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基于 Blockage 的离心压缩机扩压器优化

摘要

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

关键词

楔形扩压器；前缘开槽；边界层分离；Blockage

Abstract

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

Keywords

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

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