International Journal of Heat and Mass Transfer 78 (2014) 311–320

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental investigation of pressure loss and heat transfer in a rotor–stator cavity with two outlets

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ARTICLE INFO

Article history:
Received 18 February 2014
Received in revised form 17 June 2014
Accepted 19 June 2014
Available online 23 July 2014

Keywords:
Heat transfer
Pressure loss
Thermochromic liquid crystal
Rotor–stator cavity
Rotational Reynolds number

ABSTRACT

This article presented detailed measurements of the pressure distribution and heat transfer in a rotor–stator cavity with inlet of orifices on the rotating disk and two outlets at both low radius and high radius. Transient thermochromic liquid crystal (TLC) technique was employed to determine the convective heat transfer characteristics on the test surface of the rotating disk. Rotational Reynolds numbers (Re_φ) ranging from 4.9×10^5 to 2.47×10^6 and dimensionless flow rate (C_w) between 6.9×10^3 and 2.72×10^4 were considered. Experimental results indicated that the characteristics of the pressure loss coefficient between the inlet and the outlet was strongly dependent on the Re_φ and C_w. Under the current operating conditions, the heat transfer on the surface of the rotating disk was weakened at both in the upper and lower edges for the case of $r/R = 0.775$ due to the existence of the recirculation. Whereas the heat transfer were enhanced near the upper radius with relatively low flow rate and high rotational speed, as well as on the middle radius with relatively high flow rate and low rotational speed.

1. Introduction

In modern advanced gas turbine engines, cooling air extracted from the compressor is ducted through rotating cylindrical cavities to cool certain engine components. It is critical for the engine designers to acquire an accurate knowledge of the flow and heat transfer behavior in the rotor–stator system to further improve the engine efficiency. In the past decades, many research efforts have been devoted to the heat transfer in the rotor–stator cavities. In 1982, Chew [1] performed an early numerical investigation of the flow and heat transfer in a rotor–stator cavity. Later, a detailed review of the heat transfer aspects of rotor–stator cavities has been provided by Owen and Rogers [2]. Ong and Owen [3] investigated the flow and heat transfer characteristics of a rotating cavity applying a boundary-layer solver. They concluded that the boundary-layer equations could provide accurate solutions for the application to the air-cooled gas turbine disks. Pilbrow et al. [4] described a combined computational and experimental study of the flow and heat transfer characteristics in a rotating cavity. Their study highlighted that the flow structure was mainly controlled by the turbulent parameter and pre-swirl ratio. Poncet et al. [5] performed an experimental study to investigate the turbulent flow inside an annular rotor–stator cavity with and without centrifugal throughflow by means of a two component laser Doppler anemometer technique. The excellent agreement of computed results with the velocity and pressure measurements confirmed that the described Reynolds stress turbulence model (RSM) is a valuable tool for flow analysis in rotor–stator systems. Poncet and Schiestel [6] have first numerically investigated the effects of the rotation and coolant outward throughflow on the heat transfer in a rotor–stator cavity enclosed by a heated shroud and subjected to an axial outward throughflow. The numerical results were found to be in satisfactory agreement with the experimental data obtained from the research of Sparrow and Goldstein [7]. Recent work of Debuchy et al. [8] provided a combined analytical modeling and experimental study on the central core flow in a rotor–stator system with several preswirl conditions. New analytical relations were obtained for the core-swirl ratio, the static pressure on the stator, and also the total pressure at midheight of the cavity. The analytical results showed a good agreement with the experimental data. Most recently, an experimental, theoretical and numerical study was carried out by the same author [9] to investigate the fluid flow in an isolated rotor–stator system with a peripheral opening. It was

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.06.057
0017-9310/

Nomenclature

b	outer radius of disk cavity [mm]
C_w	nondimensional mass flow rate of the secondary air = $\dot{m}_s/\mu b$
G	axial gap ratio = s/b
h	local convective heat transfer coefficient [W/m K]
$\dot{m}_s$	mass flow rate of secondary air [kg/h]
Nu	local Nusselt number
Nu_{av}	average Nusselt number
p	static pressure [Pa]
p^*	total pressure [Pa]
r	radial coordinate [mm]
Re_φ	disk rotational Reynolds number = $\rho\Omega b^2/\mu$
s	axial gap between rotor and stator [mm]
T	temperature [K]
T_w	rotor disk surface temperature [K]
V_φ	tangential velocity [m/s]

Greek letters

β_s	swirl coefficient
λ_T	turbulent flow parameter
μ	dynamic viscosity [N s/m^2]
ρ	density [kg/m^3]
Φ	azimuthal coordinate
Ω	disk rotational speed [rad/s]
ξ	pressure loss coefficient modified
ξ_ω	pressure loss coefficient
ω	rotational speed

Subscripts

1	upper outlet
2	lower outlet
in	inlet
out	outlet

found that the numerical and experimental results are in good agreement with analytical solutions.

In recent years, the use of the transient thermochromic liquid crystal (TLC) technique has become a very effective means for measuring the local surface temperature and convective heat transfer over a rotating disk. TLC is not new in concept, but research interest in using TLC has increased significantly in the last two decades [10]. Metzger et al. [11] employed the TLC to measure the local convective heat transfer coefficient on a rotor disk in a rotor–stator configuration ($G = 0.1$, $b = 102$ mm). Experimental results indicated that the local radial heat transfer distribution can be controlled by varying the impingement radius, while the maximum radial average heat transfer was obtained with impingement at the disk center. Yan and Owen [12] analyzed the uncertainties of the convective heat transfer coefficient on the surface of the rotor in a rotor–stator system with a step-change in terms of the fluid temperature using the transient heat transfer measurements. It was revealed that the experimental error could be reduced with a suitable selection of the liquid crystal width according to the initial temperature and step temperature. Owen's research group [10,13–15] conducted a series of work by employing the TLC technique to measure the local temperature distribution and the local heat transfer coefficient was then obtained. In the research of [16,17], both experimental and numerical investigation were conducted on a two-stage turbine considering the impact of the stator and the rotor blade. Vadvadgi and Yavuzkurt [18] numerically simulated the flow and heat transfer in a rotor–stator system ($G = 0.1$, $Re = 106$) using Reynolds Stress Model (RSM) with a conjugate heat transfer approach. The convective heat transfer on the rotor and the flow structure in the cavity of a rotor–stator system was investigated through different ways by Pellé and Harmand [19–21]. The convective heat transfer on the stator of a partially enclosed rotor–stator disk system has been recently obtained by Howey et al. [22]. It was concluded that the increase in the local Nusselt numbers which was visible at the outer radii probably due to the peripheral ingress of the fluid. Valuable research work on rotating flow and ideal heat transfer correlations for rotor–stator systems were concluded by Childs [23]. Nguyen et al. [24] quantitatively and experimentally studied the mean and turbulent flow fields in the case of an impinging jet in an open rotor–stator system using particle image velocimetry (PIV). Most recently, Harmand et al. [25] presented a comprehensive review for the rotor–stator systems and elucidated the most important findings relating to investigations and predictions of convective heat transfer in predominantly outward air flow in rotor–stator cavities with and without impinging jets. This is very helpful to understand the complex phenomena in the rotor–stator systems as a superposition of separate effects like rotation, impingement/crossflow with different angles of attack, flow regime, etc.

To the best knowledge of the authors, there is no detailed data available in the open literature on the pressure loss and heat transfer characteristics on the surface of the rotor disk with a central inlet and two outlets at both low radius and high radius. Hence, the objective of the present study is to provide a comprehensive experimental data exploring the mechanism of the fluid flow and heat transfer in a rotor–stator system as well as acquire necessary data to provide support for the design of the cooling system in the aero-engine turbine disk cavity. Pressure distribution in the cavity was measured and the local Nusselt numbers on the surface of the rotor will be obtained using TLC technique with rotational Reynolds number, Re_φ varying from 4.9×10^5 to 2.47×10^6 and dimensionless flow rate C_w ranging from 6.9×10^3 to 2.72×10^4.

2. Experimental apparatus

An experimental test rig, as shown schematically in Fig. 1, was constructed at the National Key Laboratory of Science and Technology on Aero-engines Aero-themodynamics at Beihang University, Beijing, China. The main components of the system consisted air supply system, heating system, test section and data acquisition system. The test rig was driven by a 30 kW DC motor (Z4-132-3) and the maximum rotational speed could be up to 3600 rpm. The rotational speed was measured by a photoelectric digital tachometer.

A compressor supplies air with a maximum pressure of 8 atm and a mass flow rate of 0.42 kg/s. The mass flow rate was measured by a thermal mass flow meter (DY-EP-VF, Beijing, China) with an accuracy of ±1% FS. The mass flow meter is used to measure the temperature rise from a known supply of heat to determine the value of mass flow. In the current work, the heat supply is provided by a low power resistance heater and the temperature is measured by a resistance temperature detector. There are two resistance temperature detectors in the mass flow meter. One is heated by a low power heater that leads to a temperature difference. Another one is kept thermal balance with the air. When the air flows through the two resistance temperature detectors, the one that was heated would cool down with time proportionally. The compressed air entered a steady pressure jar after processed by a filter to remove water mist, oil drops and dust. Then the air was heated