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Effect of Reynolds number on supercritical helium axial compressor rotors performance in closed Brayton cycle

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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

Supercritical helium has been considered as an ideal working fluid in a number of design studies for closed Brayton cycle due to its thermal properties. But the low density level of supercritical helium, the characteristics of the small flow channel in the turbomachine and the variable working condition method of the system determine that the compressor may run at low Reynolds number. In this paper, the influence of Reynolds number on supercritical helium compressor rotor is investigated under different conditions by numerical simulation program. Effects of specific heat ratio on Reynolds number sensitivity of supercritical helium compressor rotor are also investigated by comparing the calculated results of different working fluids. Special attention is paid to the relationship between properties of working fluids and efficiency. Then, the equations of efficiency and total pressure ratio for different working fluids are established. The results show that the Reynolds number sensitivity of supercritical helium compressor rotor decreases with the increase of tip clearance and increases with the increase of the specific heat ratio.

1. Introduction

Energy demand has always been the most widely concerned topics with the development of the world [1]. The energy consumption is increasing. As shown in Fig. 1, nuclear energy has to be increased along with the traditional fossil fuel and renewables to meet the increasing demands. Nowadays nuclear energy is becoming more safe and available. World net electricity generation by nuclear will reach to 4.5 trillion kilowatt hours by 2040 [2]. How to make the nuclear power conversion safer and more efficient is a demanding research topic.

Nuclear power plant has evolved to the fourth generation. High temperature gas cooled reactor, which based on the closed Brayton cycle with helium as the working fluid and as a coolant of the reactor, is one of the most promising fourth generation nuclear reactors [3–5]. The turbine inlet temperature can be increased up to 900 C°with helium direct cycle and consequently the efficiency of the PCU can reach to 50% [6–8], which is far higher than the present cycles. Helium is the second lightest element in the periodic table of elements and it is a noble gas that has high temperature stability, negligible radiation transport characteristics and good heat transfer properties, which makes it an ideal coolant for reactor and a good working fluid for the closed Brayton cycle [9]. Additionally, the helium turbomachinery and direct cycle PCU could be packed in the safety shell with the reactor, and it has advantage and avoids numbers of technical problems associated with saturated wet steam cycle i.e. indirect cycle [10]. There are other optional working fluids, but according to statistics, 9 of the 15 closed Brayton cycle nuclear reactor systems ever built and applied around the world since 60s have used helium as a working fluid and as a coolant [9]. The performance comparisons of various closed Brayton cycle working fluids are listed in Table 1.

Supercritical helium compressor provides compressed helium to cool the reactor and the helium is heated in the reactor, and then helium expands in the helium turbine to generate output power. Therefore it is one of the key components of high temperature gas cooled reactor with the direct helium cycle and plays an important role in the performance of the high temperature gas cooled reactor [11]. But the low density level of supercritical helium, the characteristics of the small flow channel in the turbomachine and the variable working condition method of the system (Change the output power by changing the massflow of the working fluid) determine that the compressor may run at low Reynolds number [12–14], because the flow velocity is large enough and the viscosity

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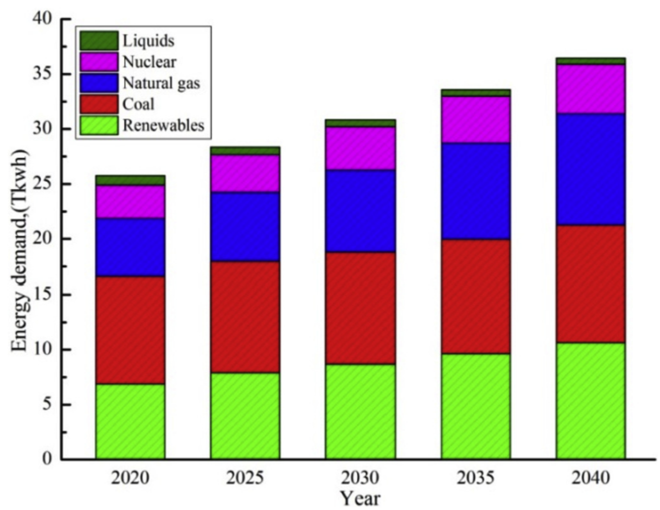

Fig. 1. World net electricity generation by energy source, 2020–2040 (Trillion kilowatt hours).

coefficient is approximately constant.

The Reynolds number has a great influence on the efficiency of air compressor under the condition of low Reynolds number [15–17]. The effects of Reynolds number on the performance of air compressor have been studied by some researchers. The design methods of compressor adapted to low Reynolds number applications were put forward [18,19]. Wassell [20] surveyed data on some 20 multistage axial compressors and suggested that the power law index, which gauges how sensitive compressor loss responds to changing Reynolds number, is the product of two factors that depend on Mach number and mean flow path aspect ratio, respectively. The sensitivity decreases with increasing Mach number and decreasing aspect ratio. Schaffler [21] confirmed the predictability of Wassell's model through testing of four aero engine transonic compressors that included from three to six intermediate to high pressure stages. The values of power law index for the four units fell to a narrow band of 0.10–0.15 in a turbulent flow regime over a smooth surface. The influence of Reynolds number and heat transfer on scaling of a small scale centrifugal compressor impeller was investigated by Ma [22]. Decreasing Reynolds numbers are associated with thicker boundary layers and the increase of wake regions. Thus the flow near the solid walls is more susceptible to separate, and the viscous losses increase. To reduce the loss under low Reynolds number conditions, a slotted compressor airfoil to blow off the boundary layer separation flow was used by Zhou [23]. Although the effects of low Reynolds number on the performance of turbomachine have been studied, most of them concentrated in the air centrifugal or axial compressors. Little is known about how low Reynolds numbers affects the performance of supercritical helium compressor rotor.

In order to understand the performance characteristics of helium compressor and set up better performance correction methods under low Reynolds number conditions, the studying on the aerodynamic loss mechanism and the flow field at low Reynolds number is necessary. In this paper, the Reynolds number's sensitivity of supercritical helium compressor rotor is studied from different aspects (Load, Thickness distribution, Clearance) by numerical simulation program firstly. Then, effects of specific heat ratio on compressor Reynolds number sensitivity are also investigated by comparing the calculated results of different working fluids. The objective of the present study is to use a numerical simulation method to set up better performance correction methods.

Table 1
Advantages and disadvantages of the closed Brayton cycle working fluids.

Working fluid	Advantages	Disadvantages
Air	(1)Considerable design experience available (2)Air is abundant and inexpensive	(1) High pressure loss (2) Poor heat transfer coefficient (3) Likely oxidation (4) Limited plant capacity
Nitrogen	(1)Composition and properties partly similar to air	(1) High pressure loss (2) Poor heat transfer property (3)Likely nitriding and embrittlement
Helium	(1)Low pressure loss (2)Good heat transfer coefficient (3)Inert and non-toxic (4)No Mach number restriction	(1)More number of turbomachinery stages (2)High leakage (3)Limited turbomachinery design experience
S-CO_2	(1)Good efficiency (2)Non-toxic (3)Low leakage rate (4)Good critical point	(1)More corrosive (2)Limited design experience (3)Likely operation and design challenges

2. Numerical techniques

Five kinds of supercritical compressor rotors with different loads are selected to study and all the simulations are used only one periodic blade passage in the present work. The geometric configuration of the compressor is displayed in Fig. 2. The blade number of rotor is 145. The camber line of the blade profile is controlled by parabola and the thickness distribution of the blade profile is cubic curve. The form of the flow passage of the supercritical helium compressor is constant inner diameter. The inlet is set in a distance equal to 2 chords up-stream of the rotor and the outlet is set in a distance equal to 2 chords down-stream of the rotor.

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

The numerical simulation software used in this paper is the commercial flow solver ANSYS-CFX17. The solution results are gained by solving the 3D steady compressible Reynolds-averaged Navier–Stokes equations and to discretize the equations, a finite-volume method is used. Predicted and experimental isentropic efficiency are shown in Fig. 4. By comparing the isentropic

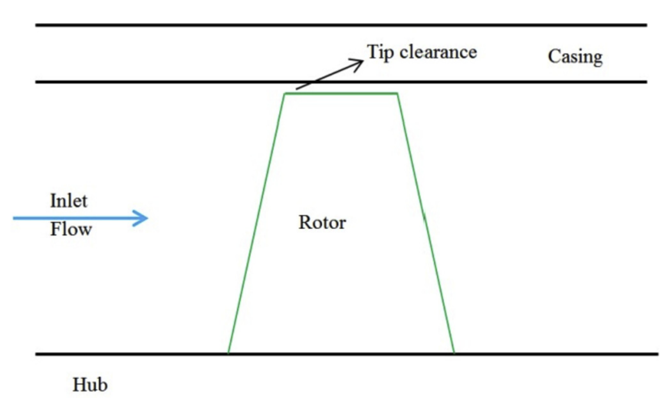

Fig. 2. Schematic of supercritical helium compressor.