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Investigations of the conjugate heat transfer and windage effect in stepped labyrinth seals

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ABSTRACT

In the current paper, conjugate heat transfer and windage heating in the stepped labyrinth seals with smooth and honeycomb lands are numerically investigated by using the commercial software ANSYS CFX11.0. Firstly, the utilized numerical approaches, such as the turbulence model and grid independence analysis, are determined to ensure a suitable numerical method for the present study. Based on the obtained measurement data, the computed heat transfer coefficients on the rotor and stator surfaces are carefully validated. To reveal the influence of the solid domain on the heat transfer computations, the comparisons between the results with and without solid domain are performed. It shows that the predicted heat transfer coefficient distributions with the presented conjugate heat transfer methods (with solid domain) agree well with the experimental data. Difference between the numerical results with and without solid domain only exists in the high temperature gradient region. Compared to the smooth labyrinth seal, the presence of honeycomb cells increases the temperature gradient in the labyrinth fin (solid domain) and significantly decreases the temperature gradient in the stator (solid domain). Secondly, in order to assess the influence of the rotating effect on the windage heating for the stepped labyrinth seal, total temperature difference between the seal inlet and outlet are computed under different effective pressure ratios for both the smooth and honeycomb configurations. Based on the energy conservation law, the windage loss for the high speed rotating seal is also obtained by taking the heat transfer between the fluid and solid into consideration. Finally, the influences of the effective pressure ratio and inlet preswirl ratio on the heat transfer coefficient distributions of rotor and stator for both the smooth and honeycomb configurations are discussed in detail.

1. Introduction

The stepped labyrinth seal in the gas turbine engine is mainly used to control leakage between the rotating and stationary parts. It has a pronounced effect on the aerodynamic performance and reliability for the whole turbomachines [1]. Since it usually locates in the high temperature, high pressure and high surface speed environments, the reliability of the sealing clearance is crucial for the modern gas turbine engine design [1]. As indicated in the earlier research, the changes of critical seal parameters (geometrical sizes and operation conditions) will significantly affect the dynamics of the entire engine [2]. Take the interstage seal for an example, the leakage flow may significantly affect the downstream flow field in the primary path (such as the incidence angle [3], mixing loss in the blade passage [4]). And also, as an important component of the internal cooling air system, the total temperature increase (windage effect) in the seal degrades the cooling quality of the internal cooling air. Moreover, in the high temperature environment, the fluid–solid heat exchange in the seal significantly affects the temperature distributions inside the solid domain [5], which will cause the inevitable structure deformations of the sealing clearance. Accordingly, the seal geometry will deviate from its original design in the actual operation conditions [2]. Particularly, since the titanic alloy materials are widely used in the aeroengine since 1960s, the spark from the rotor and stator rubbing will result in possible fire which may destroy the whole engine. Therefore, the interface between the seal rotor and stator needs to be carefully considered for the gas turbine engine designer. And the temperature distributions in the seal even inside the material have to be further investigated.

Generally, the heat transfer between the fluid and solid in the stepped labyrinth seal includes two aspects. One is the heat convection from the high temperature gas to the solid domain. The other is the windage heating effect in the rotating seal [5]. For these two aspects (heat convection and windage heating), obtaining the temperature distributions in the fluid and solid domains is the key point to these researches. After the temperature distributions having been derived, the heat transfer characteristic and total temperature increase in the seal can be calculated [3,7,8,11].

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Nomenclature

$a = \sqrt{\kappa \Re T_{static,in}}$ speed of sound (m/s)
B Gap width in circumferential direction (m)
c_p specific heat capacity (J/kg K)
$K = V_t/U$ preswirl ratio
h heat transfer coefficient (W/m^2 K)
$\dot{m}$ mass flow rate (kg/s)
$Mu = U/a$ circumferential Mach number
Nu Nusselt number
n rotor speed (rpm)
p static pressure (Pa)
P_t total pressure (Pa)
Q wall heat flux (W/m^2)
R radial distance (m)
$\Re = 287.2$ specific gas constant (J/kg K)
$\mathrm{Re}_x = \dot{m}/\mu_{in}\pi R_{in}$ axial Reynolds number
T temperature (K)
t pitch length (m)
$U = \omega \cdot R_m$ rotor circumferential velocity (m/s)
V_t fluid tangential velocity (m/s)
W viscous work (W)

Greek letters
κ ratio of specific heats
μ dynamic viscosity (N s/m^2)
$\pi = P_{t_{in}}/p_{out}$ pressure ratio
$\mathrm{Pi} = \Pi = \pi \cdot \left(1 + \frac{\kappa-1}{2} K_{in}^2 Mu^2\right)^{\frac{-\kappa}{\kappa-1}}$ effective pressure ratio
ω rotor angular velocity (rad/s)

For the heat convection studies, the representative experimental tests were utilized by Wittig et al. [7] and Willenborg et al. [8]. They experimentally investigated the heat transfer characteristics in the stepped labyrinth seals with smooth and honeycomb lands. In their studies [7,8], the heat transfer coefficient (or Nu) is the main objective for the measurements. With the measured heat transfer coefficients on the rotor and stator surfaces, correlation equations for predicting Nu in the plain and honeycomb seals were presented. However, in their experiments, the rotational effect was not taken into consideration. And less attention was paid to the temperature distributions inside the solid domain. Waschka's work [6] revealed that if the circumferential to axial speed ratio is larger than 1, the influence of rotational speed on the heat transfer can be significant. For the numerical studies on the heat transfer characteristic, Papanicolaou et al. [9] presented a conjugate heat transfer computational method to obtain the leakage rate and heat transfer coefficients for the labyrinth seal with plain stator. It shows that the computed near wall temperature distributions as well as the Nu number is agreeable with the measurement [7]. Then, Weinberger et al. [10] applied the conjugate heat transfer numerical method to compute the heat transfer performance for the honeycomb seal. Subsequently, Yan et al. [11] simplified Papanicolaou et al's [9] numerical approaches by specifying a fixed temperature on the wall surfaces. In their studies [11], the conjugate heat transfer and leakage flow field were computed without the solid domain. For the above researches [7–11], the common shortcoming is the rotating effect is not taken into consideration as well. However, in the actual operation conditions, the stepped labyrinth seal usually has a high surface speed which has a pronounced effect on the near wall boundary layer. Under such background, the heat transfer characteristic in the rotating seal is required to be further investigated.

In terms of windage heating effect studies, Tipton et al's experimental work [12] showed the total temperature increase in the rotating seal is pronounced (may reach up to 19.4 K). The representative experimental work on the windage heating effect was systematically carried out by Denecke et al. [3]. They measured the total temperature increase in the stepped labyrinth seal with smooth and honeycomb lands under different inlet preswirl and rotating speeds. Then, Yan et al. [13,14] and Nayak et al. [15,16] presented the numerical methods to compute the total temperature increase for the high speed rotating seal with honeycomb land. For the theoretical analysis, Millward and Edwards [17] and McGreehan and Ko [18] presented the empirical correlation equations to compute the windage heating power based on a large quantity of experimental tests. However, the empirical factors in the correlations equations are difficult to decide unless the designer has sufficient engineering experiences. Then, Denecke et al. [19,20] presented the dimensionless and interdependence analysis methods which provide a new way to reveal the relations between the objectives (such as the leakage rate, total temperature increase etc.) and variables (such as the sealing clearance, inlet preswirl ratio etc.). However, many of the studies mentioned above [3,12–20] were based on the adiabatic wall assumption which is not in accordance with the actual operating conditions.

Overall, the heat transfer performance in the stepped labyrinth seal, including the heat convection from the gas to the solid, as well as the windage heating effect due to viscous drag, is of great importance for the gas turbine engine. Most of the previous researches only focus on one aspect of heat transfer characteristics [3,7–20]. Less research work has been published to investigate both the heat convection and total temperature increase characteristics in the stepped labyrinth seals. In response to this circumstance, the present paper utilizes a conjugate heat transfer method to numerically investigate both the heat convection and total temperature increase characteristics for the stepped labyrinth seals with smooth and honeycomb lands. Unlike the previous numerical approach [3,13,14], the current paper adopts both the fluid domain and solid domain to compute the total temperature increase in the stepped labyrinth seals. The rotating effect is also taking into consideration in the heat transfer studies. At first, the presented numerical approach, such as the turbulence model, grid sensitivity etc., are carefully determined and validated by the measured data [8]. After the reliability of the present numerical method have been demonstrated, the influence of the stator configurations (smooth or honeycomb land) on the windage effect and heat transfer characteristic in the seal are analyzed in detail.

2. Numerical approaches

2.1. Seal geometry

The geometrical model considered here is a stepped labyrinth seal with smooth or honeycomb land (as shown in Fig. 1), which has been experimentally investigated in Ref. [8]. The detailed geometrical parameters are listed in Table 1. In order to investigate the influence of the stator configuration on the heat transfer characteristic, two types of stator (honeycomb stator and smooth stator) are considered in the present paper. In accordance with the experimental test [8], the computational geometrical models contain both the solid and the fluid domains (as shown in Figs. 2 and 3).