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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

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

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