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Experimental analysis of varied vortex reducers in reducing the pressure drop in a rotating cavity with radial inflow

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ABSTRACT

Experimental research was performed to determine the pressure drop in a rotating cavity with radial inflow. In order to decrease the pressure loss across the rotating cavity, three different vortex reducer configurations were designed and fitted in the cavity. The experiment revealed that the performance of a vortex reducer is determined by its own geometry, the inlet flow rate and the rotating speed of the cavity. For each vortex reducer configuration, a critical curve distinguishes its performance in terms of reducing the pressure drop. On one side of this curve, the pressure drop is reduced; on the other side, however, the pressure drop is even larger. The performance of each configuration was compared and presented schematically. As regards the rotating cavity without vortex reducer (empty cavity), the experimental data fitted quite well with Farthing's linear theory. For each vortex reducer configuration, a fitting curve of the pressure coefficient was given.

1. Introduction

In the secondary air system of modern aero-engines, in some cases air is taken radially inward from the final stages of the compressor. Because of the high revolving velocity, a strong vortex is formed inside the rotating cavity and it causes high pressure loss across the cavity. If appropriate measures are taken successfully to reduce the pressure loss, the bleeding point can be designed at an earlier stage and a higher efficiency of the aero-engine will be achieved. Two common ways to fulfil this goal are the use of de-swirl shroud nozzles and the installation of proper vortex reducers in the rotating cavity.

Much research has been performed on the flow structure and heat transfer in a rotating cavity with radial inflow. In 1968, Hide [1] first suggested that the flow structure of a rotating cavity with radial inflow includes a source region, an interior core, two Ekman layers and a sink region. Following Hide's work, Firouzian and Owen [2,3] confirmed the theory by conducting a flow visualisation experiment describing not only the flow structure but the velocity, pressure and other parameters of the flow field. Using the same test rig as Firouzian, Farthing and Owen [4] conducted a similar experiment concerning the radial outflow. Owen's work [5–7] laid the theoretical foundation of the study of radial inflow. In addition, Brillert et al. [8] studied the total pressure loss across the rotating cavity.

With regard to analysis of the flow resistance reduction of the radially inflow rotating cavity, Owen and Farthing [9,10] studied how de-swirl nozzles affect the pressure difference between the inlet and the outlet. Their work showed that the de-swirl nozzles change the swirl fraction of the inlet flow and thus cause a drop in the pressure loss across the cavity. Another investigation of the de-swirl nozzle can be found in Friedl [11]. Chew [12] showed that attaching radial fins to the inner side of one of the rotating disks moderately reduced the pressure drop.

However, only a few people have studied the impact of the vortex reducer fitted in the cavity. Gunther [13] may have been the first to do so. In his experiment, he installed four different configurations of vortex reducers either with tubes or tubeless in the cavity and measured their performances. The vortex reducers successfully restricted the formation of the interior core and tubeless configuration performance was better than that of long tubes. Liang et al. [14] and Chen et al. [15] experimentally studied tubed vortex reducers and the influences of the shape of the inlet nozzles. In their studies, tubes with different length were used and the total pressure at the inlet and outlet of the cavity was measured. They showed that tubed vortex reducers have great capability in terms of reducing the pressure drop compared with the traditional free cavity. Other studies include those of Negulescu and Pfitzner [16], Peitsch et al. [17] and Du et al. [18].

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Nomenclature

R_a	outer radius of cavity
R_b	inner radius of cavity
s	axial distance between disks
G	gap ratio of cavity, s/R_b
P	pressure
Ω	rotating speed
$\dot{m}$	mass flow rate
Re_Φ	rotational Reynolds number, $Re_\phi = \frac{\Omega R_b^2}{v}$
C_w	non-dimensional flow rate, $C_w = \frac{\dot{m}}{\mu R_a}$
$C_{p,c}$	pressure coefficient, $C_{p,c} = \frac{\Delta P}{\frac{1}{2}\rho\Omega^2 R_a^2}$
λ_T	turbulent flow parameter, $\lambda_T = C_w/Re_\Phi{}^{0.8}$
ΔP	pressure difference between inlet and outlet, $P_i - P_o$
ρ	density
v	kinetic viscosity
i	inlet
o	outlet
e	edge of the source region

Compared with tubed vortex reducers, tubeless vortex reducers have much simpler structures, and thus are more reliable and easier to manufacture and install. In the present paper, we put the emphasis on investigating the effect of different vortex reducers on pressure loss in the rotating cavity. The free cavity without any vortex reducer also serves as a contrast.

2. Experimental apparatus and methods

The experiments were conducted on the rotational heat transfer test rig at the National Key Laboratory of Science and Technology on Aero-Engines and Aero-Thermodynamics at Beihang University, China. The main components of the system consist of air supply 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_Φ of 8.72×10^5.

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 with a pressure regulator and flow control valve. The compressor starts working as soon as the pressure in the receiver reaches its lower limit. An air dryer and a filter are used to remove water mist, oil drops and dust. Through several valves and a thermal mass flowmeter, air is then drawn into the test section and finally leaves the test rig through the hollow shaft to the open air.

2.2. Test section

2.2.1. Overall configuration of the test section

As shown in Fig. 2, the core part of the test section consists of two rotating disks, a shroud with 12 straight cylinder nozzles, a vortex reducer fitting in the cavity and a hollow shaft. All these parts are mounted together by bolts. The outer radius of the cavity R_b is 204.5 mm, the inner radius R_a is 79.5 mm and the distance between two co-rotating disks is s = 40 mm. The corresponding non-dimensional parameters are: the gap ratio $G = s/R_b = 0.196$ and non-dimensional inner radius $x_a = R_a/R_b = 0.389$.

2.2.2. Vortex reducer configurations

Three different vortex reducer configurations (VR 1 ~ VR 3) are studied in this paper. As shown in Fig. 3a, the outer and inner diameter of the first configuration (VR 1) are 364 mm and

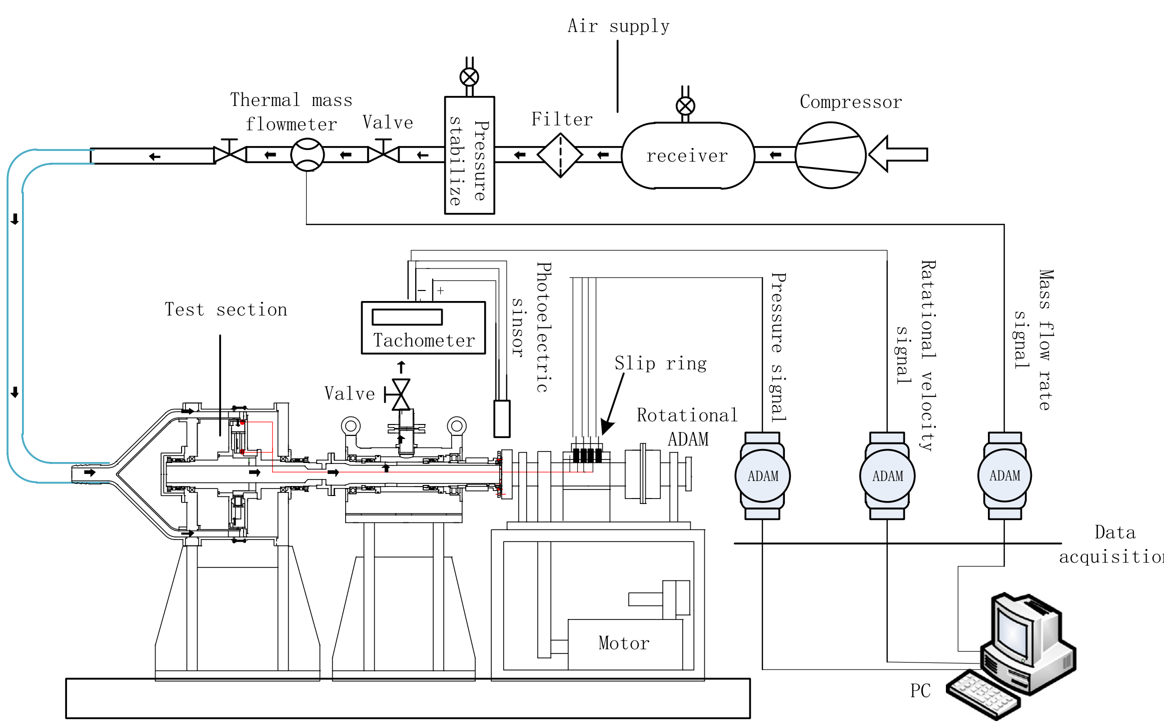

Fig. 1. Schematic diagram of experimental apparatus.