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Experimental investigation of heat transfer in a rotor–stator cavity with cooling air inlet at low radius

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ABSTRACT

This article presents an experimental investigation of the heat transfer characteristics in a typical rotor–stator system with cooling air inlet at low radius under different dimensionless flow rate (C_W) ranges from 1.32×10^4 to 4.87×10^4 at five different rotational speeds, i.e., 500, 1000, 1500, 2000 and 2500 rpm with a large range of rotational Reynolds numbers $4.18 \times 10^5 \leqslant Re_\omega \leqslant 2.484 \times 10^6$. A transient thermochromic liquid crystal (TLC) technique is employed to obtain the detailed distribution of the Nusselt number (Nu) on the surface of the rotor with effective rotating radius of 350 mm as well as with a maximum gap of 67 mm between the rotor and stator. The relationship between the Nusselt number (Nu) and the turbulent flow parameter (λ_T) which has been identified as the parameter governing heat transfer in the rotating disk system is experimentally explored. A numerical model is developed for the investigation of the flow structure inside the rotating cavity and provides a basis for further study in explaining the heat transfer behavior over the rotating disk. It is found that the heat transfer characteristics are strongly affected by the flow structure. Numerical results also clearly show the existence of three flow regimes inside the cavity, namely, viscous regime, co-dominated regime, and inertial regime. The heat transfer characteristics in a rotor–stator system are well explained by the flow structure obtained in the paper.

1. Introduction

In rotor–stator system, the optimisation of the cooling air which is extracted from stages of the intermediate high-pressure compressor and injected into the turbine cavity for cooling and sealing purpose requires a detailed knowledge of the flow structure and heat transfer on the surfaces of the rotating disks. This has been the subject of an intense interest, mostly for high-speed rotating gas turbine engines.

Many studies have been devoted to the fluid flow and heat transfer of rotor–stator system over the past decades. A detailed review of the fundamental investigations relevant to the flow and heat transfer in rotor–stator cavities can be traced back to Owen and Rogers [1]. In a recent study, Shevchuk [2] presented a comprehensive survey on convective heat and mass transfer in rotating-disk systems, i.e. over free disks, transient heat transfer, solid-body rotation of fluid and orthogonal flow impingement. A more detailed review of the rotating flow mechanisms can be found in Greitzer [3] and Childs [4].

It is recognized that the flow structure and heat transfer behavior depends strongly not only on the cavity surface temperature distribution but also on the geometric parameters in rotor–stator system. In general, the flow structure of the rotor–stator system is governed principally by the value of the turbulent flow parameter (λ_T) [1], while in the pre-swirl system, preswirl ratio (β_p) plays an important role in determining the flow structure. Daily [5] showed that λ_T can be used directly to calculate the core-swirl ratio through measuring the average velocity profiles in a rotor–stator system. The turbulent velocity fields have been studied experimentally by Brodersen and Metzger [6] using a laser doppler velocimetry method. Their experiments revealed that the jet will penetrate into the wall boundary layer deeply with sufficient jet flow. Poncet et al. [7] numerically investigated Batchelor versus Stewartson flow structures in a rotor–stator cavity with through flow and validated by two-component laser doppler anemometer (LDA) measurements. Most recently, Nguyen et al. [8] used particle image velocimetry (PIV) technique to investigate the flow characteristics

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Nomenclature

c_p	specific heat at constant pressure of air [kJ/kg K]
C_W	dimensionless flow rate
h	heat transfer coefficient [W/m^2 K]
h_r	circumferential heat transfer coefficient [W/m^2 K]
h_{av}	average heat transfer coefficient [W/m^2 K]
$\dot{m}$	mass flow rate [kg/s]
Nu	local Nusselt number
Nu_{av}	average Nusselt number
Nu_r	circumferential Nusselt number
q_W	heat flux from air to wall [W/m^3]
r	radius [m]
R	recovery factor
Re	Reynolds number
Re_ω	rotating Reynolds number
T	temperature [K]
T_0	initial temperature [K]
T_{aw}	adiabatic temperature [K]
T_f	total temperature of air [K]
T_w	surface temperature of wall [K]
V	velocity [m/s]
Greek letters	
β_p	preswirl ratio
Θ	nondimensional temperature
λ	thermal conductivity [W/m K]
λ_T	turbulent flow parameter
λ_{TX}	flow pattern parameter
μ	dynamic velocity [N s/m^2]
ρ	density [kg/m^3]
τ	time [s]
ω	rotational speed [rpm]

of an air jet impinging on an open rotor–stator system in three axial planes. It was observed that a recirculation flow region which was centered at the impingement point and had high turbulence intensities.

Heat transfer characteristics of the rotor–stator system have been studied extensively in the literature. Metzger [9] employed infrared sensing technique to obtain the average convective heat transfer coefficient on the rotor disk surface. Roy et al. [10] presented measurements of the convective heat flux distribution on the rotor disk surface with mainstream flow and secondary air flow. Results showed that the convective heat transfer was dominated by the dimensionless flow rate of the secondary air in the source region, whilst by the rotational motion of the fluid relative to the rotor disk in the core region. Metzger et al. [11] and Bunker et al. [12,13] experimentally measured the local convective heat transfer coefficient on a rotating disk in a rotor–stator system by means of transient thermochromic liquid crystal (TLC) technique. Newton [14] and Owen et al. [15] made an improvement of the transient TLC technique for the "slow transient" case. They used the exponential-series method for the rise in air temperature to calculate the heat transfer coefficient instead of the conventional step-change method. Furthermore, they analyzed the possible errors when calculating the heat transfer coefficient (h) [16,17], and described how the transient heat transfer technique captured the heat transfer coefficient on a rotating disk [18]. The more recent study of Kakade et al. [19] investigated the heat transfer characteristic in a rotating disk system with pre-swirled cooling air from the nozzles both at high and low radius. The analysis revealed that two heat transfer regimes for the low-radius pre-swirl system: a viscous regime at relatively low coolant dimensionless flow rates, and an inertial regime at higher dimensionless flow rates.

Numerical studies are useful to identify the parameters that significantly contribute to the flow and heat transfer in the rotor–stator system. Various numerical studies of the flow and heat transfer in the rotor–stator system have been carried out over the past two decades. Chen et al. [20] carried out a combined experimental and computational study of the heat transfer from an electrically heated disk rotating close to an unheated stator. Results showed that good agreement is achieved between the measured and computed velocities and Nusselt numbers. Poncet et al. [21] reported on a numerical modeling of the turbulent flow inside three different rotor–stator systems subjected to a superimposed throughflow with heat transfer. An empirical correlation law was obtained to predict the averaged Nusselt number depending on the Reynolds and Prandtl numbers and on the coolant dimensionless flow rate. Viazzo et al. [22] carried out a numerical investigation of the turbulent flow by two Large Eddy Simulation (LES) approaches in a shrouded rotor–stator system. They presented a detailed analysis of the flow for understanding the physics as well as for the assessment of the turbulence models for the rotating disk systems. Tuliszka-Sznitko et al. [23] performed a numerical investigation on the flow and heat transfer in a rotating cavity by Direct Numerical Simulation (DNS) and LES for analyzing the coherent structures of the transitional and turbulent flows and computing statistical parameters.

It appears from the previous investigations that heat transfer in rotating disk system and rotor–stator system has been studied by abundant researchers. To the best of the authors' knowledge, however, the flow and heat transfer in rotor–stator system with cooling air inlet at low radius have been far from complete and there is still much room to be enhanced in this area. There is also a lack of available experimental data concerning the heat transfer characteristics and the secondary air system design. As such, the present research is aimed to use transient thermochromic liquid crystal (TLC) technique to investigate the local heat transfer coefficients on the rotor surface in a rotor–stator system with cooling air inlet at low radius. Finally, the flow structure will be investigated numerically to better understand and explain the heat transfer behavior.

2. Experimental apparatus and methods

The experiments are conducted on the rotational heat transfer test rig at National Key Laboratory of Science and Technology on Aero-engines Aero-thermodynamics at Beihang University, China. The main components of the system consist of air supply system, heating system, test section and data acquisition system. The schematic diagram of the experimental apparatus as well as the test section is illustrated in Fig. 1. The test rig is driven by a 30 kW DC electric motor which allows the rotational speed to be varied up to 3000 rpm with a maximum Re_ω of 2.491×10^6.

2.1. Air supply system

The air is supplied by a compressor with a maximum pressure of 8 atm and regulated down to the required flow rate using a pressure regulator and flow control valve. An air dryer and a filter are