Contribution ID: **161** Type: 海报展示

空间闭式布雷顿循环氦氙工质泄漏对离心压气机性能的影响机制研究

摘要

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

关键词

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

Abstract

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

Keywords

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

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Session Classification: 海报展示

Track Classification: 海报展示: 海报展示