HEAT TRANSFER AND FLOW PHENOMENA IN A SWIRL CHAMBER SIMULATING TURBINE BLADE INTERNAL COOLING

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ABSTRACT
Heat transfer and fluid mechanics results are given for a swirl chamber whose geometry models an internal passage used to cool the leading edge of a turbine blade. The Reynolds numbers investigated, based on inlet duct characteristics, include values which are the same as in the application (18000-19400). The ratio of absolute air temperature between the inlet and wall of the swirl chamber ranges from 0.62 to 0.86 for the heat transfer measurements. Spatial variations of surface Nusselt numbers along swirl chamber surfaces are measured using infrared thermography in conjunction with thermocouples, energy balances, digital image processing, and in situ calibration procedures. The structure and streamwise development of arrays of Görtler vortex pairs, which develop along concave surfaces, are apparent from flow visualizations. Overall swirl chamber structure is also described from time-averaged surveys of the circumferential component of velocity, total pressure, static pressure, and the circumferential component of vorticity. Important variations of surface Nusselt numbers and time-averaged flow characteristics are present due to arrays of Görtler vortex pairs, especially near each of the two inlets, where Nusselt numbers are highest. Nusselt numbers then decrease and become more spatially uniform along the interior surface of the chamber as the flows advect away from each inlet.

NOMENCLATURE

\( D \) \quad \text{diameter of main swirl chamber cylinder}
\( D_H \) \quad \text{hydraulic diameter of one swirl chamber inlet}
\( h \) \quad \text{heat transfer coefficient, } \frac{q}{\left(T_w - T_i\right)}
\( k \) \quad \text{thermal conductivity}
\( L \) \quad \text{upstream (smallest axial) location of axial/radial measurement or visualization plane, measured from } x=0
\( \text{Nu} \) \quad \text{Nusselt number, } hD / k
\( p_a \) \quad \text{ambient pressure external to the swirl chamber at entrances to inlet ducts}
\( p_s \) \quad \text{static pressure in swirl chamber}
\( p_t \) \quad \text{total pressure in swirl chamber}
\( \dot{q}_w \) \quad \text{local wall heat flux}
\( R_e_d \) \quad \text{Reynolds number based on swirl chamber main cylinder characteristics, } \frac{UD}{v}
\( R_e \) \quad \text{Reynolds number based on inlet duct characteristics, } \frac{2VD_H}{v}
\( r \) \quad \text{radial distance measured from swirl chamber centerline}
\( r_0 \) \quad \text{radius of the large cylinder comprising the swirl chamber}
\( T \) \quad \text{temperature}
\( u_x \) \quad \text{axial component of velocity}
\( u_r \) \quad \text{radial component of velocity}
\( u_\phi \) \quad \text{circumferential component of velocity}
\( U \) \quad \text{average axial velocity across swirl chamber cylinder}
\( V \) \quad \text{average bulk velocity at one swirl chamber inlet}
\( x \) \quad \text{axial distance measured from swirl chamber end face}

Greek symbols
\( \psi \) \quad \text{circumferential angle measured from swirl chamber vertical plane}
\( \rho \) \quad \text{fluid density}
\( \nu \) \quad \text{fluid kinematic viscosity}
\( \omega_\psi \) \quad \text{circumferential component of vorticity}

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INTRODUCTION

Swirl chambers are internal flow passages arranged with either spinning vanes, internal inserts, or inlets and outlets configured to produce large-scale swirling of the flow (relative to the chamber dimensions) generally about the principal chamber axis. Because of their unique flow and thermal characteristics, they are applied to a considerable variety of engineering situations. Swirl chambers are used to fractionate solid particulates suspended and transported with liquids and gases, to enhance mixing processes in combustion chambers, to increase the quality at which critical heat flux occurs in two-phase flows, and for spray-drying applications when used with an atomizer. Devices producing large-scale swirling are also employed to enhance surface heat and mass transfer levels. As such, swirl chambers are employed in heat exchangers, automobile engines, furnaces, biomedical devices, and devices used for heating and cooling of metal ingots. In the present study, heat transfer and fluid mechanics within a swirl chamber are investigated as applied to augmentation of heat transfer rates for internal turbine blade cooling, a new application recently introduced by Glezer et al. (1996, 1997). Such high-pressure blades are employed in industrial gas turbines used for power generation.

Kreith and Margolis (1959) first proposed that swirl induced in tube flows can augment surface heat transfer rates relative to unswirled flows. Khalatov and Zagumennov (1990), Glezer et al. (1996, 1998), Ligrani et al. (1997), and Moon et al. (1998) and others later employed tangential jets from wall slots to induce large-scale swirling in internal tube flows. Swirling flows are also induced in tubes using twisted tape inserts to augment measured surface heat transfer rates by a number of investigators, including Date (1974), and Hong and Bergles (1976). Recent experimental investigations of fluid mechanics in swirl chambers with single-phase flow, wall injection, and no heat transfer include Kumar and Conover (1993), Dong and Lilly (1993), Bruun et al. (1993), Fitouri et al. (1995), and Chang and Dhir (1994). Rotating vanes, blades, propellers, or honeycombs are used near tube entrances by Sampers et al. (1992) and Li and Tomita (1994) and Kok et al. (1993) to induce swirl in adiabatic flows. Surveys of swirl flow investigations are presented by Gambil and Bundy (1962), Bergles (1969), Razgaitis and Holman (1976), Papadopoulos et al. (1991), and Ligrani et al. (1997).

The present study extends understanding of the physical behavior of flows in swirl chambers because both heat transfer and fluid mechanics results are given for a geometry which models an internal passage used to cool the leading edge of a turbine blade. Because multiple inlets are employed at fixed locations to induce swirling, the geometry of our swirl chamber is different from the geometries used in all other existing investigations (except for Ligrani et al. (1997) and Glezer et al. (1998)). Particular attention is devoted to flow and thermal behavior near the internal concave surface of the swirl chamber. Spatial variations of surface Nusselt numbers along swirl chamber surfaces are given, measured using infrared thermography in conjunction with thermocouples, energy balances, digital image processing, and in situ calibration procedures. The structure and streamwise development of arrays of Görtler vortex pairs, which develop along concave surfaces, are described from flow visualizations. Overall swirl chamber structure is also described from time-averaged surveys of the circumferential component of velocity, total pressure, static pressure, and the circumferential component of vorticity.

EXPERIMENTAL APPARATUS AND PROCEDURES

Swirl Chamber for Heat Transfer Measurements

A schematic of the swirl chamber used for heat transfer measurements is shown in Fig. 1a. The coordinate system is shown in Fig. 1b. The air used within the swirl chamber is circulated in a closed-loop by a Dayton 5CO87-80CFM induced draft blower, which forces air through the facility, starting with a series of three contraction-ratio nozzle. Two Bluff body cross-flow heat exchanger is located between two of these plenums, and is cooled by circulating the flow rate of liquid nitrogen required to give the desired air temperature at its exit. As the air exits the heat exchanger, it enters the third plenum, from which the air passes into one of two rectangular bell mouth inlets, each followed by a honeycomb, two screens, and a two-dimensional 10 to 1 contraction ratio nozzle. Each of the two nozzles leads to a rectangular cross-section inlet duct 21.7 hydraulic diameters in length, connected to the principle swirl chamber cylinder so that one surface is tangent to the cylinder inner circumference. The cylinder length is 1.43 m, and its inner and outer diameters are 0.191 m and 0.203 m, respectively. Because the ratio of the radial extent of the inlet duct to the radius of curvature of the swirl chamber is 0.160, the curvature near cylinder walls is considered to be "strong." With this arrangement, the flow has important axial and circumferential components of velocity, and the overall flow pattern through the cylinder is similar to a helix. The exit duct from the cylinder is oriented in a radial/axial plane near the end of the swirl chamber cylinder at a location along the cylinder farthest from the inlet ducts. This exit duct is then connected to a 0.305 m square plenum, which is followed by a pipe containing a valve and an orifice plate, used to regulate and measure the air flow rate, respectively. This pipe is then connected to the same large plenum adjoining the blower inlet.

All exterior and many interior surfaces of the facility are insulated with 2 to 3 layers of 2.54 cm thick, Elastomer Products black neoprene foam insulation (k=0.038 W/m °C) to minimize heat losses. Calibrated copper-constantan thermocouples are located between the three layers of insulation located outside of the main cylinder of the swirl chamber to determine conduction losses. Between the first layer and the 0.635 cm thick acrylic layer of the cylinder, the chamber is 11 custom-made Electrofilm etched-foil heaters (each encapsulated between two thin layers of capton) to provide a constant heat flux boundary condition on the concave test surface. The acrylic cylinder contains 30 copper-constantan thermocouples, and its inner surface is adjacent to the air stream. Each of these thermocouples is located 0.0508 cm just below this surface to provide measurements of local surface temperatures, after correction for thermal contact resistance and temperature drop through the 0.0508 cm thickness of acrylic. Acrylic is chosen because of its low thermal conductivity (k=0.16 W/m °C at 20 °C) to minimize axial and circumferential conduction along the test surface, and thus minimize "smearing" of spatially varying temperature gradients along the test surface. Acrylic also
Energy balances, performed on each heated segment of the swirl chamber cylinder, then allow determination of local magnitudes of the convective heat flux.

As the facility is prepared for measurements, frost build-up is minimized by lowering the air temperature to just below the dew point to condense all water vapor from the air within the facility. This liquid water is then drained from the facility. Air temperatures as low as -120°C are then obtained with additional cooling as the air continues to re-circulate through the closed-loop facility. The mixed-mean temperature of the air entering the swirl chamber is measured using five calibrated copper-constantan thermocouples spread across the cross-section of each inlet duct, just downstream of each nozzle. These locations are chosen for these measurements because temperature and velocity profiles are uniform across the duct, allowing simple determination of local mixed-mean temperatures. Mixed-mean temperature at each entrance to the cylinder is then determined after accounting for conduction losses through each inlet duct. With this approach, the ratio of cylinder inlet mixed-mean temperature to local wall temperature is as low as 0.57, which is close to the value in the application. All measurements are obtained when the swirl chamber is steady-state, achieved when temperatures from the 30 thermocouples (on the swirl chamber surface) vary by less than 0.1°C over a 10 minute period.

Local Nusselt Number Measurement

Spatially-resolved temperature distributions along the swirl chamber concave surface are determined using infrared imaging in conjunction with thermocouples, energy balances, digital image processing, and in situ calibration procedures. To accomplish this, the infrared radiation emitted by the heated interior surface of the swirl chamber is captured using a VideoTherm 340 Infrared Imaging Camera, which operates at infrared wave lengths from 8 µm to 14 µm. Temperatures, measured using the 30 calibrated, copper-constantan thermocouples distributed along the swirl chamber surface adjacent to the flow, are used to perform the in situ calibrations simultaneously as the radiation contours from surface temperature variations are recorded.

This is accomplished as the camera views the test surface through a custom-made, cylindrical zinc-selenide window (which transmits infrared wave lengths between 6 and 17 µm). Reflection and radiation from surrounding laboratory sources are minimized using an opaque shield which covers the camera lens and the zinc selenide window. Frost build-up on the outside of the window is eliminated using a small heated air stream from a hair dryer. The window is located on a segment of the swirl chamber which is either rotated or relocated axially so that the camera can view different portions of the interior surface of the swirl chamber. At least two, and as many as five, thermocouple junction locations are present in any field viewed by the camera. The exact spatial locations and pixel locations of these thermocouple junctions and the coordinates of a 12.7 cm by 12.7 cm field of view are known from calibration maps obtained prior to measurements. During this procedure, the camera is focused, and rigidly mounted and oriented relative to the test surface in the same way as when radiation contours are recorded.

With these data, gray scale values at pixel locations within video taped images from the infrared imaging camera are readily converted to temperatures. Examples of such calibration data are shown in Fig. 2 for three different camera views of the test surface. Because such calibration data depend strongly on camera
adjustment, the same brightness, contrast, and aperture camera settings are used for all three data sets. Each calibration data set shown in Fig. 2 is fit to a second- or third-order polynomial. The slight differences between the three calibration data sets result because transmissivity of the zinc selenide window and the emissivity of the swirl chamber test surface both exhibit small variations as camera angle, camera and test surface orientation, surface temperatures, or experimental conditions are changed. The in situ calibration approach is advantageous because it rigorously and accurately accounts for these variations.

Images from the infrared camera are recorded as 8-bit gray scale images on commercial videotape using a Panasonic AG-1960 video recorder. Images are then digitized using NIH Image v1.60 software, operated on a Power Macintosh 7500 computer. Subsequent software is used to perform coordinate transformations to correct for non-rectangular, "stretched", or distorted recorded images because of camera perspective or because camera lens orientation is not normal to the curved target surface. This software also converts each of 256 possible gray scale values to temperature at each pixel location using calibration data, and then determines values of local Nusselt numbers. Thermal conductivity in the Nusselt number is based on the average temperature of the air at the cylinder inlets. Contour plots of local surface temperature and Nusselt number (in "unrolled" planar, Cartesian coordinates) are prepared using DeltaGraph v4.0 software. Each individual image covers a 250 pixel by 250 pixel area. 42 of these images are used to produce the data presented in Fig. 9.

Swirl Chamber for Flow Measurements

A second swirl chamber is used for flow measurements and is described by Ligrani et al. (1997). Location of inlets and outlet are shown in the schematic drawing in Fig. 4. The coordinate system, shown in Fig. 1b, and overall layout, shown in Fig. 1a, also apply to this chamber. The main cylinder is 4.477 m long in the x-direction, and is made of clear acrylic to allow visualization of flow phenomena inside. It also includes several doors, and numerous slots lined with foam for insertion of the five-hole pressure probe or smoke injection tubes. Outer diameter is 0.610 m, and inner diameter is 0.597 m. Overall swirl chamber size is chosen to achieve the same inlet passage Reynolds numbers as in the application, with average mean velocities low enough to visualize the flow. Prior to entering the main cylinder of the swirl chamber, air from the laboratory is managed in the same way as in the swirl chamber used for heat transfer measurements. In this facility, flow is induced by suction from a L. J. Wing Mfg. Co. A1/4A4W5 vane axial fan. All flow measurements and visualizations in this facility are made isothermally without surface heat transfer.

Flow visualization

The smoke injection for flow visualization is used to identify vortex structures. Smoke from burning mesquite wood in a specially designed smoke generator is injected into the facility one of two ways: (i) into the inlet bellmouth, prior to conditioning the flow, using a cylindrical manifold with a row of small tubes which produce an array of quiescent, laminar jets of smoke, or (ii) through the cylinder wall through one of the slots lined with foam. In either case, the smoke forms into a single thin layer next to the concave surface of the swirl chamber cylinder as it enters the flow. The smoke in this layer is neutrally buoyant in laboratory air, very dense, and has fairly uniform particle size distribution. As the smoke is advected downstream, the secondary flows which accompany Görtler vortex development cause the smoke to be rearranged in patterns which show the locations and distributions of the Görtler vortices. Smoke patterns are illuminated in different planes using spot lights directed through slits in black paper (used to line the exterior of the experimental apparatus) to illuminate thin, axial/radial planes (or sheets) of light. Images are recorded using a Dage-MTI CCD72 camera and control box with a Compuer Inc. 12.5 mm, F1.8 lens, connected to a Panasonic AG-1960 type 4-head, multiplex video cassette recorder. Images recorded on video tape (taken individually or in sequence) are then processed and digitized using Apple Video processing and capture software employed on a Macintosh Power PC computer. Images are then enhanced, further processed, and arranged for printing using Adobe Photoshop software on the same computer. Additional details are provided by Ligrani et al. (1997).

Total Pressure, Static Pressure, and Mean Velocity Components

A United Sensor DC-250-24-CD five-hole pressure probe, and a five-hole pressure probe manufactured at the University of Utah, each with a conical shaped sensing head of 6.35 mm diameter, are used to obtain time-averaged surveys of total pressure, static pressure, and the three mean velocity components. Procedures for calibration and measurement are described by Ligrani et al. (1989a, 1989b, 1997). To obtain the surveys, the probe is mounted on an automated two-dimensional traverse, and inserted into the chamber through slots lined with foam to prevent air leakage. Outputs of the five-hole probe are connected to five Validyne DP103-06 pressure transducers which measure differential pressures up to 2.5 mm of water. Signals from each transducer are then processed using Celeeco CD10D Carrier-Demodulators. Voltages from the Carrier-Demodulators are acquired using Hewlett-Packard 44422A data acquisition cards installed in a Hewlett-Packard 3497A data acquisition control unit. This control unit, the Superior Electric type M092-FD310 Mitas stepping motors on the two-dimensional traverse, a Superior Electric Modulynx Mitas type PMS085-C2AR controller, and a Superior Electric Modulynx Mitas type PMS085-D050 motor drive are controlled by a Hewlett-Packard 362 Series computer. Contour plots of measured quantities are generated using a polynomial interpolating technique (within DeltaGraph software) between data points. In each survey plane, data points are spaced either 0.51 cm or 1.27 cm apart. Ligrani et al. (1997) provide additional details.

UNCERTAINTY ESTIMATES

Uncertainty estimates are based on 95 percent confidence levels, and determined using procedures described by Moffat (1988). The uncertainties of total pressure and static pressure (relative to atmospheric pressure) in mm of water differential pressure are ±0.015 and ±0.008, respectively (or ±0.015 and ±0.03, respectively, in Pascals). Uncertainties for circumferential, radial, and axial velocity components are ±0.07, ±0.03, and ±0.03 m/s, respectively. Uncertainty for circumferential vorticity is about ±2.4 1/s. Reynolds number uncertainty is ±20. Uncertainty of temperatures measured with
thermocouples is ±0.15 C. Spatial and temperature resolutions achieved with the infrared imaging are 0.8 mm and 0.2°C, respectively. Nusselt number uncertainty is then about ±3.5.

EXPERIMENTAL RESULTS AND DISCUSSION

Flow Visualization Results

Visualized flow patterns which show the streamwise development of the near-wall flow structure through the swirl chamber for Re=4450 are presented in Fig. 3. Results at this particular Reynolds number are presented because they illustrate many flow characteristics also observed at Reynolds numbers from 1500 to 20000. Because the smoke is a uniform, neutrally buoyant layer about 0.5 cm thick near the concave surface just after it is injected into the swirl chamber, secondary flow events which emanate from near the concave surface are smoke-rich, and correspond to light patterns in the figures. Events which originate somewhat away from the surface are free of smoke, and thus, correspond to dark patterns in the figures. Each photographic image in Fig. 3 shows flow behavior in a radial/axial plane arranged so that the concave surface of the swirl chamber is at the bottom of each image and flow moves out of the plane of the paper (axial flow then moves from right to left). Images are given for different φ (which identifies the circumferential position of the visualized plane) and different L (which identify the axial positions, at the smallest x values, of the right-most edges of visualization planes).

The images in Fig. 3 are presented for 13 different locations as the Reynolds number is held constant (Re=4450). The φ and L of the 13 locations are identified in Fig. 4, and chosen to follow the helical trajectory of the smoke as it is advected around the concave interior surface of the swirl chamber. Each image in Fig. 3 represents an instantaneous snapshot from a sequence of time-varying video images. Visualized images at almost every measurement station evidence the presence of numerous Görtler vortex pairs of different size near the concave surface of the chamber, where each vortex pair is identified by a mushroom-shaped smoke pattern. In many cases, a Görtler vortex pair is evident near the lower right-hand corner of each photographic image, formed by the end wall at z=0 m and the concave surface. This particular vortex pair seems to have a preferred axial location, due to the presence of the shear layer on the end wall. The distortion of the mushroom-shaped smoke patterns, especially at larger L values, evidences flow unsteadiness. Collections of highly distorted, highly unsteady vortex pairs of different size are also evident near the concave surface in many of the images.

The vortex pairs in Fig. 3 are initially very small for φ=30° and L/r_o=0, φ=57° and L/r_o=0, and φ=70° and L/r_o=0 just downstream of the first swirl chamber inlet, which is located at x/r_o from 0 to 1. The vortex pairs then increase in size, number, and distortion with additional streamwise development until the smoke within them becomes quite diffuse at φ=70° and L/r_o=5.77. Afterwards, a new set of smaller Görtler vortex pair are evident near the concave surface at φ=70° and L/r_o=6.83, and φ=70° and L/r_o=7.63. These are present because of the growth of a new shear layer in the air from the second swirl chamber inlet, which is located at x/r_o from 7 to 8, as shown in Fig. 4. As the flow continues to develop downstream, the vortex pairs not only become increasingly distorted because of flow unsteadiness, but also dramatically increase in size. Much of the skewness, and three-dimensionality of the Görtler vortex pairs at these locations are due to the axial component of flow in the swirl chamber. Also
particularly apparent at these locations is the continuous interactions and intermingling of different-sized Görtler vortex pairs with each other. As the Reynolds number increases, interactions between adjacent vortex pairs generally become more intense, chaotic, and frequent (Ligrani et al., 1997).

**Variation of Swirl Number Magnitudes**

According to Ogawa (1993), the swirl number is defined as the ratio of the non-dimensional moment of momentum of the flow (with respect to the swirl chamber cylinder axis) to the non-dimensional axial momentum of the flow. Radially-averaged magnitudes of the swirl number, measured in the $\psi=90^\circ$ axial/radial plane, are presented in Fig. 5 as it varies with non-dimensional axial position for $Re$ of 6000, 12000, and 18000.

Magnitudes of the swirl number are quite high near the first inlet duct, which is located at $x/r_o$ from 0 to 1. This is because of the proximity of this inlet to one swirl chamber end face, which restricts the axial component of the flow. As a result, axial flow momentum is relatively small in this portion of the swirl chamber giving high swirl numbers. Assuming one-dimensional flow leaving the inlet duct and that all axial flow components are spread uniformly over the swirl chamber cross-section, the ideal swirl number is 18.9 at these same axial positions. Measured swirl number can then not exceed this value, which is consistent with the results at $x/r_o=0-1$ in Fig. 5.

Swirl number values in Fig. 5 are then lower at other swirl chamber axial locations as $x/r_o$ increases and local axial velocities become more significant. Magnitudes seem to gradually, but steadily, decrease as $x/r_o$ increases, and the outlet of the swirl chamber at $x/r_o=14-15$ is approached. Swirl numbers measured near the second inlet located at $x/r_o=7-8$ are consistent with this trend (without any local increases) because the flow turns just after it leaves this inlet, and because of fluid velocities in the axial direction at $x/r_o=7-8$. Values as high as 6 at these locations indicate high non-dimensional circumferential moment of momentum relative to non-dimensional axial momentum.

**Variation of Wall Static Pressure**

Magnitudes of time-averaged surface static pressure are presented in Fig. 6a as dependent upon non-dimensional axial position for $Re$ of 6000, 9000, 12000, 18000, and 24000. These measurements are obtained along the length of the swirl chamber at the $\psi=45^\circ$ circumferential location. Surface static pressures are normalized by the spatially-averaged kinetic energy of the inlet duct and measured relative to pressure at the entrance of the inlet ducts. The most important decreases of time-averaged static pressure occur just downstream of inlet ducts, and are believed to be mostly due to: (i) streamline curvature as flow from the tangential inlet ducts bends in the axial direction, (ii) shear between high speed fluid from the inlet ducts and adjacent low speed fluid in the main cylinder of the swirl chamber, and (iii) the development of small-scale secondary flows within the arrays of initially developing Görtler vortex pairs. From Fig. 6a, it is evident that normalized wall static pressure data collapse together when the flow in the swirl chamber is fully turbulent for all three fully turbulent Reynolds numbers investigated ($Re=12000$, 18000, and 24000).

Ratios of time-averaged wall static pressure to time-averaged radially-averaged static pressure (where the latter are measured at the $\psi=90^\circ$ circumferential location) are presented in Fig. 6b as dependent upon non-dimensional axial position for $Re$ of 12000 and 18000. Important variations of this quantity are evident throughout the swirl chamber, with the largest changes just downstream of each inlet duct (located at $x/r_o$ from 0 to 1 and from 7 to 8). Such data are valuable to designers of internal cooling systems because they allow the determination of spatially-averaged static pressures and pressure drops from wall measured values.

**Surveys of Time-Averaged Circumferential Velocity, Static Pressure, Total Pressure, and Circumferential Vorticity**

Examples of time-averaged surveys of circumferential velocity, static pressure, total pressure, and circumferential vorticity are presented in Figs. 7 and 8. In these figures, $r/r_o=0$ represents the cylinder axis of symmetry, and $r/r_o=1$ ($r=29.85$ cm) locates the concave surface. Because $x/r_o$ increases from left to right, these plots are inverted in this direction compared to flow visualization images. Static and total pressures are both measured with respect to the pressure at the swirl chamber inlets (at laboratory air pressure), and thus, these values are negative since the swirl chamber is operated at pressures less than the ambient value. Results at a Reynolds number of 18000 are selected for presentation because of its match to the Reynolds number within the application.
Figure 5. Variation of swirl number through the swirl chamber at different Reynolds numbers.

Figure 6. Variation of static pressure through the swirl chamber at different Reynolds numbers. (a) Normalized wall static pressure. (b) Ratio of wall static pressure and radially-averaged static pressure.

Parts a, b, and c of Fig. 7 show surveys of static pressure, total pressure, and circumferential velocity, respectively, from one axial-radial measurement plane located along the entire length of the swirl chamber. These provide a complete picture of swirl chamber flow characteristics measured at $\psi = 90^\circ$ and $Re = 18000$. The gaps between plotted ranges of $x/r_o$ correspond to regions not surveyed because of the absence of probe access slots at these $x/r_o$ locations in the swirl chamber main cylinder. The figures show that the total pressure and static pressure are highest at locations near the swirl chamber inlets ($x/r_o = 0.1$ and $x/r_o = 7.8$). Magnitudes of both quantities then decrease as flow moves away from these inlets, with the lowest pressure levels (at most negative $P_t - P_a$ and $P_s - P_a$) near the swirl chamber outlet at $x/r_o = 14.15$. Static pressure distributions measured at the surface, presented in Fig. 6a, show similar qualitative trends. Static pressures also generally decrease (that is, $P_s - P_a$ becomes more negative) at each value of $x/r_o$ as $r/r_o$ decreases in Fig. 7a. Total pressure distributions in Fig. 7b have similar qualitative trends, but with local maxima near $r/r_o = 0.9-0.95$ at all locations where $x/r_o$ is near the swirl chamber outlet, and higher magnitudes compared to static pressures at all locations where circumferential velocity is greater than zero. Total pressure distributions are quite convoluted due to very large gradients (just downstream of each inlet at $x/r_o = 1.5-6.5$, $r/r_o = 0.8-1.0$, and $x/r_o = 7.15-15.8$, $r/r_o = 0.8-1.0$). Enlargements of these surveys near the second inlet are presented in Fig. 8 to provide additional information on detailed flow characteristics at that location.

Like the total pressure and static pressure, magnitudes of circumferential velocity in Fig. 7c generally decrease as flow moves away from each inlet, with the largest region of zero velocity at $x/r_o = 12.5-15$ near the swirl chamber outlet. (Inlet and outlet locations are identified on Fig. 4.) Circumferential velocity surveys are also similar to distributions in bounded wall jets, especially at $x/r_o = 0.1$ just downstream of the first inlet. Peak values are additionally evident at locations near $x/r_o$ locations near $r/r_o = 0.9-0.95$. Consequently, circumferential velocities generally increase at each value of $x/r_o$ as $r/r_o$ decreases for $r/r_o > 0.9-0.95$, and as $r/r_o$ decreases for $r/r_o < 0.9-0.95$. These two different types of behavior locate two different shear layers within the swirl chamber flow at the $\psi = 90^\circ$ circumferential position.

The results in Fig. 8 are obtained at $\psi = 0^\circ$ and $Re = 18000$ at $x/r_o = 7.15-15.8$ and $r/r_o = 0.8-1.0$, just downstream of the second inlet ($\psi = 0^\circ$, $x/r_o = 7.8$) at $r/r_o = 0.8-1.0$, just downstream of the swirl chamber outlet ($\psi = 90^\circ$, $x/r_o = 7.8$). As a result, measurements at these locations provide data corresponding to initial Görtler vortex pair development, and enlargement of the details of the surveys presented in Figs. 7a, 7b, and 7c. Distinctions of the data presented in Fig. 8 are determined from velocity components in the axial and radial directions using

$$\omega = \frac{\partial u_r}{\partial x} - \frac{\partial u_x}{\partial r}$$

Surveys of this quantity in Fig. 8 show regions of positive and negative time-averaged circumferential vorticity adjacent to each other near the concave surface at $r/r_o = 0.8-1.0$. Each of these evidences a pair of counter-rotating Görtler vortices which are either fairly steady or have preferred positions if they vary significantly in time. In Fig. 8, pairs of vorticity concentration of opposite sign are located at $x/r_o = 7.3-7.6$ and $x/r_o = 7.6-7.9$. Portions of pairs of vorticity concentration are evident in Fig. 8 at $x/r_o < 7.3$ and $x/r_o > 7.9$. Deficits of total pressure and circumferential velocity are present in upwash regions (where secondary flows are directed away from the concave surface), which are located between two regions of vorticity concentration of opposite sign in each vortex pair. These are located at or near $x/r_o$ of 7.2, 7.45, 7.75, and 8.0 in Fig. 8. Such results are im-
important because they illustrate time-averaged Görtler vortex pair structure and further demonstrate the existence of these vortices in fully turbulent swirl chamber flows.

Figure 7. Surveys along the length of the swirl chamber at \( R_e=18000 \) for the axial-radial plane located at \( \psi=90^\circ \). (a) Static pressure, \( P_s - P_a \) (Pa). (b) Total pressure, \( P_t - P_a \) (Pa). (c) Circumferential velocity, \( u_\psi \) (m/s).

Figure 8. Surveys of static pressure (\( P_s - P_a \) (Pa)), total pressure (\( P_t - P_a \) (Pa)), circumferential velocity, (\( u_\psi \) (m/s)), and circumferential vorticity (\( \omega_\psi \) (1/s)) at \( \psi=90^\circ \) and \( R_e=18000 \) for \( L/r_o=7.15-8.15 \) and \( r/r_o=0.8-1.0 \), just downstream of the second inlet.

Local Nusselt Number Variations

Fig. 9 shows the distribution of local surface Nusselt numbers at \( x/r_o=0-15 \) for \( R_e=19400 \) (\( R_e_D=7205 \)) and \( T_i/T_w=0.85 \). These distributions are measured around the entire swirl chamber circumference (\( \psi=0^\circ-360^\circ \)) using the infrared imaging procedures described earlier. Complex Nusselt number variations are evident in the figure, especially just downstream of the inlets located at \( x/r_o=0-1 \) and \( x/r_o=7-8 \). Not only are Nusselt numbers highest in this region due to arrays of Görtler vortex pairs, but gradients of the Nusselt number are evident in both the \( x \) and \( \psi \) directions. Nusselt numbers then decrease and become more spatially uniform along the interior surface of the chamber as the flows advect away from each inlet. At \( 2<x/r_o<6 \) and at \( x/r_o>9 \), Nusselt numbers are then quite uniform with \( \psi \), varying mostly only in the \( x \) direction.

Fig. 10 presents an enlarged portion of Fig. 9 to show the local surface Nusselt number distribution at \( x/r_o=7.0-8.0 \) and \( \psi=0^\circ-50^\circ \). The infrared image in Fig. 10a clearly shows surface variations due to Görtler vortex pairs in the form of light and dark stripes, which correspond to vortex pair trajectories along the concave surface of the chamber. This image is as recorded directly from the camera with some enhancement, but no corrections for camera angle and perspective. Surface temperature increases as image regions in Fig. 10a become lighter and whiter. Lower surface temperatures then coincide with higher local Nusselt numbers and higher temperatures coincide with lower local Nusselt numbers.
Spatially-resolved Nusselt numbers, determined from this infrared image, are shown in Fig. 10b. In spite of the relatively high Reynolds number of this flow, important Nusselt number variations due to the Görtler vortex pairs are evident, where higher and lower local Nusselt numbers correspond to vortex pair downwash and upwash regions, respectively. Such variations are entirely consistent with the circumferential vorticity contours shown in the bottom portion of Fig. 8 for $\psi=90^\circ$. The high Nusselt number region located at $x/r_o=7.0-7.2$ in Fig. 10b is due to the shear layer near the edge of the inlet jet. This shear layer contains an Eckman vortex like the ones seen the many of the visualization images presented in Fig. 3. The results in Fig. 10b additionally illustrate the excellent accuracy and spatial resolution obtained with the infrared imaging techniques employed for the study.
Spatially-Averaged Nusselt Number Variations

Circumferentially-averaged Nusselt number distributions, determined from the results in Fig. 9 (x/r_o = 0.15), are presented in Fig. 11a for Re = 19400 (Re_D = 7205) and T_i/T_w = 0.85. Also included in this figure are data points determined from thermocouple measurements, made at discrete point locations. Such data, along with other thermocouple measurements, are used to determine the in situ calibrations of the infrared images. All local thermocouple data thus accurately match local infrared data at all thermocouple measurement stations. The thermocouple data are a bit lower than the infrared data in Fig. 11a because they are based on averages of 3-4 measurements (spaced 90° apart), which does not give an accurate (or complete) circumferential average. Circumferential-averages of the infrared data at particular x/r_o, on the other hand, are determined from about 1300 data points spaced uniformly around the swirl chamber circumference. In both cases, Nusselt numbers show important decreases as x/r_o increases away from cylinder inlet locations.

Circumferentially-averaged Nusselt number distributions (determined entirely from thermocouple measurements) are presented in Fig. 11b for different Re, different Re_D, and different T_i/T_w, ranging from 0.62 to 0.86. Important quantitative and qualitative information is provided by these data, even though values may differ somewhat from circumferential averages based on larger numbers of data points. As for the data in Fig. 11a, Nusselt numbers in Fig. 11b also show important decreases as x/r_o increases away from cylinder inlets located at x/r_o = 0-1 and x/r_o = 7-8. In addition, Nusselt numbers at particular x/r_o decrease as Re decreases, when T_i/T_w ranges from 0.62 to 0.67.

Fig. 11b also shows that Nusselt numbers for Re = 17600-19400 change by important amounts as the T_i/T_w temperature ratio is changed. At each x/r_o value investigated, Nusselt numbers decrease significantly as the temperature ratio increases.
from 0.66 to 0.86. Changes are evident at all $x/r_o$ investigated, especially near each of the two inlets. Responsible are centrifugal forces in the swirl chamber which force cool, high density fluid near the hot surfaces by increasing amounts as $T_i/T_w$ decreases. This acts to enhance surface heat transfer coefficients, especially when the intermingling of cool dense fluid with hot, low density fluid is supplemented by arrays of interacting Görtler vortex pairs (like the ones shown in Fig. 3).

Axially-averaged Nusselt number distributions, determined from the infrared results in Fig. 9 at $x/r_o=7$-8, and at $x/r_o=0$-15 are presented in Fig. 12 for $Re=19400$ ($Re_o=7205$) and $T_i/T_w=0.85$. Also included on this figure are Nusselt numbers, determined from individual thermocouple measurements at different $x/r_o$, for the same $Re$ and $T_i/T_w$. Trends of the infrared-determined Nusselt numbers (denoted by the solid circle data) for $x/r_o=7$-8 are consistent with the thermocouple-determined data for $x/r_o=7.5$. These and other Nusselt number data in the figure show that the most important variations with $y_i$ are near and just downstream of each inlet at $x/r_o=0.5$, and at $x/r_o=7.5$. As $x/r_o$ increases relative to these values, Nusselt numbers then become approximately circumferentially uniform and invariant with $y_i$. The Nusselt number data determined from spatial averages of infrared measurements at $x/r_o=0$-15 are lower than values averaged over $x/r_o=7$-8 in Fig. 12.

Globally-averaged (in axial and circumferential directions) Nusselt numbers (determined entirely from thermocouple measurements) are compared with data from Glezer et al. (1996) and a correlation from Moon et al. (1998) in Fig. 13. The Glezer et al. data are obtained from a swirl chamber with an inlet made of a continuous axial slot spanning the entire axial length of the chamber. In spite of this difference, the present data show trends which are largely consistent with the correlation and data from those papers. In particular, the present data point for $Re=19400$ and $T_i/T_w=0.85$ is in line with all four of the Glezer et al. (1996) data points for about the same $T_i/T_w$. The other three data points from the present study for $T_i/T_w=0.62-67$ also line up with each other, but with a higher slope compared to the data at the higher $T_i/T_w$.

**SUMMARY AND CONCLUSIONS**

Heat transfer and flow measurements from a swirl chamber, which models a cooling passage located near the leading edge of a turbine blade, are presented for $Re$ from 4450 to 19400, and $T_i/T_w$ from 0.62 to 0.85. Spatially-resolved Nusselt number distributions, measured on the concave surface of the chamber using infrared imaging, show complicated variations through the chamber, especially near and just downstream of each of the swirl chamber inlets. Nusselt numbers are highest at these locations, and Nusselt number gradients are present in both the axial and circumferential directions. The most interesting Nusselt number variations are directly due to the Görtler vortex pairs, which result in arrays of parallel high and low local Nusselt number streaks, where higher and lower values correspond to vortex pair downwash and upwash regions, respectively. Such variations are entirely consistent with surveys of time-averaged circumferential vorticity, circumferential velocity, static pressure, and total pressure. Also present near inlets are augmented Nusselt numbers produced by the shear layer near the edge of the inlet jet, which contains an Eckman vortex seen in visualization images. As the flows advect away from each inlet, Nusselt numbers decrease and become more spatially uniform along the interior surface of the chamber. Such results illustrate the excellent accuracy and spatial resolution obtained with the infrared imaging techniques employed for the study.

Spatially-averaged Nusselt numbers additionally show important variations with Reynolds number $Re$, temperature ratio, $T_i/T_w$, non-dimensional axial location $x/r_o$, and circumferential location $y$. Like local data, circumferentially-averaged Nusselt number distributions show important decreases as $x/r_o$ increases relative to cylinder inlet locations. Effects of changing the $T_i/T_w$ temperature ratio are very strong and evident at all $x/r_o$ investigated, especially near each of the two inlets. When $T_i/T_w$ ranges from 0.62 to 0.67, circumferentially-averaged Nusselt numbers at particular $x/r_o$ decrease as $Re$ decreases. Axially-averaged Nusselt number distributions show the most important variations with $y$ near and just downstream of each inlet. As flow moves away from these inlets, axially-averaged Nusselt numbers then become approximately circumferentially uniform and invariant with $y$.

Especially important to augmentation of local and spatially-averaged Nusselt numbers near each of the inlets are: (i) centrifugal forces which force cool, high density fluid near the hot surfaces by increasing amounts as $T_i/T_w$ decreases, (ii) small-scale secondary flows within the arrays of initially developing Görtler vortex pairs, (iii) continuous interactions and intermingling of different-sized Görtler vortex pairs with each other, especially at higher Reynolds numbers and at locations just downstream of inlet ducts, and (iv) skewness, and three-dimensionality of Görtler vortex pairs produced by the axial component of flow in the swirl chamber.

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**REFERENCES**


