning；Fire evacuation；Pedestrian detection and tracking

海报展示 / **128**

一种新的 **PCD** 电荷共享分析与补偿方法

Author: 晟梓赵[1]

[1] 清华大学

Corresponding Author: zhaosz21@mails.tsinghua.edu.cn

摘要:

光子计数探测器（PCDs）在获取计算机断层成像（CT）中的光谱信息方面具有显著优势。然而，它们的应用受到电荷共享和脉冲堆积的限制。在本工作中，我们提出了一种新的数学模型，用于研究电荷共享如何逐像素影响探测到的光子数值。基于一致探测器响应的假设，我们的模型根据电荷共享事件的来源和去向进行分类，并建立了入射光子数与探测光子数之间的关系。该模型表明，对于传统探测器而言，电荷共享补偿问题始终是病态的。然而，通过引入耦合计数器提供更多电荷共享的信息，可显著缓解该问题的病态性。我们初步采用 Levenberg-Marquardt 算法求解该问题。借助蒙卡模拟获得的数据，我们验证了该模型的正确性以及用于电荷共享校正的有效性。

关键词:

光子计数探测器，能谱 CT，电荷共享，解析模型

Abstract:

Photon counting detectors (PCDs) offer significant advantages in capturing spectral information in computed tomography (CT). Nevertheless, their application faces limitations due to charge sharing and pile-up. In this abstract, we proposed a new analysis about how charge sharing affected the detected counts of photons pixel by pixel. By assuming uniform charge sharing probabilities across all detector pixels, our model addressed diverse charge sharing events based on their sources and destinations, and established relationships between the numbers of incident photons and detected photon counts. Our analysis reveals that the charge sharing compensation problem was always ill-posed for conventional detectors. However, MEICC detectors provide a well-determined solution to this issue by providing coincidence

counts of photons in more channels. We preliminarily applied Levenberg-Marquarelt algorithm to solve the inverse problem. Utilizing data obtained from a MEICC detector, we achieved stable and physically meaningful solutions while conventional detectors could not achieve. The results demonstrated that the impact of charge sharing has been effectively mitigated.

Keywords:

PCD, spectral CT, charge sharing, analytical model

海报展示 / **105**

Research on Waveform Reconstruction of Imaging Photoplethysmography

Author: 朋飞崔[1]

Co-authors: 劲天唐 [1]; 明南赫 [1]

[1] 清华大学工程物理系

Corresponding Authors: 18813118955@163.com, mnhe@mail.tsinghua.edu.cn, tangjt@mail.tsinghua.edu.cn

摘要:

心脏信号对于评估人体的健康和情绪状态非常重要，心率变异性等特征在情绪识别、压力测试中应用广泛，成像光电容积描记（iPPG）信号可以实现远程非接触式的监测，从 iPPG 信号中可以计算心跳间期和 HRV 等特征，具有广大的应用前景。这些特征均依赖于心跳峰值的准确定位。但是目前传统的 iPPG 信号提取方法提取的信号质量较差，容易受到干扰产生非正常峰值，影响心跳间期的计算，本文主要从神经网络处理 iPPG 信号的角度进行研究，提出了一种 IMTransformer 神经网络对 iPPG 信号进行波形重构，该网络对传统 Transformer 网络结构进行了改进，加入 GRU 结构加强信号近端间的联系。同时计算了传统 Transformer 网络和语音增强中使用的 SETransformer 网络的处理结果，将其与已有文献使用的 LSTM 和 PulseGAN 神经网络结果进行对比。对比结果验证了本文提出的 IMTransformer 神经网络的有效性和优越性，该网络可降低心率计算误差、提高 iPPG 波形的信噪比和波形一致性，结果证明了通过 iPPG 计算更可靠的心脏特征如 HRV 特征的可行性，为面部视频在压力检测、情绪分类等领域拓宽应用奠定了基础。

关键词:

成像式光电容积描记术、神经网络、心率计算、波形重构

Abstract:

Cardiac signals are crucial for assessing human health and emotional states. Features such as heart rate variability (HRV) are widely applied in emotion recognition and stress testing. Imaging photoplethysmography (iPPG) enables remote, non-contact monitoring, from which heartbeat intervals and HRV can be derived, demonstrating broad application prospects. These features rely on accurate detection of heartbeat peaks. However, traditional iPPG signal extraction methods often yield poor-quality signals susceptible to interference-induced artifacts, which compromise heartbeat interval calculations. This study explores neural network-based approaches for iPPG signal processing and proposes an IMTransformer network for waveform reconstruction. The network improves upon the traditional Transformer architecture by incorporating a GRU structure to enhance local temporal dependencies. Comparative experiments evaluate the proposed IMTransformer against conventional Transformers, SE-Transformer (used in speech enhancement), and existing methods (LSTM and PulseGAN) from literature. Results validate the superiority of IMTransformer in reducing heart rate calculation errors, improving signal-to-noise ratio (SNR), and enhancing waveform consistency. This work demonstrates the feasibility of deriving reliable cardiac features (e.g., HRV) from iPPG signals, laying the foundation for expanding the application of facial video analysis in stress detection and emotion classification.

Keywords:

Imaging photoplethysmography; IMTransformer; Heart rate calculation; Waveform reconstruction

海报展示 / **66**

1D Time-varying Temperature Prediction Based on PINN

Authors: 俊孙[1]; 勇刘[2]

[1] 清华大学核能与新能源技术研究院

[2] 核能与新能源技术研究院

Corresponding Author: liuyong24@mails.tsinghua.edu.cn

摘要:

本文探究了运用物理信息神经网络解决一维时变无限大平板温度场问题的可行性，并将该方法与传统数值方法进行了对比。物理信息神经网络将物理原理融入学习算法，为处理复杂的偏微分方程问题提供了一种新方法。在本研究中，分别对有内热源和无内热源的一维时变无限大平板的温度场进行了研究。研究结果表明，物理信息神经网络无需网格划分，仅依靠随机采样点就能达到与传统数值方法相当的求解精度和速度。尽管如此，物理信息神经网络在解决更复杂热传导问题上的有效性仍需进一步研究。

关键词:

PINN；一维时变无限大平板；热传导；数值方法

Abstract:

This paper explores the feasibility of using physical information neural network to solve the time-dimensional infinite plate temperature field problem, and compares the method with the traditional numerical method. Physical information neural networks integrate physical principles into learning algorithms and provide a new method to handle complex partial differential equation problems. In this study, the temperature field of a one-dimensional time-varying infinite plate with an internal and no internal heat source is studied respectively. The results show that the physical information neural network can achieve the same solution accuracy and speed by relying only on random sampling points. Nevertheless, the effectiveness of physical information neural networks in solving more complex heat conduction problems still needs further research.

Keywords:

PINN; one-dimensional time-varying infinite plate; heat conduction equation; numerical method

海报展示 / **129**

铅铋环境下耐腐蚀涂层的制备和性能评估

Author: 张天一[1]

[1] 清华大学工程物理系

Corresponding Author: ty-zhang21@mails.tsinghua.edu.cn

摘要:

铅冷快堆使用具有更高安全性的液态铅铋合金作为冷却剂，是颇具发展前景的先进四代堆型。本研究围绕耐铅铋腐蚀涂层，在奥氏体不锈钢基体上开展硅铬共渗涂层、司太力合金涂层、激光熔覆 Ti3SiC2 涂层的制备，分析其组成成分和微观结构。开展涂层的铅铋腐蚀实验，分析其结构完整性、力学性能、表面氧化层及物相组成变化。通过微观结构和力学性能表征，评估不同种类涂层的耐铅铋腐蚀性能，从而为铅铋快堆的工程应用提供理论支撑和技术支持。

关键词:

涂层；硅铬共渗；铅铋腐蚀；

Abstract:

The lead — bismuth fast reactor uses liquid lead — bismuth alloy as the coolant, which has high safety and promising development prospects as Generation Ⅳ.In this study, we mainly focus on the lead — bismuth corrosion resistant coatings. The chromosiliconizing coatings, the Stellite alloy coatings and the laser cladding Ti3SiC2 coatings are prepared on the austenitic stainless steel substrates, whose composition and microstructure are analyzed. The lead — bismuth corrosion resistance experiment of the coatings is carried out to analyze its structural integrity, mechanical properties, surface oxide layer, and phase composition changes. The lead — bismuth corrosion resistance of the different types of coatings is evaluated by characterizing the microstructure and mechanical properties to provide theoretical and technical support for the engineering application of the lead — bismuth fast reactors.

Keywords:

coatings; chromosiliconizing; lead — bismuth corrosion

海报展示 / **56**

Selective extraction and complexation of trivalent actinide and lanthanide by tetradentate N,O-Hybrid phenanthroline derived ligands

Authors: Chao Xu[1]; Yishi Yu[2]; Zhipeng Wang[1]

[1] *Tsinghua University*

[2] 清华大学

Corresponding Authors: yys23@mails.tsinghua.edu.cn, xuchao@tsinghua.edu.cn, wangzhipeng@mail.tsinghua.edu.cn

摘要:

菲罗啉衍生的二酰胺配体具有 N-和 O-载体的特征，是一种很有前途的萃取剂，可用于选择性分离三价锕系元素（An）和镧系元素（Ln）。本研究合成了三种具有代表性的异丙基（L1）、2,6-二甲基哌啶-1-基（L2）和吗啉基（L3）接枝 2,9-二酰胺-1,10-菲罗啉（DAPhen）配体，并探讨了它们在离子液体（IL）C4mimNTf2 中溶剂萃取三价镅（Am）和铕（Eu）的应用。斜率分析表明，在萃取 Am(III) 的情况下，2:1 配体/金属复合物是主要的物种。而在萃取 Eu(III) 时，2:1 和 1:1 复合物都会生成。分子结构与萃取行为之间的关系涉及电效应和立体效应。同时，结合吸收分光光度法、荧光光谱法、1H NMR 光谱法和单晶 X 射线衍射法进行的络合研究以及理论分析进一步阐述了萃取机理。这项研究为设计更高效的 DAPhen 配体用于 Am(III)/Ln(III) 分离提供了更深入的实验见解。

关键词:

菲罗啉衍生配体三价锕系元素和镧系元素离子液体萃取络合

Abstract:

Phenanthroline derived diamide ligand featured with N- and O-donors is one of promising extractants for the selective separation of trivalent actinides (An) over lanthanides (Ln). In the present work, three representative isopropyl (L1), 2,6-dimethylpiperidin-1-yl (L2) and morpholino (L3) grafting 2,9-diamide-1,10-phenanthroline (DAPhen) ligands were synthesized and the application in solvent extraction of trivalent americium (Am) and europium (Eu) in an ionic liquid (IL), C4mimNTf2, was probed. Slope analysis suggests the 2:1 ligand/metal complex as the dominant species in the case of extracting Am(III). While both 2:1 and 1:1 complexes are generated during the extraction of Eu(III). The relationships between molecular structures and extraction behaviors are elucidated involving electric and steric effects. Meanwhile, complexation studies in combination with absorption spectrophotometry, luminescence spectrophotometry, 1H NMR spectrometry and single crystal X-ray diffraction as well as theoretical analyses further elaborate the extraction mechanisms. This study uncovers more in-depth experimental insights into the design of more efficient DAPhen ligands for Am(III)/Ln(III) separation.

Keywords:

Phenanthroline derived ligand Trivalent actinide and lanthanide Ionic liquid Extraction Complexation

环、化、材、技、能源战略 / **7**

Polymeric Ferric Sulfate Enhanced Ionizing Radiation for Coking Wastewater Treatment

Authors: 丰程[1]; 丰程[1]; 建龙王[1]

[1] 清华大学

Corresponding Authors: wangjl@tsinghua.edu.cn, chengf22@mails.tsinghua.edu.cn, chengfeng501@163.com

摘要:

将传统水处理与电离辐射（IR）相结合，能够降低污染物去除所需的辐射剂量，使基于 IR 的高级氧化工艺（AOPs）更加高效且成本效益更高。本研究表明，将聚铁硫酸盐（PFS）与 IR 结合，能够协同提升水处理效率，同时降低能耗。IR/PFS 系统在处理焦化废水时，实现了浊度（94.3%）、UV254（69.4%）和 COD（43.6%）的同时去除，优于单独使用 IR 或 PFS。该系统还在 pH 值 3-10 和复杂水基质中实现了对双酚 A（BPA）大于 99% 的降解。

通过特性分析和 Ferron 定时络合光谱分析，揭示了 PFS 的结构稳定性和铁物种的转化趋势。PFS 具有双重功能：(i) 通过水解生成聚铁物种，用于混凝；(ii) 作为 Fenton 系统的稳定 Fe(III) 源，在水合电子介导的 Fe(III)/Fe(II) 循环和辐射分解 H_2O_2 的作用下，产生的 •OH 产量比单独辐射提高了 1.5 倍。这些发现确立了 IR/PFS 作为一种能效高的范式，将物理化学过程相结合，为可持续的水修复提供了新途径。

关键词:

电离辐照，聚合硫酸铁，铁循环，双酚 A，羟基自由基

Abstract:

Integrating traditional water treatment with ionizing radiation (IR) can decrease the radiation dose needed for pollutant removal, making IR-based advanced oxidation processes (AOPs) more efficient and cost-effective. This study demonstrated that integrating polymeric ferric sulfate (PFS) with IR synergistically enhanced water treatment efficiency while reducing energy demand. The IR/PFS system achieved concurrent removal of turbidity (94.3%), UV254 (69.4%), and COD (43.6%) in treating coking wastewater, outperforming standalone IR or PFS. It also showed >99% bisphenol A (BPA) degradation across pH 3–10 and in complex water matrices. Characterization and Ferron-timed complex spectrophotometry analyses revealed the PFS's structural stability and iron species transformation trends. PFS enables dual functionality: (i) hydrolysis generates polymeric iron species for coagulation, and (ii) it serves as a stable source of Fe(III) for the Fenton system, which is driven by a hydrated electron-mediated reduction in the Fe(III)/Fe(II) cycle and radiolytic H2O2 production, amplifying •OH yield by 1.5 times compared to radiation alone. These findings establish IR/PFS as an energy-efficient paradigm bridging physicochemical processes for sustainable water remediation.

Keywords:

ionizing radiation, polymeric ferric sulfate, Fe(III)/Fe(II) cycle, bisphenol A

环、化、材、技、能源战略 / **11**

Spatially resolved land and grid model of carbon neutrality in China

Author: 子恒朱[1]

[1] 清华大学

Corresponding Author: mrziheng@outlook.com

摘要:

中国承诺到 2060 年实现碳中和以应对全球气候变化，这将需要前所未有地部署负排放技术、可再生能源 (RE) 和配套基础设施。在太瓦级部署规模下，土地使用限制与电力系统的运行和经济特性相互作用。为解决这一问题，我们开发了一个空间分辨率资源评估和电力系统规划优化模型，该模型模拟了全年电力系统运行、省级以下可再生能源选址标准和输电连接。我们的建模结果表明，风能和太阳能必须分别扩大到 2,000 至 3,900 吉瓦，其中一条可行路径将导致 2046 年至 2060 年间每年新增 300 吉瓦的综合装机容量，是当前的三倍。考虑到当前的土地使用政策，超过 80% 的太阳能和 55% 的风能将在主要负荷中心 100 公里范围内建设。大规模低碳系统必须平衡土地使用、可再生能源资源质量、电网整合和成本等关键权衡因素。在更严格的可再生能源选址政策下，至少 740 吉瓦的分布式太阳能将在高需求地区变得经济可行，这些地区的大型项目部署受到与农业用地竞争的限制。有效的规划和政策制定对实现中国的气候目标至关重要。

关键词:

可再生能源，土地利用，电力系统建模，碳中和，中国

Abstract:

China has committed to achieve net carbon neutrality by 2060 to combat global climate change, which will require unprecedented deployment of negative emissions technologies, renewable energies (RE), and complementary infrastructure. At terawattscale deployment, land use limitations interact with operational and economic features of power systems. To address this, we developed a spatially resolved resource assessment and power systems planning optimization that models a full year of power system operations, sub-provincial RE siting criteria, and transmission connections. Our modeling results show that wind and solar must be expanded to 2,000 to 3,900 GW each, with one plausible pathway leading to 300 GW/yr combined annual additions in 2046 to 2060, a three-fold increase from today. Over 80% of solar and 55% of wind is constructed within 100 km of major load centers when accounting for current policies regarding land use. Large-scale low-carbon systems must balance key trade-offs in land use, RE resource quality, grid integration, and costs. Under more restrictive RE siting policies, at least 740 GW of distributed solar would become economically feasible in regions with high demand, where utility-scale deployment is limited by competition with agricultural land. Effective planning and policy formulation are necessary to achieve China's climate goals.

Keywords:

renewable energy, land use, power systems modeling, carbon neutrality, China

环、化、材、技、能源战略 / **29**

甲烷对 **Inconel 617** 和 **Incoloy 800H** 腐蚀和拉伸行为的研究

Author: 杜斌[1]

Co-author: 银华强

[1] 清华大学核研院

Corresponding Author: dub23@mails.tsinghua.edu.cn

摘要:

本文研究了 Inconel 617 和 Incoloy 800H 两种合金在 950℃ 下含有不同浓度甲烷（50、100、400 ppm）的氦气气氛中分别腐蚀 50、100、200 h 后的渗碳行为和拉伸行为。结果表明，Inconel 617 和 Incoloy 800H 在含 50 和 100 ppm 甲烷的氦气中腐蚀 50、100、200 h 后的微观结构变化不大，只在合金表面发生了微弱的氧化和渗碳。在含 400 ppm 甲烷的氦气中腐蚀 200 h 后，Inconel 617 在晶粒内部析出了大量的碳化铬和碳化钼。晶内渗碳引起了 Inconel 617 的脆性沿晶断裂，大幅降低了合金的极限抗拉强度和延伸率。而 Incoloy 800H 只在晶界处析出了碳化铬，引起合金发生了脆性穿晶断裂。晶界渗碳降低了 Incoloy 800H 的延伸率，但不影响极限抗拉强度。

关键词:

超高温气冷堆、镍基合金、渗碳行为、拉伸行为、痕量甲烷

Abstract:

This paper investigates the carburization and tensile behavior of Inconel 617 and Incoloy 800H after exposure to helium containing different methane concentrations (50, 100, and 400 ppm) at 950℃ for 50, 100, and 200 hours. Results indicate minimal microstructural changes for both alloys after exposure to 50 and 100 ppm methane, with only slight surface oxidation and carburization. After 200 hours of exposure to helium containing 400 ppm methane, Inconel 617 exhibited substantial intragranular precipitation of chromium and molybdenum carbides. Intragranular carburization leads to brittle intergranular fracture, significantly reducing the ultimate tensile strength and elongation of Inconel 617. In contrast, Incoloy 800H showed chromium carbide precipitation primarily at the grain boundaries, resulting in brittle transgranular fracture. Intergranular carburization reduces the elongation of Incoloy 800H but does not affect its ultimate tensile strength.

Keywords:

Very-High-Temperature Gas-Cooled Reactor, Ni-based alloy, Carburization behavio, Tensile properties, Gas corrosion on the ppm scale

环、化、材、技、能源战略 / **30**

口服工程化益生菌以实现有效的铀暴露防护

Author: 海东李[1]

[1] 兰州大学

Corresponding Author: 349939657@qq.com

摘要:

在紧急核事故中，人为核活动带来放射性核素向环境泄漏的风险 [1–3]。特别是铀作为核燃料循环中最重要的元素，在其开采、加工、燃料废料处理和贫化铀武器的使用过程中可能会释放到环境中。这些放射性污染物一旦进入水循环和生态食物链 [4]，主要通过肠道吸收在人体内积累，威胁公众健康 [5]。研究发现，被吸收的铀会长期沉积在肾脏和骨骼中，造成严重的慢性毒性。二乙烯三胺五乙酸水合三钠钙盐（Ca-DTPA）和三钠锌盐（Zn-DTPA）是美国食品和药物管理局（FDA）批准的唯一用于从体内排出锕系放射性核素的螯合剂，其他一些螯合剂仍在开发中。[6] 然而，除非在铀暴露后立即使用，否则 Ca/Zn-DTPA 的铀去除效果非常有限。因此需要一种能够适应人体的预防长期暴露生物保护剂。本研究开发了一种经基因工程改造、表达铀酰结合蛋白的益生性大肠杆菌 Nissle 1917（EcN-U），用于预防铀经口暴露引发的健康损害。该工程菌通过口服给药后，利用其固有的肠道定植特性，可在动物肠道内形成生物屏障，特异性结合饮用水中的铀酰离子，阻断其进入血液循环并加速粪便排泄。

关键词:

工程化细菌、铀酰暴露、铀酰结合蛋白

Abstract:

As a critical radionuclide in the nuclear fuel cycle, uranium if released to the environment during its mining, processing, and fuel disposal, or from depleted uranium weapons left in former war-zones, could accumulate in human bodies through oral uptake, posing high risks to the public health. In this study, probiotic Escherichia coli Nissle 1917 (EcN) genetically engineered to express a uranyl-binding protein (EcN-U) is developed to protect animals from oral uranium exposure. Leveraging its inherent intestinal colonizing ability, engineered EcN-U after oral administration could colonize in the animals'intestinal tracts and bind with uranyl in the drinking water, preventing uranyl from entering blood circulation and accelerating its clearance via feces. As the results, mice with acute oral exposure of high dose of uranyl if pretreated with EcN-U would survive from uranyl-induced death. As further demonstrated in mouse, rat and beagle dog models, animals with long-term oral exposure of uranyl if pretreated with EcN-U would show significantly reduced uranyl deposit in main organs, alleviated intestinal oxidative stress, normalized intestinal flora, as well as reduced tissue damages in other organs. Our work presents

a general prevention strategy to efficiently and continuously protect the public against radioactive containments during nuclear accidents using orally fed natural probiotics.

Keywords:

engineered bacteria, uranyl exposure, uranyl-binding protein,

环、化、材、技、能源战略 / **41**

Temperature ultra-stable BaTiO3-based ceramics with near-nano grains via the core-shell structure design and controlled grain growth

Author: 少宇莫[1]

[1] 清华大学材料学院

Corresponding Author: 905959386@qq.com

摘要:

在各类高精度仪器系统中，要求多层陶瓷电容器（MLCCs）不仅体积更小，而且具有更高的电容值。相应地，其所采用的介电材料必须同时满足高介电常数、晶粒尺寸小和严格的温度稳定性要求。然而，开发能够兼备这些特性的介电陶瓷仍然是该领域的一项关键技术瓶颈和研究空白。为了解决这一挑战，本研究通过精确的多离子掺杂和核壳结构比例控制，制备了近纳米级晶粒（晶粒尺寸约为 158.22nm，壳层结构约 10nm）的陶瓷，成功实现了温度稳定性上的突破（温度系数范围为-55℃~125℃，且在 25℃ 时电容变化率 ΔC/C25℃≤±1.97%，符合 X7C 规范）。与此同时，陶瓷表现出高介电常数（1418.4），满足现代 MLCC 对高容量的需求。此外，高绝缘电阻（I4.31×10^12 Ω·cm）和低介电损耗（0.60%）确保了漏电流引起的热损失最小化。陶瓷的出色能量存储稳定性及每单位电场下高能量密度（240 kV^-1·m^-2：W_rec/E 达到 131.25 J·kV^-1·m^-2）进一步保证了其在低至中等电场条件下的能量存储功能最大化及长期耐久性。该改性 BaTiO3 基陶瓷集高介电常数、细小晶粒尺寸和超稳定温度性能于一体，有望推动高精度高容量电路中的 MLCC 向小型化方向发展。

关键词:

MLCCs，BaTiO3，多离子掺杂，核壳结构，温度超稳定性，近纳米级晶粒

Abstract:

In various high-precision systems, it is required that Multilayer Ceramic Capacitors (MLCCs) not only have smaller volumes but also higher capacitance values. Correspondingly, the dielectric materials used must simultaneously meet requirements for high permittivity (ε_r), small grain size, and strict temperature stability. However, the development of dielectric ceramics that fulfill all these properties remains a critical technical bottleneck and research gap in this field. To address this challenge, this work employs precise multi-ion doping and core-shell structure ratio control to prepare ceramics with near-nano grains (dg~158.22nm, with shell structure~10nm) successfully achieving breakthrough temperature stability (TCC: -55℃~125℃, ΔC/C25℃ ≤ ±1.97%, meeting the X7C specification). Simultaneously, ceramics exhibit high ε_r (1418.4) which aligns with the high capacity demands of modern MLCCs. Additionally, high insulation resistivity (Ir: 4.31 × 1012 Ω·cm) and low dielectric loss (tan δ=0.60%) ensure minimized thermal losses caused by leakage currents. The ceramics'excellent energy storage stability and high energy density per unit electric field (240 kV-1·m-2: Wrec /E reached 131.25 J·kV-1·m-2) further ensure their ability to maximize energy storage functionality under low-to-medium electric field conditions with long-term durability. The modified BaTiO3-based ceramics integrating high permittivity, small grain size, and temperature ultra-stability, hold promise for advancing MLCCs in high-precision circuits possessing high capacity and the potential for miniaturization.

Keywords:

MLCCs, BaTiO3, multi-ion doping, core-shell structure, ultra-stable, near-nano grains.

环、化、材、技、能源战略 / **48**

玻璃金属封接中冷却诱发应力的起源及演变

Authors: Keqian Gong[None]; Yong Zhang[None]; Zifeng Song[1]

[1] 清华大学核研院

Corresponding Author: szf23@mails.tsinghua.edu.cn

摘要:

玻璃-金属（GTM）密封中的残余应力是决定其机械性能的关键因素。本研究主要关注冷却诱导应力的形成和演化。K 型热电偶和光纤布拉格光栅（FBG）传感器用于获取 GTM 密封在冷却过程中的原位温度和应力数据。同时，还建立了该过程的热力耦合有限元分析（FEA）模型。研究发现，玻璃的内部温度分布呈"水煮蛋"形状。这是由于导热系数低，导致中心出现延时效应。分析其应力形成曲线，当温度降至 200℃ 以下时，观察到应力反弹，这在有限元分析中已被证实是由热膨胀系数（CTE）的差异决定的。冷却速率直接决定了应力形成速率。本研究加深了对 GTM 密封件冷却过程中应力形成和演变的理解，并强调了不同冷却速率对应力形成的影响。它为优化工艺和定制应力分布提供了理论指导。

关键词:

玻璃-金属封接；应力分布；有限元分析

Abstract:

The residual stress in the Glass-to-Metal (GTM) seal is a key factor determining its mechanical performance. This study focuses on the cooling-induced stress formation and evolution. K-type thermocouples and fiber Bragg grating (FBG) sensors were used to obtain the in situ temperature and stress data of the GTM seal during the cooling process. At the same time, a thermo-mechanical coupling finite element analysis (FEA) model for this process has also been established. It was found that the internal temperature distribution of the glass exhibits a "soft-boiled egg" shape. This is due to the low thermal conductivity, which causes a time-delay effect at the center. Analyzing its stress formation curve, stress rebound was observed when the temperature dropped below 200℃, which has been confirmed in the FEA to be determined by the difference in thermal expansion coefficients (CTE)s. The cooling rate directly determines the rate of stress formation. This study enhances the understanding of the stress formation and evolution during the cooling process of GTM seals and emphasizes the impact of different cooling rates on stress formation. It provides theoretical guidance for optimizing the process and tailoring stress distribution.

Keywords:

Glass-to-metal seal; stress distribution; finite element analysis

环、化、材、技、能源战略 / **49**

锕系元素的可控配位组装与限域识别

Author: 维晋[1]

Co-authors: 伟群石 [2]; 雷梅 [1]

[1] 中国科学院高能物理研究所

[2] 上海交通大学

Corresponding Authors: meil@ihep.ac.cn, shiwq@ihep.ac.cn, jinwei@ihep.ac.cn

摘要:

锕系配位化学在核燃料循环体系优化中具有关键科学意义和应用潜力。本研究聚焦锕系元素的配位行为调控与新型分离材料开发，通过多齿配体与金属离子的协同配位效应，成功构建了过氧桥

接二核铀酰功能化修饰的铀酰-雷索烃四羧酸胶囊型配位笼。基于该体系提出了一种新型放射性核素分离策略，采用多维表征技术（单晶 X 射线衍射、核磁共振波谱及质谱分析）系统阐明了配位笼与碱/碱土金属离子的主-客体作用机制，发现其对 Sr2+ 离子展现出显著特异性识别能力（分配系数 Kd = 1.36×107 mL g-1），性能指标优于现有报道材料。理论分析表明，该优异选择性源于配位空腔中供体原子的几何排布与 Sr2+ 离子半径（1.16 Å）及配位环境的精准匹配。本研究不仅揭示了锕系配位笼在放射性核素分离领域的独特优势，更建立了通过配位空腔微环境工程化设计高选择性分离材料的新方法，为复杂体系中战略金属资源的高效回收提供了新思路与技术支撑

关键词:

锕系元素、超分子笼、可控配位、核素分离

Abstract:

The investigation of actinide coordination chemistry holds pivotal scientific significance and application potential for optimizing nuclear fuel cycle systems. Elucidating the coordination behavior of actinides and developing novel separation materials not only advance fundamental theories in actinide chemistry but also offer innovative solutions for critical radioactive nuclide separation. Herein, we demonstrate a synergistic coordination strategy between polydentate ligands and metal centers to precisely control ligand conformation and metal-binding preferences, enabling the programmable assembly of polynuclear uranium/thorium coordination cages. Building upon this approach, we propose a groundbreaking methodology utilizing actinide coordination cages for selective extraction of key elements from nuclear fission products. Through modular design, we successfully constructed a peroxo-bridged diuranyl-functionalized uranyl-calix[4]resorcinarene capsule system. Comprehensive characterization via NMR spectroscopy, mass spectrometry, and single-crystal X-ray diffraction revealed its host-guest interaction mechanism with alkali/alkaline-earth metal ions, demonstrating exceptional Sr2+ selectivity with a remarkably high distribution coefficient (Kd = 1.36×107 mL g-1 under low-concentration conditions), surpassing existing Sr2+ adsorbents. This superior performance originates from the geometric complementarity between the precisely arranged donor atoms in the cage cavity and the ionic radius (1.16 Å) of Sr2+, coupled with optimal coordination environment matching. Our findings not only validate the unique advantages of actinide coordination cages in radionuclide separation but also establish a new paradigm for designing high-selectivity separation materials through cavity microenvironment engineering, offering both theoretical insights and technical frameworks for strategic metal recovery in complex systems.The investigation of actinide coordination chemistry holds pivotal scientific significance and application potential for optimizing nuclear fuel cycle systems. Elucidating the coordination behavior of actinides and developing novel separation materials not only advance fundamental theories in actinide chemistry but also offer innovative solutions for critical radioactive nuclide separation. Herein, we demonstrate a synergistic coordination strategy between polydentate ligands and metal centers to precisely control ligand conformation and metal-binding preferences, enabling the programmable assembly of polynuclear uranium/thorium coordination cages. Building upon this approach, we propose a groundbreaking methodology utilizing actinide coordination cages for selective extraction of key elements from nuclear fission products. Through modular design, we successfully constructed a peroxo-bridged diuranyl-functionalized uranyl-calix[4]resorcinarene capsule system. Comprehensive characterization via NMR spectroscopy, mass spectrometry, and single-crystal X-ray diffraction revealed its host-guest interaction mechanism with alkali/alkaline-earth metal ions, demonstrating exceptional Sr2+ selectivity with a remarkably high distribution coefficient (Kd = 1.36×107 mL g-1 under low-concentration conditions), surpassing existing Sr2+ adsorbents. This superior performance originates from the geometric complementarity between the precisely arranged donor atoms in the cage cavity and the ionic radius (1.16 Å) of Sr2+, coupled with optimal coordination environment matching. Our findings not only validate the unique advantages of actinide coordination cages in radionuclide separation but also establish a new paradigm for designing high-selectivity separation materials through cavity microenvironment engineering, offering both theoretical insights and technical frameworks for strategic metal recovery in complex systems.

Keywords:

Actinides, Supramolecular cage, Controlled coordination, Radionuclide separation

环、化、材、技、能源战略 / **50**

新型铀酰 **MOF** 高效光催化 **CO2** 还原

Author: Zhiheng Zhou[None]

Corresponding Author: zhouzh@ihep.ac.cn

摘要:

在过去的几十年里，随着化石燃料的大量消耗，空气中的二氧化碳含量逐渐增加，全球变暖和能源危机等环境问题日益严重。利用太阳光将 CO2 光催化还原为 CO、CH4 等高附加值产物是保护环境、解决能源危机的重要手段之一。金属-有机框架（MOFs）是由有机配体和无机金属离子/团簇组成的一种晶态多孔结构，具有高结晶性、高的比表面积、灵活可调的多孔结构以及易修饰等特点，在光催化领域具有广阔应用前景。此外，独特的光化学性质和多样的配位模式使得铀酰离子既可以作为 MOFs 材料的金属节点，又可以作为光催化反应的活性中心。因此，铀酰 MOFs 有望成为新型异相光催化剂。在此，我们设计并制备了一种新型铀基 MOF 材料 IHEP-101[(CH3)2NH2][UO2][UO2(L)(DMF)][UO2(L)(H2O)]0.5·(DMF)1.5。其中，Salen 配体的 N2O2 空腔被铀酰离子占据，形成线性的 [UO2L] 金属化二羧酸配体，该金属化配体继续与铀酰离子配位，形成一个扭曲的二维蜂窝网状结构。相邻层通过 π - π 相互作用堆叠成三维框架结构。IHEP-101 表现出良好的光催化 CO2 还原活性，在不添加任何牺牲剂的条件下，CO 的产率可达 458 μmol·g-1·h-1，CO 的选择性可达 98.6%。通过原位红外光谱、DFT 计算进一步揭示 IHEP-101 活化 CO2 的反应机理，IHEP-101 活化 CO2 在热力学和动力学上是可行的，并伴有 U 原子氧化态在 +VI 和 +V 之间的转变。根据已有的实验数据和文献报道，提出了 IHEP-101 光催化还原 CO2 的可能反应路径。本研究揭示了 UO22+ 阳离子作为光催化 CO2 还原反应活性位点的潜力，为设计和合成新型铀酰 MOFs 光催化材料提供了参考。

关键词:

铀酰离子、金属-有机框架材料、光催化、二氧化碳还原、配位化学

Abstract:

In the past few decades, with the massive consumption of fossil fuels, the carbon dioxide content in the air has gradually increased, and environmental problems such as global warming and energy crisis have become increasingly serious. Using sunlight to photocatalytically reduce CO2 to high value-added products such as CO and CH4 is one of the important means to protect the environment and solve the energy crisis. Metal-organic frameworks (MOFs) are a kind of crystalline porous structure composed of organic ligands and inorganic metal ions/clusters. They have the characteristics of high crystallinity, high specific surface area, flexible and adjustable porous structure, and easy modification, and have broad application prospects in the field of photocatalysis. In addition, the unique photochemical properties and diverse coordination modes make uranyl ions can be used as both the metal nodes of MOFs materials and the active centers of photocatalytic reactions. Therefore, uranyl MOFs are expected to become a new type of heterogeneous photocatalyst. Here, we designed and prepared a new type of uranium-based MOF material IHEP-101 [(CH3)2NH2][UO2][UO2(L)(DMF)][UO2(L)(H2O)]0.5·(DMF)1.5. Among them, the N2O2 cavity of the Salen ligand is occupied by uranyl ions to form a linear [UO2L] metallized dicarboxylic acid ligand, and this metallized ligand continues to coordinate with uranyl ions to form a distorted two-dimensional honeycomb network structure. Adjacent layers are stacked into a three-dimensional framework structure through π - π interactions. IHEP-101 shows good photocatalytic CO2 reduction activity. Without adding any sacrificial agent, the yield of CO can reach 458 μmol·g-1·h-1, and the selectivity of CO can reach 98.6%. The reaction mechanism of IHEP-101 activating CO2 is further revealed by in situ infrared spectroscopy and DFT calculations. It is feasible for IHEP-101 to activate CO2 thermodynamically and kinetically, accompanied by the transformation of the oxidation state of U atoms between +VI and +V. According to the existing experimental data and literature reports, a possible reaction path for the photocatalytic reduction of CO2 by IHEP-101 is proposed. This study reveals the potential of UO22+ cations as the active sites for the photocatalytic CO2 reduction reaction, providing a reference for the design and synthesis of new uranyl MOFs photocatalytic materials.

Keywords:

uranyl ion, Metal-Organic Frameworks, photocatalysis, carbon dioxide reduction, coordination chemistry

环、化、材、技、能源战略 / **51**

熔盐合成 **MXene** 负载纳米零价铁对铀的高效吸附还原

Author: 昊威涂[1]

[1] 哈尔滨工程大学

Corresponding Author: tuhw@ihep.ac.cn

摘要:

纳米零价铁（nZVI）的环境修复潜力通常受到颗粒团聚严重或稳定性差的阻碍。克服这些挑战的直接方法是将 nZVI 均匀、牢固地分散到二维材料等高比表面积基底上。在此我们报道了一种基于共晶熔盐（MS）一锅合成 MXene-nZVI 复合材料的新策略。批次吸附实验表明，纳米层状 MXene 和 nZVI 之间的有效协同作用在提高复合材料消除 U(VI) 的性能方面发挥了关键作用, 且最大去除量达到 1750 mg/g。进一步的环境应用评估表明，MS-MXene-nZVI 在去除复杂酸性矿井排水中的 U(VI) 方面潜力巨大。先进光谱分析清楚地证明了反应过程中 Fe0 向结构型 Fe2+ 的转化，并确定了 U(VI) 的去除机制主要是还原固定，伴随着表面化学吸附和水解沉淀。这项研究为通过熔盐法绿色、简便地制备 MXene 基 nZVI 复合材料及其在高效分离放射性核素和其他污染物方面的环境修复应用提供了新的见解。

关键词:

MXene、纳米零价铁、熔盐合成、铀、环境修复

Abstract:

The environmental remediation potential of nanoscale zero-valent iron (nZVI) is generally hindered by severe particle agglomeration or poor stability. A straightforward approach to overcome these challenges is to uniformly and firmly disperse nZVI onto high surface area substrates such as two-dimensional materials. Herein, we propose a novel method for one-pot synthesis of MXene-nZVI composites based on the eutectic molten salt (MS) etching of MAX phase materials. Batch adsorption experiments showed that the effective synergy between nano-lamellar MXene and nZVI played a pivotal role in boosting U(VI) elimination performance of the composites, and the maximum removal capacity reached 1750 mg/g. Further environmental application assessment indicated an excellent potential of MS-MXene-nZVI for U(VI) sequestration from complex acid mine drainage. Advanced spectroscopic analyses provided clear evidence of the conversion of Fe0 to structural Fe2+ during the reaction and established that the removal mechanism of U(VI) was primarily reductive immobilization, concomitantly with surface chemisorption and hydrolysis precipitation. This study offers new insights into the green and facile preparation of MXene-based nZVI composites via MS strategy, as well as their environmental remediation application in the highly efficient separation of radionuclides and other contaminants.

Keywords:

MXene、nZVI、Molten salt synthesis、Uranium、Environmental remediation

环、化、材、技、能源战略 / **120**

超声置换与机制研究

Author: 建强叶[1]

[1] 昆明理工大学

Corresponding Author: 1247530226@qq.com

摘要:

目前，利用锌粉去除硫酸锌电解液中的钴存在锌粉结块、包封等问题，导致锌粉用量增加，去除效果差。针对这些问题，提出新型超声波强化锌粉净化方法，以去除硫酸锌电解质中的钴 (II)。在超声条件 60 min，温度 80℃，锌粉用量 3 g/L, 钴 (II) 的去除率为 95.02%，钴 (II) 的剩余浓度为 0.99 mg/L。与常规置换相比，超声强化置换反应将反应时间缩短 100 min，反应温度降低 10℃，锌粉用量降低 50%，去除率提高 23.65%，显著降低钴的浓度。超声波的空化效应与机械效应可以细化颗粒，打破包裹体，加速传质过程，提高钴 (II) 的去除率，从而显著降低锌粉的消耗，减少成本。因此，采用超声强化硫酸锌电解液净化技术对锌电积和钴的综合回收具有重要意义。本研究提出

了超声波强化锌粉净化硫酸锌溶液的新工艺，为湿法炼锌企业提供了一个新的研究方向，以期达到节能减排和为企业增效的目的。

关键词:

超声，湿法炼锌，净化，锌粉

Abstract:

At present, the use of zinc powder to remove cobalt from zinc sulfate electrolyte has problems such as zinc powder agglomeration and encapsulation, resulting in an increase in the amount of zinc powder and a poor removal effect. In order to solve these problems, a new ultrasonic enhanced zinc powder purification method was proposed to remove cobalt (II) from zinc sulfate electrolyte. The removal rate of cobalt (II) was 95.02 % and the residual concentration of cobalt (II) was 0.99 mg / L under the ultrasonic condition of 60 min, 80 ℃ and 3 g / L zinc powder. Compared with conventional replacement, the ultrasonic enhanced replacement reaction shortens the reaction time by 100 min, reduces the reaction temperature by 10 ℃, reduces the amount of zinc powder by 50 %, increases the removal rate by 23.65 %, and significantly reduces the concentration of cobalt. The cavitation effect and mechanical effect of ultrasonic can refine the particles, break the inclusions, accelerate the mass transfer process, improve the removal rate of cobalt (II), thus significantly reducing the consumption of zinc powder and reducing the cost. Therefore, the use of ultrasound-enhanced zinc sulfate electrolyte purification technology is of great significance for the comprehensive recovery of zinc electrowinning and cobalt. This study proposes a new process of ultrasonic strengthening zinc powder to purify zinc sulfate solution, which provides a new research direction for zinc hydrometallurgy enterprises, in order to achieve the purpose of energy saving and emission reduction and efficiency improvement for enterprises.

Keywords:

Ultrasonic, zinc hydrometallurgy, purification, zinc powder

环、化、材、技、能源战略 / **53**

以氮气为介质扩散分离氮同位素的可行性研究

Author: 飞王[None]

Corresponding Author: hexiaoer17@qq.com

Abstract:

As a stable isotope marker, nitrogen-15 isotope has a wide range of applications. To explore the separation methods of nitrogen-15 isotope, single-stage and fourth-order diffusion separation experiments were conducted, and cascade design was carried out based on the experimental results. Under existing experimental conditions, the single-stage concentration coefficient of nitrogen separation by gas diffusion method can reach 0.008 in single-stage experiments; The single-stage concentration coefficient in the four stage cascade can reach 0.007; Using natural nitrogen as raw material, high abundance nitrogen isotopes can be prepared through two cascade steps. This study demonstrates the feasibility of using nitrogen as a medium to separate nitrogen isotopes through gas diffusion.

Keywords:

Nitrogen isotope; Nitrogen; Gas diffusion method; Squared-off cascade

摘要:

氮-15 同位素作为稳定同位素标记物，具有十分广泛的应用场景，为探索氮-15 同位素的分离方法，开展单级及四级扩散分离实验，并在实验基础上开展级联设计。在现有实验条件下，气体扩散法分离氮气在单级实验中的单级浓缩系数可以达到 0.008；四级级联中的单级浓缩系数可以达到 0.007；以天然氮气为原料，通过两次阶梯级联可以制备高丰度氮同位素。本研究证明了使用氮气为介质通过气体扩散法分离氮同位素的可行性。

关键词:

氮同位素；氮气；气体扩散法；阶梯级联

环、化、材、技、能源战略 / **61**

亲水性配体对放射性锕系元素的配位与分离

Author: 李斌[None]

Corresponding Author: li-b22@mails.tsinghua.edu.cn

Abstract:

Hydrophilic chelators are crucial for coordinating and separating radioactive elements in nuclear fuel recycling, hazardous waste treatment, environmental remediation, radiopharmaceuticals, and related fields. However, their development and understanding lag behind their lipophilic counterparts. This review summarizes the development of hydrophilic ligands across four categories based on their structural similarities and chronological order. For each category, representative examples are discussed, highlighting their advantages and disadvantages. The review also outlines current design challenges, and emphasizes the importance of establishing structure-function relationships to guide future ligand design. Additionally, we propose four novel f-block chelating ligands, some of which have shown efficiency in solid-liquid radionuclide separation, aiming to inspire the search for more robust systems for f-block element utilization and recycling. This review aims to provide a comprehensive overview of hydrophilic f-block element chelators and suggest promising approaches for future ligand development.

Keywords:

hydrophilic ligands; solution coordination chemistry; lanthanides/actinides separation; acid resistance; nuclear waste management

摘要:

亲水性配体对于核燃料循环、废物处理、环境修复、核药等相关领域中的放射性元素的配位和分离至关重要。然而其发展和研究程度落后于亲脂性配体。本研究根据配体的结构相似性和研究历程，总结了四类亲水性配体的发展情况。对于每一类亲水性配体，讨论了典型研究案例并详细论述了其优缺点。同时本研究概述了当前亲水性配体设计面临的挑战，强调了建立构效关系以指导配体设计的重要性。此外，提出了四种新型的亲水性配体的构建策略，部分已在放射性核素固液分离中展现出有效性，以启发人们寻找更强大的系统来利用和回收放射性元素。本综述旨在全面概述亲水性 f 区元素螯合剂，并为未来配体开发提出有前景的方法。

关键词:

亲水性配体；溶液配位化学；镧/锕分离；耐酸性；核废料管理

环、化、材、技、能源战略 / **65**

通过延长陶瓷微粒停留时间制备包覆陶瓷微粒

Author: Bowen Li[1]

[1] *Tsinghua University*

Corresponding Author: libw23@mails.tsinghua.edu.cn

摘要:

Geldart C 类陶瓷微粒的流化床化学气相沉积包覆容易出现团聚现象，导致粒径分布宽，表现为在恒温反应区停留时间短，进而导致包覆层质量差和不均匀。为了增加陶瓷微粒在恒温反应区的停留时间，通过螺旋管将微粒轨迹延长了 20 倍。采用经简单设计的流化床-化学气相沉积技术，在陶瓷微粒表面制备了百纳米级厚度的碳包覆层。研究了包覆层的微观结构、形成机理、结合方式

和性能。结果表明，首先形成小球形碳，然后形成球壳包覆层。此外，包覆层中的碳原子与陶瓷微粒中的氧原子结合。纳米级厚度的碳包覆层可以作为屏障，保护陶瓷微粒免受纯氢氟酸的长时间腐蚀。

关键词:

流化床-化学气相沉积；包覆陶瓷微粒；停留时间；耐腐蚀性

Abstract:

Fluidized bed-chemical vapor deposition coating for the Geldart C class ceramic microparticles is prone to aggregate, which leads to a wide particle size distribution and short residence time in the constant temperature reaction area, resulting in poor quality and uneven coating. To increase the residence time of ceramic microparticles in the constant temperature reaction zone, the microparticle trajectory is extended by twenty times through helical pipes. A carbon coating of nanoscale thickness (~ 400 nm) was prepared on the surface of ceramic microparticles using fluidized bed-chemical vapor deposition with a facile design. The microstructure, formation mechanism, bonding mode, and property of the coating were studied. The results show that the coating first forms small spherical carbon and then forms spherical shell coating. Furthermore, the carbon atoms in the coating are combined with the oxygen atoms in the ceramic microparticle. The carbon coating of nanoscale thickness can serve as a barrier to protect ceramic microparticles from long-term corrosion (5 days) by pure hydrofluoric acid.

Keywords:

FB-CVD; Coated ceramic microparticles; Residence time; Corrosion resistance

环、化、材、技、能源战略 / **76**

基于质量评估碳移除技术的气候效益

Authors: 泽雨王[1]; 飞滕[2]

[1] 清华大学核研院 *901* 室

[2] 清华大学

Corresponding Authors: wangzeyu22@mails.tsinghua.edu.cn, tengfei@tsinghua.edu.cn

摘要:

碳移除技术（Carbon Dioxide Removal, CDR）是实现《巴黎协定》气候目标战略中的重要组成部分，基于质量（即永久性、即时性、移除效率）评估 CDR 技术的气候效益有助于推进 CDR 技术的大规模开发和部署。本研究建立了一个定量评估 CDR 技术气候效益的框架，该框架全面评估了所选五种典型 CDR 技术的永久性、即时性和移除效率，从而得到最真实的 CDR 气候效益，帮助决策者或投资者进行技术选择。研究表明，EW 气候效益最高，其次是 DACCS，而 BC 气候效益最低；从效益成本比角度，AR 最好，DACCS 由于现阶段成本很高，不具备经济可行性。

关键词:

碳移除技术；质量；气候效益；成本效益分析

Abstract:

Carbon dioxide removal (CDR) technologies have become crucial for meeting the climate targets set in the Paris Agreement. Assessing the climate benefits of CDR technologies based on quality—permanence, timing, and removal efficiency—is essential for guiding their large-scale development and deployment. This study establishes a framework for quantitatively assessing the climate benefits of CDR technologies, which comprehensively evaluates the permanence, timing and removal efficiency of five selected typical CDR technologies. The framework obtains the true climate benefits of CDR technologies, assisting policymakers or investors in technology selection and promoting the large-scale deployment of CDR technologies. The results demonstrate that EW consistently shows the highest climate benefits, followed by DACCS, while BC exhibits the lowest climate benefits. In terms of economic feasibility, AR is the most favorable. Currently, DACCS is not economically feasible due to its high costs.

Keywords:

Carbon dioxide removal technologies; Quality; Climate benefit; Cost-benefit analysis

环、化、材、技、能源战略 / **121**

铜冶金工业过程能效-碳效评价与节能降碳方法研究

Author: 从玮唐[1]

Co-authors: 一平胡 [2]; 劲松罗 [2]; 华王 [1]; 建杭胡 [1]; 浩宸黄 [2]

[1] 昆明理工大学

[2] 云南铜业有限公司

Corresponding Author: tangcongwei06@163.com

摘要:

降低金属冶炼工业过程中的能耗和碳排放量是当前一项紧迫而重要的任务。本研究对铜冶炼的能效和碳效率评价方法进行了研究和分析，并探索对应的效率提升方法。在这项工作中，基于松弛变量数据包络分析方法（SBM-DEA）和超效率 SBM-DEA 模型评估过去三年中某典型铜冶炼企业不同月份的铜冶炼相对能源效率，并定量分析了最佳能效和较低能效月份对应的铜冶炼过程能流与碳排放流分布特性。在最佳能效月，三个不同计算边界范围内精炼铜生产的能耗分别为 5044、8446 和 10037MJ/t·Cu；三个不同计算边界内的铜冶炼碳效率分别为 1.804、1.027 和 0.855 kg·Cu/kg·CO2。并对冶炼能效的影响因素进行了分析，根据分析结果提出了提高冶炼能效、碳效的建议或措施。该研究将为铜冶金行业的能效评估与提升、减少碳排放量提供可用的方法和理论参考，也将为能源密集型的冶金行业的碳中和进程做出贡献。

关键词:

精炼铜；能源效率；碳排放；有色金属冶金；铜冶炼

Abstract:

Reducing energy consumption and carbon emissions in the metal smelting industry is an urgent and essential task at present. This study investigated and analyzed the energy efficiency and carbon efficiency evaluation methods for copper smelting, and explored corresponding efficiency improvement methods. The relative energy efficiency of copper smelting in different months of a typical copper smelting enterprise over the past three years was evaluated based on the slack variable data envelopment analysis method (SBM-DEA) and the super efficiency SBM-DEA model. The distribution characteristics of energy flow and carbon emissions during the copper smelting process corresponding to the best energy efficiency and lower energy efficiency months were quantitatively analyzed. In the optimal energy efficiency month, the energy consumption for refined copper production within three different calculation boundary ranges is 5044, 8446, and 10037 MJ/t·Cu, respectively; The carbon efficiencies of copper smelting within three different calculation boundaries are 1.804, 1.027, and 0.855 kg·Cu/kg·CO2, respectively. The influencing factors of smelting energy efficiency, and proposed suggestions or measures to improve smelting energy efficiency and carbon efficiency based on the analysis results are investigated. This study will provide practical methods and theoretical references for energy efficiency assessment and improvement, as well as reducing carbon emissions in the copper metallurgical industry. It will also contribute to the carbon neutrality process in the energy-intensive metallurgical industry.

Keywords:

Reined copper; Energy efficiency; Carbon emission; Nonferrous metallurgy; Copper smelting

环、化、材、技、能源战略 / **126**

LiNi0.5Co0.2Mn0.3O2 碳热还原中 **Ni-Co** 选择性回收及物化行为研究

Author: 国琛胡[1]

Co-author: 雯罗 [1]

[1] 昆明理工大学冶金与能源工程学院

Corresponding Authors: wen_luo2022@qq.com, karrot_hu@163.com

摘要:

本研究针对新能源汽车及储能领域退役锂离子电池的资源化需求，开发了碳热还原煅烧新技术以实现正极材料中镍钴的高效选择性回收工艺。通过热力学计算与实验验证相结合，系统揭示了煅烧温度、碳含量及持续时间对镍钴选择性还原行为的调控机制。创新性采用高温原位 XRD 技术，动态解析了还原过程中 (NiO)x·(MnO)y 中间相的形成与分解过程，明确了其物相演变路径。实验数据表明，在优化工艺条件为 800℃、10% 含碳量、60 min 时，镍、钴回收率分别达 99.70% 和 99.43%，锰元素向合金相的迁移率仅为 0.49%。机理研究表明，碳含量的提升可有效降低正极材料分解活化能并稳定反应热力学条件，而煅烧时间的延长对镍钴回收率呈现边际递减效应，但会显著提升锰元素的回收效率。该研究不仅深化了选择性金属回收的机理认知，更为退役电池战略金属资源化提供了兼具规模化潜力与环境友好性的解决方案，有力推动电池产业的资源循环与绿色制造进程。

关键词:

碳热还原煅烧、退役锂离子电池、镍、钴、选择性还原、相变过程

Abstract:

This study addresses the resource recovery requirements of spent lithium-ion batteries from the new energy vehicle and energy storage sectors by developing a novel carbothermal reduction calcination technology. This technology enables an efficient and selective recovery process for nickel and cobalt from cathode materials. Through the integration of thermodynamic calculations and experimental validation, this research systematically elucidates the regulatory mechanisms of calcination temperature, carbon content, and duration on the selective reduction behavior of nickel and cobalt. An innovative high-temperature in-situ XRD technique was utilized to dynamically analyze the formation and decomposition processes of the (NiO)x·(MnO)y intermediate phase during reduction, thereby clarifying its phase evolution pathway. Experimental data show that under optimized conditions of 800 ℃, 12.99 wt.% carbon content, and 60 min, the recovery rates of nickel and cobalt reached 99.70% and 99.43%, respectively, while the migration rate of manganese to the alloy phase was only 0.49%. This study not only deepens the understanding of selective metal recovery mechanisms but also provides a scalable and environmentally friendly solution for the resource recovery of strategic metals from spent batteries, thereby promoting resource recycling and green manufacturing in the battery industry.

Keywords:

Carbothermal reduction calcination; Spent lithium-ion battery; Nickel; Cobalt; Selective recovery; Phase evolution

环、化、材、技、能源战略 / **122**

耦合生物质热转化的冶金熔渣余热回收技术

Authors: 超维马[1]; 建杭胡[2]; 华王[2]

[1] 昆明理工大学冶金与能源工程学院

[2] 昆明理工大学

Corresponding Author: 1109492001@qq.com

摘要:

冶金行业作为高能耗产业存在大量余热资源亟待回收利用，其中熔渣余热的有效回收已成为行业关键课题。本研究针对传统余热回收技术效率不足的问题，创新性地将生物质热转化与冶金熔渣余热回收相结合，开发出耦合生物质热转化的新型余热回收系统。采用计算流体力学-离散元耦合方法（CFD-DEM）构建回转式反应器三维模型，基于密集离散颗粒模型（DDPM）对热态铜渣与生物质颗粒的多相流动及传热传质特性进行数值模拟研究。研究表明：1）反应器内颗粒床层呈现典型的滚转流动模式，可分为主动区（颗粒随壁面运动）和被动区（颗粒内部滑移）两个特征区域，该流动分区直接影响固体停留时间分布及反应器可放大性；2）当铜渣添加量达到 20wt%、转速为 4 rpm 时，生物质颗粒升温至目标温度所需时间较无铜渣工况缩短约 188 秒，且颗粒粒径比（dp,slag/dp,biomass）降低至 0.5 时升温速率提升显著；3）反应器转速对混合特性影响显著，混合指数随转速增加呈线性增长，而粒径比增大导致偏析效应增强，混合指数下降；4）数值模拟结果与实验数据对比显示最大相对偏差为 4.7%，验证了模型的可靠性。本工作建立的 CFD-DEM 多尺度模型成功揭示了回转式反应器中颗粒体系的传热机制与混合特性，为生物质热解气化反应器的优化设计提供了理论依据，对实现冶金余热高效回收与生物质能源化利用具有重要指导意义。

关键词:

冶金熔渣；余热回收；生物质；热化学转换；回转窑；CFD-DEM 方法；颗粒运动和传热

Abstract:

The metallurgical industry, characterized by high energy consumption, generates substantial waste heat resources requiring efficient utilization, particularly the critical challenge of recovering thermal energy from molten slag. This study addresses the limitations of conventional waste heat recovery technologies through the innovative integration of biomass thermochemical conversion with metallurgical slag heat recovery, developing a novel hybrid thermal energy recovery system. A three-dimensional rotary reactor model was established using coupled Computational Fluid Dynamics-Discrete Element Method (CFD-DEM) simulations, with the dense discrete particle model (DDPM) employed to investigate multiphase flow dynamics and heat-mass transfer characteristics between copper slag and biomass particles. Key findings reveal: 1) Particulate bed behavior exhibits distinct rolling flow patterns, partitioned into active (wall-adherent particle motion) and passive (internal particle slippage) regions, fundamentally governing solid residence time distribution and reactor scalability. 2) Under optimized conditions (20 wt% slag addition, 4 rpm rotation), biomass particle heating duration to target temperature reduced by 188 seconds compared to slag-free operation, with particle size ratio (dp,slag/dp,biomass=0.5) demonstrating 23.7% thermal enhancement. 3) Rotational velocity linearly regulates mixing efficiency, while increased particle size disparity amplifies segregation effects, reducing mixing index. 4) Model validation shows maximum 4.7% deviation between simulated and experimental data. The developed multiscale CFD-DEM framework elucidates particle-scale heat transfer mechanisms and mixing behavior in rotary reactors, providing theoretical foundations for biomass gasification reactor optimization and advancing synergistic utilization of metallurgical waste heat with renewable biomass resources.

Keywords:

Metallurgical slag; Waste heat recovery; Biomass; Thermochemical conversion; Rotary kiln; CFD-DEM method; Particle motion and heat transfer

环、化、材、技、能源战略 / **78**

中国潜在分割碳减排机制的省级经济和空气质量健康影响

Author: 汉唐彭[1]

Co-authors: 明威李; 达张; 心怡刘; 希良张

[1] 清华大学

Corresponding Author: pht21@mails.tsinghua.edu.cn

摘要:

中国已启动全国碳排放交易体系（ETS），并计划形成一种新的省级碳排放控制机制。虽然先前研究分别探讨了 ETS 和省级减排目标，但整合两种机制的潜在分割碳减排机制对经济及空气质量相关健康的影响尚未得到充分研究。本研究采用综合建模框架，比较了 2035 年在相同全国碳排放

总量目标下，三种省级控制机制对经济和 PM2.5 及臭氧相关健康结果的影响。研究发现，与传统省级控制机制（PRO_CAP）相比，ETS 使全国福利至少提高 0.12%。分割碳减排机制（PART_REG）将全国 ETS 应用于电力和高耗能行业，同时对其他行业设定省级减排目标，实现了全面 ETS 覆盖（FULL_ETS）下福利改善的 85%。ETS 使 CO2 及共同排放的空气污染物从中国北方转移至南方，改善了北方省份的空气质量，但恶化了中部和南方省份的空气质量。与 PRO_CAP 相比，PART_REG 下全国早逝人数增加 32,700 人（95% 置信区间：23,200—41,600 人）。综合考虑福利变化和货币化健康损害，ETS 在全国层面仍具成本效益，PART_REG 下的净效益中位数为 66 亿美元，比 FULL_ETS 高 20%。北方和东南沿海省份获得净正收益，而部分中部省份面临净负影响。

关键词:

可计算一般均衡（CGE）；气候政策；空气质量；人群健康；成本效益分析

Abstract:

China has launched the national emissions trading system (ETS) and intends to form a novel mechanism to control provincial carbon emissions. While previous studies have examined ETS and provincial reduction targets separately, the impacts of the potential integration of these approaches on welfare and air quality-related health remain underexplored. In this study, we employ an integrated modeling framework to compare the economic impacts and health outcomes associated with PM2.5 and ozone under three provincial control mechanisms with the same target for national total carbon emissions in 2035. Our findings indicate that ETS improves national welfare by at least 0.12% compared to the conventional provincial control mechanism (PRO_CAP). The partitioned carbon regulation mechanism (PART_REG), which applies the national ETS to power and energy-intensive industry sectors while assigning reduction targets to other sectors at the provincial level, achieves 85% of the welfare improvement observed under full ETS coverage (FULL_ETS). ETS redistributes CO2 and co-emitted air pollutant emissions from northern to southern China, improving air quality in northern provinces but worsening it in central and southern provinces. The national premature deaths increase by 32,700 (95% CI: 23,200—41,600) under PART_REG compared to PRO_CAP. When comparing the changes in welfare and monetized health damages, ETS remains cost-effective nationally, with a median net benefit of US$6.6 billion under PART_REG —20% higher than that under FULL_ETS. Northern and southeastern coastal provinces experience net positive benefits, while some central provinces face net negative impacts.

Keywords:

computable general equilibrium (CGE), climate policy, air quality, human health, cost-benefit analysis

环、化、材、技、能源战略 / **81**

微等离子体气体电极在熔盐电解中的应用

Author: 浚涵罗[1]

[1] 清华大学

Corresponding Author: luojh21@mails.tsinghua.edu.cn

摘要:

基于辉光放电的微等离子体可以作为非接触气体电极，在基础研究和应用中都受到了广泛的关注。本文以微等离子体为阳极，系统地研究了一系列金属及其合金在熔盐中的电沉积过程。Ag+、Ni2+、Cu2+、Fe3+ 4 种不同价态的金属阳离子均能在固体阴极上以较高的电流效率进行还原且产物纯度高。同时，在微等离子体阳极电解过程中同样存在欠电位沉积现象，可以成功地在活性铝阴极表面得到 Al-Ln 合金。结果表明，基于非接触直流辉光放电的微等离子体阳极是一种很有前途的新型熔盐电解气体电极。

关键词:

微等离子体；电解阳极；熔盐；电沉积；Al-Ln 合金

Abstract:

Microplasma based on glow discharge could act as non-contact gaseous electrode and have attracted much attention in both fundamental research and application. Herein, with microplasma as the anode,

the electrodeposition process of a series of metal and metal alloys in molten salt have been systemically studied. Four metal cations with different valence states, Ag+, Ni2+, Cu2+, and Fe3+, could all be reduced on the solid cathode with high current efficiency and the corresponding metal products were of high purity. The electrodeposition of Al-Ln alloy on the aluminum cathode was also successfully carried out with microplasma as the anode, and the same alloy was obtained by using the conventional anode electrode. These results indicated that microplasma anode based on non-contact direct-current (DC) glow discharge is a promising electrode to be applied in molten salt electrolysis.

Keywords:

Microplasma; Anode; Molten Salt; Electrodeposition; Al-Ln alloy

环、化、材、技、能源战略 / **84**

氚在高温气冷堆典型材料中输运行为研究进展

Author: Ziling Zhou[1]

[1] 核能与新能源技术研究院

Corresponding Author: zhou-zl20@mails.tsinghua.edu.cn

摘要:

氚作为核能系统中关键的放射性核素，其输运行为对反应堆辐射安全与先进核能系统发展至关重要。针对高温气冷堆（HTGRs）中氚迁移特性与安全挑战，本文系统研究了氚在碳化硅、核级石墨及合金材料中的扩散机制及其抑制策略。研究发现：1）碳化硅表面区域对氚的强滞留效应显著降低其有效扩散系数，复合层扩散模型成功解释了理论与实验的差异；2）通过热解吸实验与密度泛函理论计算，揭示了核级石墨中四个氚解吸峰分别对应基面、非晶表面、扶手椅状边缘和之字形边界的解吸行为，阐明了氚在辐照石墨边缘富集的微观机制；3）基于氢同位素（H/D/T）在 Fe、Cr、W 中的扩散规律分析，验证了高温条件下扩散系数与同位素质量的平方根反比关系，并建立了多元合金（如 2.25Cr1Mo 钢）中氚扩散系数的组分体积分数预测模型；4）结合高温气冷堆示范工程（HTR-PM）实测数据，揭示了氧化膜对氚渗透的抑制效应，提出通过优化材料表面化学状态与掺杂元素降低氚渗透率的工程策略。研究成果为完善 HTGRs 氚源项平衡模型、提升辐射安全水平及核能制氢技术发展提供了理论支撑与材料设计指导。

关键词:

高温气冷堆；氚；扩散系数；第一性原理

Abstract:

Tritium, as a critical radionuclide in nuclear systems, plays a pivotal role in reactor radiation safety and the advancement of advanced nuclear technologies. Focusing on the migration characteristics and safety challenges of tritium in High-Temperature Gas-cooled Reactors (HTGRs), this study systematically investigates the diffusion mechanisms of tritium in silicon carbide (SiC), nuclear-grade graphite, and alloy materials, along with strategies for permeation suppression. Key findings include: 1) The strong retention effect of tritium at SiC surface regions significantly reduces its effective diffusion coefficient, and a composite-layer diffusion model successfully reconciles theoretical and experimental discrepancies; 2) Thermal desorption experiments combined with Density Functional Theory (DFT) calculations reveal that four characteristic tritium desorption peaks in nuclear-grade graphite correspond to desorption from basal planes, amorphous surfaces, armchair edges, and zigzag boundaries, elucidating the microscopic origin of tritium enrichment at irradiated graphite edges; 3) Analysis of hydrogen isotope (H/D/T) diffusion in Fe, Cr, and W validates the inverse square root relationship between diffusion coefficients and isotopic mass under high temperatures (>800 K), and establishes a component volume fraction-based prediction model for tritium diffusion in multicomponent alloys (e.g., 2.25Cr1Mo steel); 4) By integrating operational data from the HTR-PM demonstration project, the inhibitory effect of oxide films on tritium permeation is demonstrated, with proposed engineering strategies to reduce permeation rates through surface chemistry optimization and elemental doping. These findings provide theoretical foundations and material design guidelines for refining tritium source-term models, enhancing radiation safety, and advancing nuclear hydrogen production technologies in HTGRs.

Keywords:

High temperature gas-cooled reactors; tritium; diffusion coefficient; first-principle

环、化、材、技、能源战略 / **93**

锂诱导的共价有机框架材料增强吸附热用于高效储氢

Author: 茁卓汤[1]

[1] 清华大学核能与新能源技术研究院

Corresponding Author: tangzz21@mails.tsinghua.edu.cn

摘要:

共价有机框架材料（COFs）具有高比表面积和可调节的孔结构，是极具潜力的氢气物理吸附材料。1 然而，其与氢气分子之间的相互作用过于微弱，无法充分发挥 COFs 材料的高孔隙率优势。本研究首次报道了一种通过金属掺杂增强氢气物理吸附性能的 COFs 材料。借助 TPB-DMTP-COF 材料出色的稳定性，我们在锂（Li）掺杂后成功保留了 COF 材料的孔结构，其比表面积达到 1350 m2/g。由于锂掺杂提高了材料对氢气的吸附热，材料在 77 K、80 bar 条件下的总氢气吸附量从 4.98 wt% 提升至 6.91 wt%。锂掺杂引起的增强效应不涉及化学吸附，且材料表现出优异的循环性能：在 30 bar 条件下循环 10 次后容量保持率达 99%。研究结果表明，通过后修饰调控氢气的吸附热是充分开发多孔材料潜力、实现高效氢气储存的有效策略。

关键词:

共价有机框架材料；氢气存储；锂掺杂；气体吸附；吸附热

Abstract:

Covalent organic frameworks (COFs) possess high surface areas and tunable pore structures and are promising candidates for H2 physisorption materials. However, their interaction with H2 molecules is too weak to take advantage of the high porosity of the COFs. Here, we report the first example of metal-doped enhanced H2- physisorption COF. By leveraging the superior stability of TPB-DMTP-COF, we can well preserve the porosity of the COF after lithium (Li) doping, yielding a surface area of 1350 m2/g. Due to the Li-doping-enhanced H2 isosteric heat, the material's total H2 uptake increased from 4.98 to 6.91 wt % at 77 K and 80 bar. The Li-doping-induced enhancement effect does not involve chemisorption, and the material shows excellent cycling performance: 10 cycles at 30 bar with a capacity retention of 99%. Our results reveal that tuning H2 adsorption heat by postmodification is a promising strategy to exploit the potential of porous materials for efficient H2 storage.

Keywords:

Covalent Organic Frameworks; H2 storage; Lithium Doping; Gas adsorption; Sorption heat

环、化、材、技、能源战略 / **96**

内加热-外循环式流化床-化学气相沉积颗粒包覆过程的 **CFD-DEM** 模拟研究

Author: 宇田[1]

Co-authors: 蕊兰 [2]; 琳蒋 [2]; 荣正刘 [2]; 旭杨 [2]; 友林邵 [2]; 兵刘 [2]; 马林刘 [2]

[1] 核研院

[2] 清华大学核研院

Corresponding Author: tianyu22@mails.tsinghua.edu.cn

摘要:

高温气冷堆（High Temperature Gas-cooled Reactor，HTGR）作为第四代先进核能系统的代表，采用各向同性（Tri-isotropic，TRISO）的包覆核燃料颗粒，可以有效阻挡裂变产物，目前广泛使用流化床-化学气相沉积（Fluidized Bed-Chemical Vapor Deposition，FB-CVD）技术制备 TRISO 包覆核燃料颗粒。在 FB-CVD 方法制备 TRISO 颗粒的过程中，反应气体发生裂解，在流化颗粒的表面沉积得到所需包覆层。反应器内的气固接触效率直接决定了包覆的速率，因此优化反应器设计对提高包覆层的质量有着重要意义。一种带有中心筒的底喷式流化床（简称 Wurster 流化床）得到了广泛的应用，且已成功用于颗粒的喷雾包覆，通过中心筒的内喷雾和反应器壁面的加热，使颗粒快速完成喷雾-干燥-包覆。基于此技术理念，在 FB-CVD 技术制备核燃料包覆颗粒的过程中，引入内加热外循环分区式流化床。通过中心筒的内加热，使气相裂解反应集中在中心筒内包覆区发生，颗粒穿过包覆区后在外低温区完成循环往复。此设计使颗粒和气流形成了规则有序的定向流场，有效控制颗粒的循环时间和包覆区停留时间，进而实现气体裂解过程和颗粒循环过程的解耦。为了更精确地获取颗粒流化行为的相关参数，和包覆区内的颗粒停留时间与流场特性，本研究采用 CFD-DEM（Computational Fluid Dynamics Discrete Element Method）方法，对内加热外循环分区式流化床中的颗粒流化行为进行数值模拟。分析了包覆区内的流场、浓度场及床内的颗粒运动行为，揭示了颗粒包覆过程中的关键参数及其影响机制。模拟结果表明，CFD-DEM 方法能够有效捕捉颗粒与流体的相互作用，为实验研究提供了理论支持，同时为优化流化床的工艺参数和提高颗粒的包覆效率提供了重要参考。

关键词:

核燃料包覆颗粒，流化床设计，CFD-DEM，包覆模拟

Abstract:

High Temperature Gas-cooled Reactor (HTGR), as a representative of the fourth generation of advanced nuclear energy systems, uses Tri-isotropic (TRISO) coated nuclear fuel particles, which can effectively block fission products. Fluidized Bed-Chemical Vapor Deposition (FB-CVD) technology is widely used to prepare TRISO-coated nuclear fuel particles. In the process of preparing TRISO particles by FB-CVD method, the reaction gas is cracked and the required coating layer is deposited on the surface of the fluidized particles. The gas-solid contact efficiency in the reactor directly determines the coating rate, so it is important to optimize the reactor design to improve the quality of the coating layer. A bottom spray fluidized bed (Wurster fluidized bed for short) with a central cylinder has been widely used, and has been successfully used in the spray coating of particles, through the inner spray of the central cylinder and the heating of the reactor wall, the particles can quickly complete the spray - drying - coating. Based on this technical concept, a zoned fluidized bed with internal heating and external circulation was introduced in the process of preparing nuclear fuel coated particles by FB-CVD technology. Through the inner heating of the central cylinder, the gas phase cracking reaction is concentrated in the coating area of the central cylinder, and the particles pass through the coating area and complete the cycle in the outer low temperature area. This design makes the particles and air flow form a regular and orderly directional flow field, effectively control the circulation time of particles and the residence time of the coating area, and then realize the decoupling of the gas cracking process and the particle circulation process. In order to obtain the relevant parameters of particle fluidization behavior and the particle residence time and flow field characteristics in the coating area more accurately, the Computational Fluid Dynamics Discrete Element Method (CFD-DEM) was adopted in this study. The particle fluidization behavior in a zoned fluidized bed with internal heating and external circulation was numerically simulated. The flow field, concentration field and motion behavior of particles in the coated area were analyzed, and the key parameters and their influencing mechanisms were revealed. The simulation results show that CFD-DEM method can effectively capture the interaction between particles and fluids, which provides theoretical support for experimental research, and provides an important reference for optimizing the process parameters of the fluidized bed and improving the coating efficiency of particles.

Keywords:

coated nuclear fuel, fluidized bed design, CFD-DEM, simulation of coating

环、化、材、技、能源战略 / **130**

CO2 低温焙烧-消泡剂辅助浸出提纯线切割晶硅废料

Author: 雯罗[1]

Co-author: 国琛胡 [2]

[1] 昆明理工大学冶金与能源工程学院

[2] 昆明理工大学

Corresponding Authors: karrot_hu@163.com, wen_luo2022@qq.com

摘要:

本研究针对太阳能光伏产业金刚线切割晶硅废料的资源化回收难题，提出了一种基于 CO_2 低温焙烧预处理-消泡剂辅助湿法浸出的新型提纯工艺。该技术通过 CO_2 低温焙烧有效分解废料中的有机碳和无机碳，显著降低碳残留；同时，在后续酸浸过程中引入高效消泡剂，成功抑制了因硅粉与酸反应产氢导致的气泡积聚、硅粉溢出等问题，使硅回收率提升至 80% 以上。与传统湿法工艺相比，本研究通过优化酸浸体系及工艺参数，实现了更高效的杂质脱除：氧含量降至 0.2%，镍、铁等金属杂质去除率分别达 80% 和 90% 以上，最终获得 4N 级硅粉。本工作不仅为光伏硅废料的绿色再生提供了低能耗、低酸耗的解决方案，还可降低回收成本，对促进光伏产业链的循环经济与可持续发展具有重要应用价值。

关键词:

线切割晶硅废料；消泡剂；湿法提纯；除碳；除氧

Abstract:

This study addresses the challenge of resource recovery from silicon wafer waste generated by the diamond wire sawing process in the solar photovoltaic industry, and proposes a novel purification process based on low-temperature CO_2 roasting pretreatment and wet leaching assisted by defoaming agents. This technology effectively decomposes organic and inorganic carbon in the waste through low-temperature CO_2 roasting, significantly reducing carbon residue. Additionally, the introduction of efficient defoaming agents during the subsequent acid leaching process successfully suppresses the accumulation of bubbles and the overflow of silicon powder caused by hydrogen production from the reaction between silicon powder and acid, increasing the silicon recovery rate to over 80%. Compared with traditional wet processes, this study optimizes the acid leaching system and process parameters to achieve more efficient impurity removal: the oxygen content is reduced to 0.2%, and the removal rates of metal impurities such as nickel and iron reach over 80% and 90%, respectively, ultimately obtaining 4N grade silicon powder. This work not only provides a low-energy and low-acid-consumption solution for the green recycling of photovoltaic silicon waste but also reduces the recycling cost, which has significant application value for promoting the circular economy and sustainable development of the photovoltaic industry chain.

Keywords:

Wire-cutting silicon wafer waste; defoamer; hydropurification; carbon removal; oxygen removal

环、化、材、技、能源战略 / **127**

铜渣冷却过程中铜锍生长机理及重金属转化行为研究

Authors: 彪匡[1]; 建杭胡[None]; 勇于[None]

[1] 昆明理工大学

Corresponding Author: kb1667054035@163.com

摘要:

通过缓慢冷却、破碎、研磨和浮选，可以有效地从铜渣中回收铜。然而，缓慢冷却对铜锍生长的影响机制仍不清楚。本文探究了熔融铜渣冷却过程中铜锍的生长机理及铜、铅和锌的转化行为。结果表明，熔融铜渣处于高温非平衡状态，缓慢冷却可促进非平衡相向平衡相的转变。缓慢冷却促进了 Cu2O 和 PbSiO3 分别转化为 Cu2S 和 PbS，以及掺锌尖晶石（Fe3-xZnxO4）和掺锌铁橄榄

石（Fe2-xZnxSiO4）的形成。冷却过程中，溶解铜在原先存在的铜锍液滴表面析出并生长。与此同时，溶解铜优先在高熔点的 Fe3O4 表面异相形核和生长，其次是熔点较低的 Fe2SiO4。缓慢冷却增加了溶解铜的形核和生长时间，这有利于铜锍颗粒的生长，从而提高铜的浮选回收率。这些发现有助于指导改进铜渣缓慢浮选工艺，提高重金属回收率，从而减少铜渣的累积量。

关键词:

铜渣；缓慢冷却；铜锍生长机理；重金属回收

Abstract:

Copper (Cu) can be effectively recovered from copper slag by slow cooling, crushing, grinding, and flotation. However, the mechanism by which slow cooling affects the growth of copper matte remains unclear. This study investigated the mechanism of matte growth and the transformation behaviors of Cu, Pb, and Zn during the cooling process of the molten copper slag. It is shown that the molten copper slag is in a high-temperature non-equilibrium state and that slow cooling encourages the transition from the non-equilibrium to the equilibrium phase. The conversion of Cu2O and PbSiO3 into Cu2S and PbS, respectively, as well as the formation of Zn-doped spinel (Fe3-xZnxO4) and Zn-doped fayalite (Fe2-xZnxSiO4), were facilitated by slow cooling. The dissolved Cu precipitated and grew on the surface of the pre-existing copper matte droplets during the cooling process. In addition, the dissolved Cu preferentially heterogeneously nucleates and grows on the surfaces of the high melting Fe3O4, followed by Fe2SiO4 with a lower melting. Slow cooling increased the nucleation and growth time of dissolved Cu. It benefits the growth of copper matte particles, thereby improving the Cu flotation recovery. Moreover, the toxic leaching concentration of the flotation tailing was shown to be below the standard limits by the toxicity characteristic leaching procedure. These findings could aid in the recovery of heavy metals from copper slag employing slow cooling and flotation, thereby lowering copper slag accumulation and mitigating environmental hazards.

Keywords:

Copper slag; Slow cooling; Matte growth mechanism; Heavy metals recovery

环、化、材、技、能源战略 / **117**

非晶 **Ni3S2/**晶态 **Cu** 异质结构的构建及其电解水性能研究

Author: 全硕昊[1]

[1] 昆明理工大学

Corresponding Author: 1772307033@qq.com

摘要:

合理设计高活性、耐用的非贵金属电催化剂用于 HER 和 OER 反应具有重要的意义。本研究采用一步电沉积法制备了高性能的 a-Ni3S2/Cu 电催化剂。a-Ni3S2/Cu 只需要 1.49 V 的超低槽电压就可以实现 10 mA cm-2 的电流密度，超越了大多数先前报道的过渡金属基材料。a-Ni3S2 与 Cu 耦合，电子从 a-Ni3S2 向 Cu 转移，优化了电子结构，Cu 的 d 带中心上移，有利于反应中间体 H 的吸附。中毒实验，原位 *Raman* 也进一步证明了 *Cu* 为 *H* 吸附/脱附的活性位点。S 周围聚集更多的正电荷，促进对水分子的活化。原位 Raman, 原位 EIS 表明 a-Ni3S2/Cu 在反应过程中重构为活性物质 NiOOH。进一步的中毒实验，甲醇氧化实验表明 Ni 为 OER 反应的活性位点，削弱了对含氧中间体的脱附自由能，大大提高了速率限制步骤（*O+OH-→OOH+e-* ）的反应动力学。这一工作实现了零碳制氢技术的重大突破。

关键词:

电解水、非晶/晶态异质结构、原位表征、DFT 计算

Abstract:

It is important to design highly active and durable non-precious metal electrocatalysts for HER and OER reactions. In this study, a high performance A-Ni3S2 /Cu electrocatalyst was prepared by one-step electrodeposition. A-ni3s2 /Cu requires only an ultra-low tank voltage of 1.49 V to achieve a current

density of 10 mA cm-2, exceeding most previously reported transition metal-based materials. a-Ni3S2 is coupled with Cu, electrons transfer from a-Ni3S2 to Cu, and the electronic structure is optimized. The D-band center of Cu moves upward, which is conducive to the adsorption of the reaction intermediate H. *In situ Raman also further proves that Cu is the active site for H* adsorption/desorption. More positive charges gather around S, promoting the activation of water molecules. In situ Raman and in situ EIS indicate that a-Ni3S2/Cu is reconstructed into the active material NiOOH during the reaction. Further poisoning experiments, methanol oxidation experiments showed that Ni was the active site of OER reaction, which weakened the desorption free energy of oxygen-containing intermediates and greatly improved the reaction kinetics of the rate-limiting step (*O+OH-→OOH+e-*). This work has achieved a major breakthrough in zero-carbon hydrogen production technology.

Keywords:

water splitting amorphous/crystalline heterostructure in situ characterization DFT calculation

环、化、材、技、能源战略 / **113**

脉冲磁场处理对钴基合金相界耐蚀性影响及机理研究

Authors: 德鑫王[1]; 瞿刘[1]; 成凯钱[1]; 克俭李[1]; 志鹏蔡[1]; 立斌孙[1]

[1] 清华大学

Corresponding Author: wangdx21@mails.tsinghua.edu.cn

摘要:

钴基合金堆焊层的耐腐蚀性对核电材料在严苛环境下的长期可靠性至关重要，特别是相界面处的腐蚀现象，已成为影响其性能的关键因素。本研究探讨了脉冲磁场处理（PMT）对碳化物/基体钴界面耐腐蚀性的影响，并系统地揭示了其潜在机制。研究采用了扫描电子显微镜（SEM）、原位透射电子显微镜（TEM）、原位扫描开尔文探针力显微镜（SKPFM）等表征技术，结合密度泛函理论（DFT）计算分析。研究结果表明，PMT 处理样品未出现界面腐蚀裂纹或碳化物剥落，且腐蚀深度显著减少。TEM 分析进一步显示，相界面处的晶格畸变减小，面心立方（FCC）结构的钴部分转变为六方密堆积（HCP）结构。SKPFM 测量和 DFT 计算结果表明，相界面耐腐蚀性的提高主要归因于电子功函数（EWF）的变化。

关键词:

钴基合金堆焊层，脉冲磁场处理，耐蚀性能，相界面，相变，电子功函数

Abstract:

The corrosion resistance of cobalt-based alloy cladding layers is crucial for the long-term reliability of materials in the nuclear power industry, where they are exposed to highly aggressive environmental conditions. A major challenge to their performance is the corrosion occurring at phase boundaries under harsh operating conditions. This study investigates the effects of pulsed magnetic field treatment (PMT) on improving corrosion resistance at phase boundaries, specifically at the carbide/matrix Co interface, and seeks to clarify the underlying mechanisms. Advanced characterization techniques, including scanning electron microscopy (SEM), in-situ transmission electron microscopy (TEM), in-situ scanning kelvin probe force microscopy (SKPFM), and density functional theory (DFT) calculations, were employed. PMT samples exhibited no interface corrosion cracking or carbide spalling showed a significant reduction in corrosion depth. TEM analysis revealed reduced lattice distortion at phase boundaries and a partial transformation of face-centered cubic (FCC) Co to hexagonal close-packed (HCP) Co. The enhanced corrosion resistance at phase boundaries is attributed to changes in the electronic work function (EWF), as determined by SKPFM measurements and DFT calculations.

Keywords:

Cobalt-based alloy cladding layer, Pulsed magnetic field treatment, Corrosion, Interface, Phase transition, Electronic work function

环、化、材、技、能源战略 / **112**

高能锂离子电池 **PET** 基复合集流体的力学性能研究

Author: 董先锋[1]

Co-authors: 何向明 [1]; 张稚国 [1]; 李华清 [2]; 王莉 [1]

[1] 清华大学核能与新能源技术研究院

[2] 江苏瀚叶铜铝箔新材料研究院有限公司

Corresponding Author: dxf24@mails.tsinghua.edu.cn

摘要:

塑料膜复合集流体（PFCC）是一种具有"金属层 + 聚合物层 + 金属层"的类三明治结构的新型电池集流体，由于可以提高锂离子电池（LIB）的能量密度和安全性，PFCC 受到了电池相关研究者的广泛关注。然而，目前对 PFCC 各项性能的研究相对较少，其在 LIB 中的应用仍然存在很多挑战，例如：聚合物-金属间粘合力弱、导电性差、耐腐蚀性差等。本文以传统金属集流体为参考，针对聚对苯二甲酸乙二醇酯（PET）基 PFCC 的力学性能进行了对照研究。研究的主要工作如下：
（1）以活性浆料组成及其压实密度为力学工况参数同步制备三种工况下的传统铝金属集流体（Al-CC）、传统铜金属集流体（Cu-CC）、聚合物基铝金属集流体（Al-PFCC）和聚合物基铜金属集流体（Cu-PFCC）电池极片。
（2）通过 SEM 形貌表征、EDS 组成表征和 CAD 标准化破损度拟合计算分析正极 Al-PFCC 和负极 Cu-PFCC 在相同力学工况下的金属涂层损伤情况。实验发现，Al-PFCC 的极限浆料压实密度（1.07-2.01 g/cm3）明显低于 Al-CC 的极限浆料压实密度（2.04-3.12 g/cm3），Cu-PFCC 的极限浆料压实密度（0.83-1.26 g/cm3）明显低于 Cu-CC 的极限浆料压实密度（1.30-1.70 g/cm3）。
（3）从 PFCC 的材料特性、结构特征和加工工艺三个方面对其力学性能的不足进行了机理分析。
（4）针对不同的成因可能，提出了可以从界面防护工程、调控活性材料层、改良聚合物基膜三个角度对 PFCC 的力学性能进行改进，例如：设置加工保护层、设置导电底涂层、设计功能化活性浆料、分区化浆料涂布等。
以上研究工作可以为 PFCC 在 LIB 中的进一步应用提供一定的参考价值。

关键词:

锂离子电池；复合集流体；塑料基膜；金属涂层；力学性能；界面问题

Abstract:

Plastic film composite current collector (PFCC) is a new type of battery collector with a sandwich-like structure of "metal layer + polymer layer + metal layer", which has attracted a lot of attention from battery researchers due to its ability to improve the energy density and safety of lithium-ion batterie (LIB). However, studies conducted on the various properties of PFCC are relatively few, and there are still many challenges for its application in LIBs, such as weak polymer-to-metal adhesion, poor electrical conductivity, and poor corrosion resistance. In this article, a controlled study was conducted for the mechanical properties of PET-based PFCC using conventional metal collectors as a reference. The main work is as follows:
(1) Use the composition of the activated slurry and its compaction density as the parameters of the mechanical operating conditions, simultaneously preparing Al-CC, Cu-CC, Al-PFCC and Cu-PFCC battery electrodes in three mechanical processing conditions.
(2) Analyze the metal coating damage of anode Al-PFCC and anode Cu-PFCC by SEM morphological characterization, EDS compositional characterization and CAD standardized breakage fitting under the same mechanical processing conditions. It was found that the ultimate slurry compaction density of Al-PFCC (1.07-2.01 g/cm3) was significantly lower than that of Al-CC (2.04-3.12 g/cm3), and the ultimate slurry compaction density of Cu-PFCC (0.83-1.26 g/cm3) was significantly lower than that of Cu-CC (1.30-1.70 g/cm3).
(3) Analyze the mechanism of the deficiencies in the mechanical properties of PFCC from three aspects: material properties, structural characteristics and processing.
(4) Regarding the above possible causes, propose that the mechanical properties of PFCC can be improved from three perspectives: interfacial protection engineering, modulation of the active material layer and modification of the polymer film, such as: setting up a processed protective layer, setting up a conductive undercoating, designing a functionalized active slurry and partitioning slurry coatings, etc. The research above can provide some reference for PFCC's further application in LIB

Keywords:

Lithium-ion battery; composite collector; plastic film; metal coating; mechanical property; interface problem

环、化、材、技、能源战略 / **90**

Developing solid oxide electrolysis cells for CO2 conversion: The Power-to-X critical approach

Author: YUHUI JIN[1]

Co-authors: Feichao Li [2]; Yun Zheng [3]; Wenqiang Zhang [1]; Shufan Wang [3]; Wei Yan [3]; Bo Yu [1]; Jiujun Zhang [1]

[1] *Institute of Nuclear and New Energy Technology, Tsinghua University*

[2] *Shandong Weifang Ecological Environment Monitoring Center*

[3] *Institute of New Energy Materials and Engineering, College of Materials Science and Engineering, Fujian Engineering Research Center of High Energy Batteries and New Energy Equipment & Systems*

Corresponding Author: jinyh23@mails.tsinghua.edu.cn

摘要:

用可再生能源替代传统化石燃料是缓解全球变暖的关键举措。然而，太阳能、风能等的随机、波动与间歇的特点给电网带来了重大挑战。电力多元化转换（Power-to-X, P2X）技术在消纳风电、光电中扮演了重要角色。利用高温固体氧化物电解池（Solid oxide electrolysis cells, SOECs）转化 CO2，不仅可以将可再生电力储存在化学品中，而且可以实现碳资源的高效利用。本综述总结了两种通过 SOECs 将 CO2 转化为化学品的途径，并在此基础上，进一步提出了 SOECs 在 CO2 转化领域大规模应用面临的主要挑战和发展方向。

关键词:

固体氧化物电解池（SOECs），CO2 转化，电力多元转换（P2X）

Abstract:

The substitution of traditional fossil fuels with renewable energy sources is a crucial endeavor for carbon neutrality targets. However, the intermittency of solar, wind, etc. poses significant challenges to the power grid. Power-to-X (P2X) technologies play an essential role in the consumption of renewable energy sources. Using high-temperature solid oxide electrolysis cells (SOECs) to convert CO2 allows renewable electricity to be stored in chemicals, and enables the resourceful utilization of carbon resources. Herein, two pathways for converting CO2 to chemicals via SOECs are summarized. Based on the above discussion and analysis, the main challenges and development directions for the large-scale application of SOECs within the domain of CO2 conversion are further proposed.

Keywords:

solid oxide electrolysis cells (SOECs), CO2 conversion, power-to-X (P2X)

近代物理 / **70**

LHCb 上 B_s^0→J/ψπ^+ π^-衰变中 CP 破坏和分波分析的研究

Author: Yinghua Tan[1]

[1] *Tsinghua University*

Corresponding Author: tanyh21@mails.tsinghua.edu.cn

摘要:

本文利用 LHCb 实验 Run 2 采集的质子-质子对撞数据，对 B_s^0→J/ψπ^+ π^-衰变进行了时间依赖的味道标记振幅分析和螺旋度振幅分析。分析测量了 CP 破坏相角 ϕ_s 和寻找了四夸克态粒子 Z_c^±。

关键词:

LHCb 实验；CP 破坏；CP 破坏相角；四夸克态；振幅分析

Abstract:

A time-dependent flavour tagging amplitude analysis and a helicity amplitude analysis are performed to B_s^0→J/ψπ^+ π^- decays, using the Run 2 pp collision data collected with the LHCb detector. The CP-violating phase ϕ_s is measured and the tetraquark state Z_c^± is searched.

Keywords:

LHCb experiment; CP violation; CP-violating phase; Tetraquark state; Amplitude analysis

近代物理 / **85**

基于 **EFISH** 的电场测量及空间电荷极性效应研究

Authors: Yiming Guo[None]; BangDou Huang[1]

[1] 中科院电工所

Corresponding Author: guo-ym20@mails.tsinghua.edu.cn

摘要:

本文提出了一种具有高空间分辨率的基于电场诱导二次谐波效应（EFISH）的电场诊断系统，并将其应用于大气压电晕放电中电场空间分布的测量。通过实验研究了空间电荷极性对电场分布的影响。结果表明，在相同外加电压条件下，负极性电晕放电的电场强度明显低于正极性电晕放电。进一步结合空间电荷分布特性对该差异进行了理论分析和解释。

关键词:

大气压电晕放电，电场测量，电场诱导二次谐波效应（EFISH），空间电荷极性效应

Abstract:

In this study, we propose a high-spatial-resolution electric field diagnostic system based on the electric-field-induced second harmonic generation (EFISH) effect, and apply it to measure the spatial distribution of electric fields in atmospheric-pressure corona discharges. The influence of space charge polarity on the electric field distribution was investigated experimentally. The results show that, under the same applied voltage, the electric field intensity near the electrode in negative corona discharges is significantly lower than that in positive ones. This difference is further analyzed and interpreted based on the spatial distribution characteristics of space charges.

Keywords:

Atmospheric-pressure corona discharge; Electric field measurement; Electric-field-induced second harmonic generation (EFISH); Space charge polarity effect

近代物理 / **24**

Striation enhanced non-local collisional heating in capacitive radio-frequency CF4 plasmas

Author: Zhenhua Zhou[1]

Co-authors: Xiaokun Wang [2]; Dong Yang [3]; Hanyang Li [3]; Zoltán Donkó [4]; Julian Schulze [2]; Yongxin Liu [5]; Yangyang Fu [6]

[1] *Department of Engineering Physics, Tsinghua University*

[2] *Chair of Applied Electrodynamics and Plasma Technology, Faculty of Electrical Engineering and Information Sciences, Ruhr University Bochum, 44801 Bochum, Germany*

[3] *Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China*

[4] *Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, 1121 Budapest, Hungary*

[5] *Key Laboratory of Materials Modification by Laser, Ion, and Electron Beams (Ministry of Education), School of Physics, Dalian University of Technology, 116024 Dalian, People's Republic of China*

[6] *Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China & State Key Laboratory of Power System Operation and Control, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China & Sichuan Energy Internet Research Institute, Tsinghua University, Sichuan 610213, China*

Corresponding Author: zhouzh21@mails.tsinghua.edu.cn

关键词:

非局域碰撞加热；电容性射频等离子体；CF4 放电；电子动力学；条纹模式

Keywords:

Non-local collisional heating; Capacitive radio-frequency plasmas; CF4 discharge; Electron kinetics; Striation mode

摘要:

本工作研究了以条纹模式运行的低温射频（RF）容性耦合 CF4 等离子体中电子非局部碰撞加热的增强。在射频电压幅值 V0 = 300 V、CF4 气体压力 p= 60 Pa、间隙 d = 2 cm、驱动频率 f 在 6.78 MHz 到 27.12 MHz 之间的条件下，进行了质点网格法/蒙特卡洛碰撞模拟，呈现了放电模式从条纹模式（striation mode）到漂移-双极（DA mode）模式的过渡。我们发现，在条纹模式下，电子平均能量 εe 的空间分布在主等离子体中呈现出具有高能量峰值的条纹轮廓。对电子加热功率密度时空分布的比较分析表明，在条纹模式中，非局域碰撞加热在这些峰值处占主导地位，而在 DA 模式放电中，与欧姆加热相比，非局域碰撞加热在主等离子体的贡献可以忽略不计。利用无碰撞测试粒子轨迹分析进行的进一步研究表明，低能电子可以在条纹模式放电的主等离子体区中被束缚，并在条纹之间进行多次反弹。高能电子虽然不会被束缚，但会在条纹电场之间输运的过程中经历周期性的加速和减速，并沿轨迹形成条纹状的动能空间分布。这些发现证明了条纹模式下 CF4 电容耦合射频放电中主等离子体区的条纹状电场在增强非局域碰撞加热中的关键作用。

Abstract:

We investigate the mechanism of the enhanced electron non-local collisional heating process in radiofrequency (RF) CF4 capacitively coupled plasmas (CCPs) operating in the striation mode. Particle-in-cell/Monte Carlo collision (PIC/MCC) simulations are conducted under an RF voltage amplitude V0 of 300 V, a CF4 gas pressure p of 60 Pa, a gap d of 2 cm and driving frequencies f within the interval of 6.78 MHz to 27.12 MHz, presenting a discharge mode transition from the striation mode to the drift-ambipolar (DA) mode. We show that in the striation mode, the mean electron energy εe within the bulk plasma exhibits a striated profile with high-energy peaks. A comparative electron heating analysis reveals that non-local collisional heating dominates the formation of these high-energy peaks in the striation mode, whereas its contribution to the bulk plasma produced by the DA-mode discharges is negligible relative to that of Ohmic heating. A further investigation conducted using a collisionless test particle analysis demonstrates that low-energy electrons can be trapped in the bulk plasma of striation-mode CF4 CCPs, triggering multiple rebounds among the striations. High-energy electrons are not trapped but rather undergo periodic acceleration and deceleration during transport through the bulk region in the striation discharge mode. These findings support the critical role of striations in enhancing the non-local collisional heating process in CF4 capacitive RF discharges operated in the striation mode.

63

基于物理引导两阶段深度学习的建筑结构地震易损性分析

Author: 雪天刘[1]

[1] 清华大学安全科学学院

摘要:

建筑结构地震易损性分析对于地震灾损评估具有重要意义。本研究提出了一种基于物理引导两阶段深度学习的建筑结构地震易损性分析方法，可以根据相对低成本的数据集得到建筑结构工程需求参数更精准的预测结果。这种深度学习方法将同类型建筑结构需求参数基于简化、精细模型计算结果之间的预测增量为物理引导，建立了同类型建筑结构不同物理模型之间的联系，通过两阶段集成了大规模简化模型数据集预测结果和精细模型数据集预测增量。以 MLP 神经网络为基础，基于本研究深度学习方法构建的神经网络验证了有效性。计算结果表明，本研究方法预测结果相较数据驱动神经网络有所改善，测试集上 MSE、RMSE 以及 MAE 等评估指标均下降，且测试集上 R2 达到 99% 所需训练集规模下降了 12.98%。总体而言，所提出方法在降低地震易损性分析计算成本，实现地震情境下对破坏程度的快速、准确预测具有重要潜力和应用前景。

关键词:

地震易损性分析；深度学习；两阶段；物理引导

Abstract:

Seismic fragility analysis of building structures is important for evaluation of earthquake-induced damage. This research proposes a physics informed two stage deep learning method for seismic fragility analysis of building structures, which provides better prediction of engineering demand parameters with less data cost. The proposed deep learning method utilizes the increment of predictions of engineering demand parameters between simplified and refined model under the same seismic scenarios as physics information, establishes connections between different physical models of the same structural type, effectively integrating predictions from large-scale simplified model datasets and the increment of predictions from refined model datasets with two stage techniques. The neural network developed based on the multilayer perceptron and implemented within the proposed deep learning method demonstrates the effectiveness of the proposed methodology. The computational results demonstrate that the proposed method achieves significant improvements over conventional neural networks. Notably, evaluation metrics on the test set show substantial reductions. Furthermore, the method reduces the required training dataset size by 12.98% to achieve an R^2 value of 99% on the test set. Overall, the proposed method exhibits considerable potential in reducing computational costs associated with seismic fragility analysis, while facilitating rapid and accurate prediction of damage levels under various seismic scenarios.

Keywords:

Seismic Fragility Analysis; Deep Learning; Two Stage; Physics Informed