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Numerical investigation of the effect of highly loaded design on the tip leakage in helium compressor rotors

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A R T I C L E I N F O

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A B S T R A C T

The highly loaded design method of helium compressors can effectively solve the compression problem of helium in high-temperature gas-cooled reactors. However, the reduction in blade height and the increase in transverse pressure gradient lead to more leakage flow problems at the tip clearance. This study aims to develop a deeper understanding of the tip leakage flow physics and its influence on the loss mechanism. The tip leakage loss characteristics and loss mechanisms in a highly loaded helium compressor are analyzed by numerical simulation to provide the necessary knowledge for optimizing the blade tip aerothermal design. Five different blades are designed with different loading conditions and analyzed with five different blade tip clearances. The sensitivity of the aerothermal performance on tip clearance scales in the highly loaded helium compressor rotor is also analyzed. Based on the results and analysis, a new loss model is developed, which can be fully utilized to predict the tip clearance loss in highly loaded helium compressors. The deviations between the predicted values and CFD values can be less than 3%.

1. Introduction

In power conversion units of high-temperature gas-cooled reactors, the axial compressor for helium is one of the key components and its performance has significant effects on the plant efficiency (No et al., 2007; McDonald, 2012; Moore et al., 1982; Wang, 2009). Helium is difficult to compress owing to its thermodynamic properties (high specific heat, high sonic speed, and high specific heat ratio). Helium compressors require more number of stages than air compressors in order to achieve a certain pressure ratio (Brodt, 1995; JAEA, 2011; Dong, 2011). Therefore, the aerodynamic design of helium compressors is a difficult task.

To solve this problem, Russian scholars proposed a compressor design method considering the characteristics of helium for closed cycle systems (Mihayiluofu et al., 1964). This method increases the flow coefficient in order to achieve the goal of increasing the Euler work at identical efficiency. This method was based on the comparison and analysis of the flow coefficient effect on air and helium compressors. Long (Long et al., 2008; Long et al.,) analyzed the velocity triangles of a highly loaded helium compressor elementary stage in detail and identified the design characteristics of the helium compressor such as high reaction, large flow deflection, and negative pre-whirl. Then, she analyzed the flow field characteristics of the compressor with the support of the Chinese government 863 Program in 2008. Later, based on the highly loaded design method of helium compressors, Ke (Ke and Zheng, 2011, 2012, 2010) investigated an appropriate airfoil to be used for helium compressors and examined the inlet flow characteristic distribution of a highly loaded helium compressor. JAEA 300 MW, which was a low-pressure compressor, was selected and a design validation was conducted. Ke (Ke and Zheng, 2011, 2012, 2010) obtained a similar compression ratio with only 6 stages against 16 stages by utilizing the highly loaded design method. In 2015, Jiang (Bin et al., 2015) analyzed the blade surface boundary layer growth characteristics of a highly loaded helium compressor. The flow characteristics of the highly loaded helium compressor were further analyzed by Tian and Zheng (Tian et al., 2017a, 2017b, 2017c). A method of applying a cascade structure in order to control the development of boundary layer of a highly loaded helium compressor was presented, which further improved the stage loading. A 16-stage compressor was reduced to 3 stages at identical efficiency, which is a major progress made in the field of helium compressor design technology. The aforementioned research validated the efficacy of the highly loaded design method. Simultaneously, numerous preliminary design schemes were proposed by researchers worldwide. However, a research on the characteristics of tip leakage in highly loaded helium compressor rotors is still nonexistent.

The tip clearance flow in compressors is always very complex and has a significant influence on a compressor's performance (Syed et al., 2016; Ren and Gu, 2016; Wang et al., 2015; Mao and Liu, 2017). The

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highly loaded design technique has solved the problem of large number of stages, which concerns conventional helium compressors. However, the reduction in blade height and increase in transverse pressure gradient lead to leakage problems at the tip clearance in highly loaded helium compressors. Therefore, it is important to study the loss mechanism of tip leakage flow in order to improve the aerodynamic performance of highly loaded helium compressors.

The objective of this study is to develop a deeper understanding on the tip leakage flow physics in highly loaded helium compressors, which influences the loss mechanisms. First, five different blades are designed with different loading conditions and analyzed, in order to study the influence of loading on tip leakage flow in helium compressors. Afterward, five tip clearances, namely 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% of blade span are selected and analyzed, in order to investigate the sensitivity of the aerothermal performance of a transonic tip leakage flow at various tip gap heights in a highly loaded helium compressor rotor. Finally, based on the tip leakage flow characteristics, a new loss model of tip clearance leakage flow is developed for highly loaded helium compressors.

2. Highly loaded design method

The velocity vectors and associated velocity diagrams of a typical highly loaded axial helium compressor stage and a conventional axial helium compressor stage are compared in Fig. 1. The velocity triangle of the highly loaded helium compressor is relatively different from that of a conventional helium compressor. Owing to the higher sonic speed of helium, the velocity triangle of the highly loaded compressor increases the torsional velocity enormously with the increase in axial velocity and a negative pre-whirl velocity. As shown in Equation (1) and Equation (2), if the circumferential velocity is unchanged, the stage load coefficient will increase significantly.

The stage load coefficient can be defined as

$$\phi = \Delta h / U^2 \tag{1}$$

The enthalpy rise along the streamline is given as follows:

$$\Delta h = \Delta W_u * U \tag{2}$$

where $\Delta W_u = W_{1u} - W_{2u}$ for the conventional helium compressor. $\Delta W_u = W_{1u} + W_{2u}$ for the highly loaded helium compressor.

3. Numerical techniques

The number of rotor blades is 145 and the flow passage of the helium compressor is fixed as a constant inner diameter. The inlet boundary is located at a distance of 2 chords up-stream of the rotor, and the outlet boundary is situated at a distance of 2 chords down-stream of the rotor. The schematic of the helium compressor rotor is shown in Fig. 2.

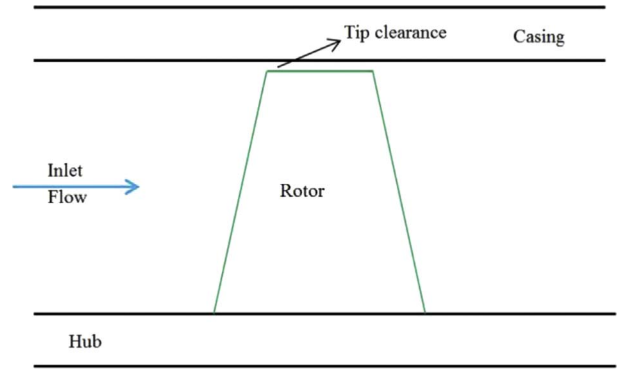

Fig. 2. Schematic of helium compressor rotor.

In each flow-path, the periodic multi-block O4H-type structured grid, which is created by Autogrid5 (NUMECA preprocessor), is used. O-type grids surround the rotor surface and the rest of the regions have H-type grids. Fig. 3 shows the grid structure of the rotor blade. The cell-centers adjacent to the solid surfaces are placed at y+ < 1 for all the computations.

The numerical simulation software used in this study is the commercial flow solver ANSYS-CFX17. The solution results are obtained by solving the 3D steady compressible Reynolds-averaged Navier–Stokes equations and a finite-volume method is used to discretize the equations. The axial compressor rotors are simulated in a rotating coordinate system in this study. The predicted and experimental isentropic efficiency are shown in Fig. 4. By comparing the isentropic efficiency between the experimental data (Zhu et al., 2010) and the calculation results with different turbulence models, the SST *k-ω* turbulence model can provide an accurate prediction of the isentropic efficiency.

A numerical simulation of a single-blade passage with periodic boundary conditions in the circumferential direction is conducted. The total temperature and total pressure are specified along with the flow angle, and the turbulence intensity is 5% at the inlet. At the outlet, the static pressure is specified. All solid surfaces are treated as adiabatic with no-slip.

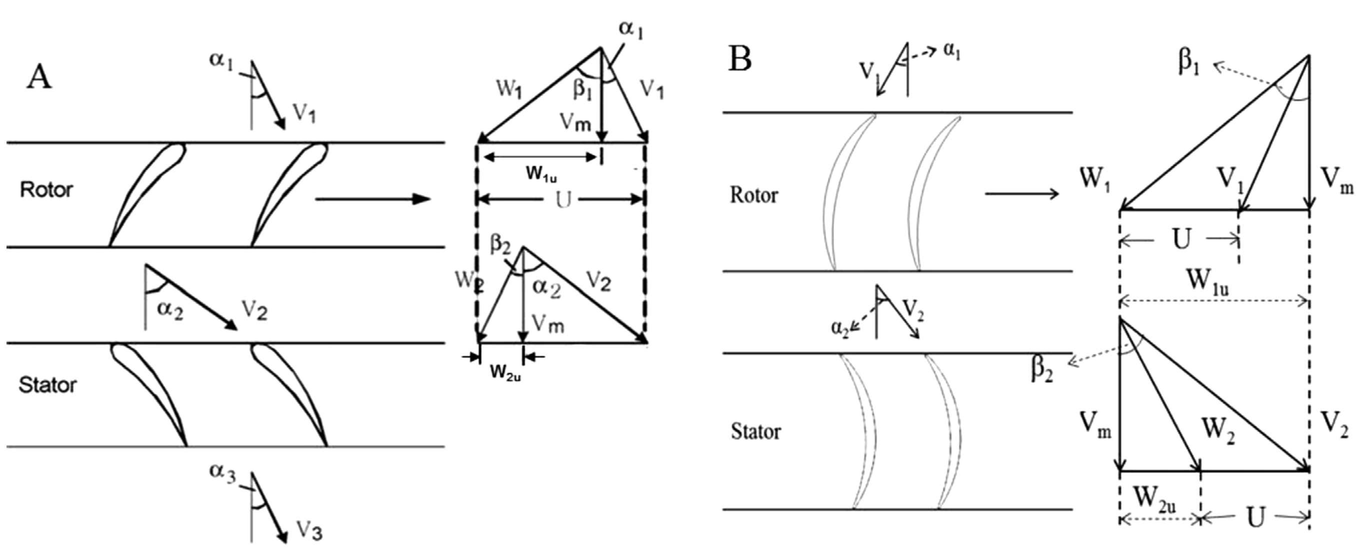

Fig. 1. Velocity diagram of helium compressor: A: conventional design method; B:highly loaded design method.