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Similarity and cascade flow characteristics of a highly loaded helium compressor

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HIGHLIGHTS

- The deviation of different similarity criteria is analyzed theoretically.
- Flow difference between helium and air compressor cascades is analyzed numerically.
- The analysis of calculated results validates the theoretical derivation.
- Flow characteristics of highly loaded helium compressor blade profile are computed.

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ABSTRACT

Helium compressor is a major component of the Power Conversion Unit (PCU) used in a High Temperature Gas Cooled Reactor (HTGR). Because the high cost of closed cycle test and leakage problem of helium gas, air could be used as working fluid instead of helium in compressor performance tests. However, the properties of Helium are largely different from those of air, e.g. the adiabatic exponent of Helium is 1.6, while the adiabatic exponent itself is a criterion of similarity between the two compressors. The characteristics of compressor will be different due to the effect of the adiabatic exponent of working fluid, especially for highly loaded compressor working at higher inlet Mach number. In this paper, a theoretical study on the similarity between air compressor and a highly loaded helium compressor is carried out and the deviation of similarity is analyzed. Numerical simulations are then used to confirm the theoretical analysis. The results indicate that the similarity deviation could not be neglected for highly loaded compressor cascade, which means the experience and experimental results of those conventional air compressor cannot be applied directly to the design of highly loaded helium compressor. The flow characteristics of a highly loaded helium compressor at different Reynolds numbers, attack angles, Mach numbers and cascade geometries are then investigated.

1. Introduction

Nuclear energy remains one of the major choices for most countries in tackling global energy shortage and climate change. The high temperature gas-cooled reactor (HTGR) is an advanced nuclear reactor which has obvious advantages in terms of security, economy and environmental protection. It has a promising application in nuclear power plants and ship power systems. The key technology of HTGR thermodynamic cycle has received considerable attentions in nuclear engineering field (Jenny and Anthony, 2009).

Helium is an ideal coolant for the HTGR and acts as the working fluid of the power conversion unit (Ke and Zheng, 2012). It can use nuclear reactor as heat sources of which the temperature is more than 900 degrees and the efficiency of such kind of nuclear units is 30% higher than conventional pressurized water reactor. Though the helium compressor plays an important role in HTGR system, the aerodynamic design of the compressor could not developed directly from the air compressor. In the 1970s, the 50 MWe nuclear plant Energieversorgung Oberhausen (EVO) was constructed by Germany. The unit operated successfully for about 24,000 accumulated hours until 1988 but only achieved a maximum power of 30.5 MWe, which was well below the rated level. Subsequent research found that the aerodynamic design defect of the helium compressor was one of the reasons of the underrated power (Weisbrodt, 1995). The newest lecture about the EVO II (Bentivoglio and Tauveron, 2008) gave the analysis that many

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Nomenclature

CFD	computational fluid dynamics
PCU	power conversion unit
HTGR	high temperature gas cooled reactor
GT-MHR	gas turbine-modular high temperature reactor
PBMR	pebble bed modular reactor
R	gas constant
λ	velocity coefficient
A	flow section area
X_{air}	velocity similarity factor of air
C_p	surface pressure coefficient
k_0	adiabatic exponent of air
k_{he}	adiabatic exponent of helium

different factors contributed to the power deficit the most important being that the isentropic efficiencies of the turbo-machines were lower than predicted at the design phase. In addition, the leakage and cooling bypass flows were larger the expected, such as the system pressure drop.

The US DOE launched GT-MHR project in cooperation with Russia (Baxi et al., 2009). In South Africa and Netherlands, PBMR and ACACIA projects were on-going, respectively (Heek, 2002; Dobson, 2008; Bruyn et al., 2008). Japan and China also announced their research programs (Yasushi, 2001; Wu, 2002; Yan et al., 2008). Generally, the aerodynamic design and flow field control techniques of helium compressor follow traditional design methods of air compressor. But as the adiabatic index and specific heat of helium are higher than those of air, using traditional design methods of air compressor could not obtained a well-designed helium compressor. Such a designed helium compressor may be of numerous stages, shorter blades and lower Mach number, which greatly increase the difficulty of bearing design, rotor stability etc.

A very comprehensive work, based on experimental data has been performed by Roberts (2001) and Roberts and Sjolander (2005) on the subject of impact of the use of alternative gas with different adiabatic exponent on centrifugal compressor. The results showed that k was an important criterion of similarity in the performance of turbomachinery and for compressors, in particular, the choking mass flow rate, the isentropic efficiency and the pressure ratio were all related to the adiabatic exponent k. Methods were proposed for predicting the changes in performance of compressors when substitute working medium were used in the research. Unfortunately, there are not the experimental data and theory for axial compressor. The "best" data from Fort-Sain-Vrain axial helium compressor can be founded but without efficiency data.

Design models and aerodynamic loss empirical correlation of multi-stage, axial-flow helium turbine and compressor were developed for HTGR with Closed Brayton Cycle for energy conversion (Tournier and El-Genk, 2010) and described in detail in the paper (Tauveron et al., 2011). The effect of the molecular weight of helium on the very high temperature reactor plant performance, the number of stages and the size of the compressor were investigated. The 10 MW HTGR (HTR-10) had been built by the INET of Tsinghua University in China (Shi et al., 2012). The aerodynamic characteristics of the helium compressor of HTR-10 were analyzed and the simulation method of prototype helium compressor with model air compressor was investigated theoretically and experimentally. Based on the previous studies, the similitude laws Sr, Re, Eu for compressible fluids flow in the compressor were derived and proposed by physics forces analysis, differential equation analysis and dimensional analysis (Zhu et al., 2008a,b). The results were verified by computational fluid dynamics. JAERI, cooperate with Toshiba, Hitachi and Mitsubishi, carried out aerodynamic design study for the multistage axial helium compressor of 300 MWe and 600 MWe class nuclear gas turbine (Yasushi, 2001; Yan et al., 2008).

Ke and Zheng proposed and investigated a new highly loaded helium compressor with large flow coefficient and high reaction by increasing the inlet axial velocity value greatly. In addition, as the relatively March number was lower in the helium compressor, a new velocity triangle of helium compressor was proposed with higher stage loading (Ke and Zheng, 2011). Their research offered a way to overcome the difficulties of helium compression. In a design study of the multistage axial helium compressor of a 300 MWe nuclear gas turbine, Ke et al. increased the single pressure ratio from 1.03 to 1.05 and decreased the stage number from 16 to 10, while the efficiency was still acceptable (Ke et al., 2011). Long et al. had analyzed and optimized a cascade of helium compressor with large turning angle in order to increase the pressure ratio and decrease stage numbers; the cascade was validated by computational fluid dynamics method (Long et al., 2010, 2012).

Compared with conventional air compressor, the inlet Mach number of the highly loaded helium compressor increases greatly, so the compressibility of helium must be taken into account. What the similitude laws between air and helium are, and whether the air experimental data can be used for reference by highly loaded helium compressor have always been problems that need to be considered seriously. In this paper, a theoretical study on the similarity of air compressor and highly loaded helium compressor is carried out and the deviation of similarity is analyzed. The flow difference between helium and air compressor cascades is investigated by numerical simulation. Combining with the properties of helium, the influences of geometry and aerodynamic conditions on the adverse pressure gradient flow in the helium compressor cascade are studied and analyzed systematically.

2. Similarity deviation analysis

If the gas constant R and specific heat ratio k are included in the speed and flow parameters, the compressor map is applicable to other working fluids. However, similarity arguments show that the specific heat ratio, or say adiabatic exponent k itself is a criterion of similarity. The turbomachinery characteristics, even when appropriately nondimensionalized, will vary as the k of air and helium varies. So there will be deviations when transforming air compressor map to the helium compressors. In this paper, the deviation resulted from similarity criteria is analyzed.

The flow passage of compressor cascade can be taken as variable area nozzle, so under the adiabatic, isentropic conditions and the ideal gas assumption, dimensionless flow function $q(\lambda) = \rho c/\rho_{cr}c_{cr}$ can be introduced to represent the ratio of velocity density with critical parameters at arbitrary sections.

According to the continuity Eq. (1), the ratio of the flow section area A and imaginary critical one A_{cr} can be expressed as (2):

$$\frac{d\rho}{\rho} + \frac{dv}{v} + \frac{dA}{A} = 0 \tag{1}$$

$$\frac{A}{A_{cr}} = \frac{\rho_{cr}c_{cr}}{\rho c} = \frac{1}{q(\lambda)} \tag{2}$$

While the area increases from A to $A + \Delta A$, the velocity coefficient vary from λ to $\lambda + \Delta\lambda$. So, under the infinitesimal change condition, the "logarithm differential equation" (3) can be got:

$$\frac{\Delta A}{A_{cr}} = -\frac{\Delta q}{q} \tag{3}$$