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Convective heat transfer of a rotating multi-stage cavity with axial throughflow

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ABSTRACT

The heat transfer characteristics in an engine-like rotating multi-stage cavity with axial throughflow are experimentally investigated. The cavity is a model of high pressure compressor in gas turbine, which has a gap ratio of 0.24 and a radius ratio of 0.23. Herein, the effects of inertial force, centrifugal buoyancy force, Coriolis force on the heat transfer coefficient (HTC) and the surface temperature distribution are analyzed and discussed. The heat transfer coefficient is measured with an innovative HTC sensor whereas the surface temperature is measured by embedded thermocouples when the shroud is heated by an induction heater. The measurements are conducted in a wide range of non-dimensional parameters: the maximum axial Reynolds numbers, rotational Reynolds numbers and buoyancy parameter can reach 9.87×10^4, 1.81×10^6 and 0.3, respectively. According to the experimental results, two regions with significantly different heat transfer characteristics could be identified on both side of the interested disc, namely, the forced convection zone caused by impingement cooling in the low radius area, and the Rayleigh-Bénard-like convection zone in the medium and high radius areas. On both windward and leeward sides of the disc, the heat transfer coefficients are zigzagging along the radial direction with two observed peak values.

1. Introduction

In modern aircraft gas turbines, the compressed air is sucked from the compressor to cool the high temperature components, such as the combustors; turbines and bearings. The bled cooling air then has to travel through the discs of high pressure compressors to reach the cooling site. However, the cavities between the compressor discs can generate the significant secondary flows, which give rise to the resulting convective heat transfer between the cooling air and the discs. Therefore, it is necessary to know the temperature distribution and heat transfer characteristics of the compressor discs since they influence the temperature of the cooling air as well as the thermal stress of the rotating discs. The convective heat transfer in rotating cavities has been widely investigated. The three dimensional unsteady flow inside the rotational cavities attracts many research attentions due to its complexity and importance. Both flow and heat transfer related investigations have been conducted.

1.1. Flow structure

It is recognized that the flow structure in the cavity with axial throughflow depends strongly not only on the surface temperature distribution but also on the geometric parameters. Farthing et al. [1] made flow visualization and velocity measurements under isothermal and non-isothermal conditions in the study of a simplified model for the flow that occurs between adjacent corotating compressor discs. Isothermal tests were conducted over a series of gap ratios with $0.133 < G = s/b < 0.533$. For a gap ratio of $G = 0.24$, which corresponded to this study, the axial throughflow of air created two toroidal vortices, one on top of the other (Fig. 1a). Reducing the gap ratio G (or Rossby number Ro) resulted in a weaker vortex. However, once the heated flow was involved, the flow structure was significantly different, and it was no longer axisymmetric. Both cyclonic and anti-cyclonic circulations were observed in the cavity. The cold air entered the cavity through a so-called "radial arm" (Fig. 1b). The low pressure of cyclonic circulation and the high pressure of anti-cyclonic circulation led to the pressure variations in the circumferential direction. The resulting pressure gradient provided the Coriolis force for the radial flow of fluid between two discs. Different from the heated disc, when the shroud was heated, the multiple "radial arms" could be observed [2]. More than single-stage cavities, Long et al. [3]

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Nomenclature

A	heat transfer area [m^2]
a	inner radius of cavity [m]
b	outer radius of cavity [m]
r	radial coordinate [m]
s	axial space between discs [m]
m	mass flow [kg/s]
T	temperature [K]
G	gap ratio [$=s/b$]
X	nondimensional radius [$=r/b$]
Gr	generic Grashof number $\left[=\frac{\beta\rho_0^2\omega_0^2(T_{sh}-T_0)b^4}{\mu_0^2}\right]$
h (HTC)	heat transfer coefficient [$w/(m^2{\cdot}K)$]
Nu	Nusselt number [$=hb/\lambda_0$]
Ro	Rossby number [$=W_0/(\Omega \cdot b)$]
Re_z	axial Reynolds number $\left[=\frac{2\rho_0 W_0 a}{\mu_0}\right]$
Re_ω	rotational Reynolds number $\left[=\frac{\rho_0\omega_0 b^2}{\mu_0}\right]$
β	volume expansion coefficient 1/k $\left[=\frac{1}{T_0}\right]$
ΔT_{max}	maximum temperature difference k [$=T_{sh}-T_0$]
Φ	heat power
λ	thermal conductivity [$w/(m{\cdot}K)$]
μ	dynamic viscosity [$kg/(m{\cdot}s)$]
ρ	density [kg/m^3]
Ω	angular speed [rad/s]

Subscripts

0	mainstream parameters
max	maximum
Sh	Shroud
f	reference value
w	wall
net	net value
loss	heat loss
ses	value of the sensor
std	value of the calibration
ave	average value

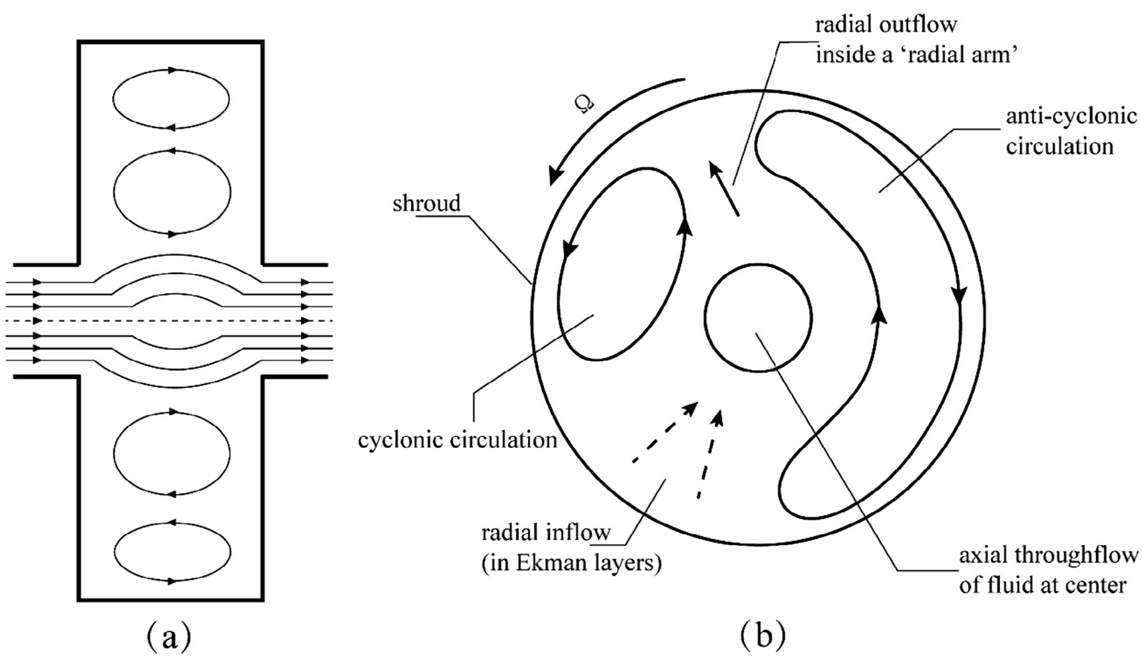

Fig. 1. Flow structures for an isothermal cavity (r-z-plane, a) and a heated rotating cavity (r-θ-plane, b).

conducted the flow visualization inside a heated multiple rotating cavity with axial throughflow. The velocities inside the cavities were in accord with the flow structure consisting of pairs of contra rotating vortices.

Buoyancy-induced flow occurs in the cavities when the temperature of the discs and shroud is higher than that of the air in the cavities. Owen et al. [4] focused on the effects of buoyancy force on the flow structure. The results showed that the velocity field was three dimensional and highly unsteady due to the buoyancy force. Moreover, the buoyancy-induced flow could be described by the Ekman-layer equations, in which only the core flow and the Ekman-layer were focused on [5]. Besides, Owen et al. [6] had studied the buoyancy-induced flow occurred in the rotating cavities with the principles of far-from-equilibrium thermodynamics. These thermodynamic concepts could be used to explain how many vortex pairs are formed in the rotating cavities. As mentioned above, the buoyancy could drive the instable flows in the rotating cavities [7,8]. The results indicated that two regions with distinct characteristics could be identified: a free convection in the high radius area and a forced convection in the low radius area. The higher rotational Reynolds number or Grashof number resulted in the lesser vortices, the stronger free convection, the weaker forced convection and vice versa.

1.2. Heat transfer

The convective heat transfer in the rotating cavities majorly depended on the flow parameters such as Re_z, Re_ω, Gr as well as the temperature distribution of the rotating disc. Farthing et al. [9] compared the heat transfer on the discs with the positive or