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Flow and Heat Transfer in Gas Turbine Disk Cavities Subject to Nonuniform External Pressure Field

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Introduction

Injestion of hot gas from the mainstream gas path into turbine disk cavities, particularly the first-stage disk cavity, has become a serious concern for the next-generation industrial gas turbines featuring high rotor inlet temperature [1,2]. Fluid temperature in the cavities increases further due to windage generated by fluid drag at the rotating and stationary surfaces. The resulting problem of rotor disk heat-up is exacerbated by the high disk rim temperature due to adverse (relatively flat) temperature profile of the mainstream gas in the annular flow passage of the turbine.

A designer is concerned about the level of stresses in the turbine rotor disk and its durability, both of which are affected significantly by the disk temperature distribution. This distribution also plays a major role in the radial position of the blade tip and thus, in establishing the clearance between the tip and the shroud.

To counteract mainstream gas ingestion as well as to cool the rotor and the stator disks, it is necessary to inject cooling air (bled from the compressor discharge) into the wheel space. Since this bleeding of compressor air imposes a penalty on the engine cycle performance, the designers of disk cavity cooling and sealing systems need to accomplish these tasks with the minimum possible amount of bleed air without risking disk failure. This requires detailed knowledge of the flow characteristics and convective heat transfer in the cavity.

The flow in the wheel space between the rotor and stator disks is quite complex. It is usually turbulent and contains recirculation regions. Instabilities such as vortices oscillating in space have been observed in the flow. It becomes necessary to obtain both a qualitative understanding of the general pattern of the fluid motion as well as a quantitative map of the velocity and pressure fields. These information are indispensable in the development and validation of a computational model of the flow, such a model being a useful design tool. Hence the need for careful and comprehensive experiments.
Industrial gas turbines must be designed for long hours of continuous operation with little maintenance. This requires, that, in addition to cooling air injection into the wheel space, the designers incorporate a durable rim seal capable of protecting the disk cavity from hot mainstream gas ingestion. An effective rim seal configuration coupled with optimum coolant air injection may eliminate ingress of hot mainstream gas into the cavity for all practical purposes, at the same time maintaining efficient engine performance.

Objectives

Our study has four objectives.

I. **Local convective heat transfer coefficient and cooling effectiveness distributions on the rotor disk.** Measurements are to be performed, by the thermochromic liquid crystal (TLC) technique, of radially local (and circumferentially-averaged) convective heat transfer coefficient and cooling effectiveness on the rotor disk surface facing the cavity. A nozzle vane-rotor disk combination, which would impart circumferential periodicity in the pressure field in the space between the vane and the blade external to the disk cavity, is to be used in the experiments. Two rim seal configurations are to be studied.

II. **Flow field in the disk cavity.** Velocity and pressure fields in the cavity are to be measured. The flow is expected to be turbulent and unsteady with recirculation regions. Particle image velocimetry [3] has been chosen as the technique for velocity interrogation and spatially distributed pressure taps communicating with a pressure transducer via scanivalve for pressure measurement.

III. **Computation of flow field and heat transfer in the disk cavity.** Computational fluid dynamic (CFD) modeling of the velocity, pressure, and temperature fields in the cavity are to be carried out. The modeling is to be performed in synergy with the experiments.

IV. **Mainstream gas ingestion and rotor disk cooling effectiveness by mass transfer analogy.** The cooling air flow is to be seeded with CO₂ gas (tracer gas) and isothermal experiments conducted. The distribution of CO₂ concentration in the cavity will be measured and radially local cooling effectiveness at the rotor disk surface will be determined via heatmass transfer analogy. Ingestion of mainstream air into the cavity is to be studied also by gas concentration measurement.

Experimental Rig

Major parts of the disk cavity rig are shown schematically in Figure 1 (one-eighth scale drawing). All hardware components have been procured and the rig is presently under construction. The main blower is capable of maintaining a flow rate of approximately 4000 cfm (at standard temperature and pressure) through the rig. The auxiliary blower which supplies the cooling air can deliver about 380 cfm at standard temperature and pressure. The maximum rotational speed of the rotor disk is 5000 rpm.
Preliminary Results - TLC Technique

We plan to use a relatively new TLC technique for measurement of the convective heat transfer coefficient at the rotor disk surface and the disk cooling effectiveness. This technique is referred to as the quasi-steady state TLC technique.

The technique has been validated very recently in our laboratory. Simple experiments were conducted in which a main airflow was established over a heated flat aluminum plate of 12.4 mm thickness. Four equally spaced air injection holes (at an angle of 30° degrees to the surface) 10 mm in diameter were located 6 mm upstream of a 29.2 cm x 12.7 cm area of the plate surface. This area was first provided with a 1 mm epoxy layer and then with a TLC coating.

Figure 2(a) is a plot of the transverse (y)-averaged axially (x)-local convective heat transfer coefficient \( \overline{h_y} \) versus the axial distance from the upstream edge of the TLC-coated surface nondimensionalized by the hole diameter \( x/d \). Figure 2(b) shows a plot of the axially-averaged transversely-local convective heat transfer coefficient \( \overline{h_x} \) versus \( y/d \), \( y \) being measured from one side edge of the TLC-centered surface. Both plots exhibit correct characteristics.

Figure 3(a) contains a plot of the y-averaged plate cooling effectiveness \( \overline{\eta_y} \) versus \( x/d \). Figure 3(b) shows a plot of the x-averaged plate cooling effectiveness \( \overline{\eta_x} \) versus \( y/d \). The cooling effectiveness is defined here as

\[
\eta = \frac{T_{\text{adiabatic wall}} - T_{\text{main air}}}{T_{\text{cooling air}} - T_{\text{main air}}}
\]  

Future Activities

We are addressing Objectives I and II during the first year of this project. Work will soon be initiated on Objective III as well, in cooperation with Allied Signal Engines.

Objectives I-III will be the focus of our work during the second year of this project also. Objective IV will be addressed during the third and final year.

References

Figure 1. The Disk Cavity Experimental Rig
Figure 2. Convective Heat Transfer Coefficient by Quasisteady State TLC Technique
Figure 3. Film Cooling Effectiveness by Quasisteady State TLC Technique