FLOW FIELD INVESTIGATION IN THE EXIT REGION OF A RADIAL INFLOW TURBINE USING LDV

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Abstract

Detailed flow investigation in the downstream region of a radial inflow turbine has been performed using a three component Laser Doppler Velocimetry. The flow velocities are measured in the exit region of the turbine at off-design operating conditions. The results are presented as contour and vector plots of mean velocities, flow angles and turbulent stresses. The measured parameters are correlated to the rotor blade rotation to observe any periodic nature of the flow. The measurements reveal a complex flow pattern near the tip region at the rotor exit due to the interaction of the tip clearance flow. The degree of swirl of the flow near the tip region at the rotor exit is observed to be high due to the gross under-turning of the flow near the tip region. The effect of the rotor on the exit flow field is observed in the proximity of the rotor exit.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>IGV</td>
<td>inlet guide vane</td>
</tr>
<tr>
<td>LDV</td>
<td>Laser Doppler Velocimetry</td>
</tr>
<tr>
<td>N</td>
<td>data sample size</td>
</tr>
<tr>
<td>U, V</td>
<td>velocity components</td>
</tr>
<tr>
<td>Ubl</td>
<td>rotor blade velocity</td>
</tr>
<tr>
<td>Vo</td>
<td>total velocity</td>
</tr>
<tr>
<td>VR</td>
<td>reference total velocity used for normalizing (time and passage averaged)</td>
</tr>
<tr>
<td>W</td>
<td>on-axis velocity component</td>
</tr>
<tr>
<td>r</td>
<td>radial direction</td>
</tr>
<tr>
<td>t</td>
<td>tangential direction</td>
</tr>
<tr>
<td>z</td>
<td>axial direction</td>
</tr>
<tr>
<td>α</td>
<td>absolute flow angle</td>
</tr>
<tr>
<td>σ, σ'</td>
<td>standard deviation in a velocity component data</td>
</tr>
<tr>
<td>AU, AV</td>
<td>measurement uncertainty of velocity component U, V</td>
</tr>
<tr>
<td>θ</td>
<td>coupling angle between the purple optical axis and the blue-green optical axis</td>
</tr>
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</table>

ϕ angle between the resultant velocity and the blue component velocity

Subscripts

b  blue component

g  green component

i  measurement point

j  rotor blade position

m  mean value

p  purple component

r  radial component

rz  radial-axial plane

rt  radial-tangential plane

t  tangential component

z  axial component

zt  axial-tangential plane

Introduction

Due to their ease of manufacture and high efficiency at low Reynolds number, radial turbines are extensively used in automobiles as turbochargers, as expanders in environmental control systems, in aircraft/rotorcraft auxiliary power units, in spacecraft auxiliary power units and in many other small gas turbine units. The flow inside the turbine is actually three dimensional and it is further complicated by the interaction of the rotor with its neighboring components. Increasing application of the radial turbines necessitates better understanding of the flow behavior in the radial turbine, which helps us in optimizing the design with minimum losses.

Various experimental and theoretical investigations on radial inflow turbines have been undertaken by many researchers over the years. Most of these investigations concentrated on the effect of the basic design variables such as nozzle setting angle [Khalil et al. (1977)], shroud clearance [Zangeneh et al. (1988)], Reynolds...
number [Watanabe et al. (1971), Khalil et al. (1977)], pressure ratio [Khalil et al. (1977)], specific speed [Kofskey et al. (1972)], mass flow [Watanabe et al. (1971)], splitter blades [Ariga et al. (1967)] and others.

As part of an on going research program on the radial inflow turbine at the University of Cincinnati, Khalil et al. (1976) presented contour-maps of the measured total pressure, Mach number and flow angles at the inlet and exit of the vaned nozzle of a radial inflow turbine using wedge type pressure probes. The experimental results showed strong end wall cross flows, significant losses and large mixing effects at the nozzle exit. Tabakoff et al. (1983) obtained hot-wire measurements in the scroll that revealed the presence of two counter rotating vortices. However, the errors introduced by conventional measuring probes can be very serious in the flow investigation of a radial turbine, since the flow paths are small and highly complex in geometry. A non-intrusive technique such as Laser Doppler Velocimetry can overcome these difficulties. Malak et al. (1986) measured the detailed flow field with LDV in a rectangular cross-section scroll and observed only one vortex in this unsymmetric scroll geometry. Eroglu and Tabakoff (1989) investigated the flow field in the nozzle guide vane using LDV. Lakshminarasanmila et al. (1989a) reported the flow measurements in the vaned free vortex region using LDV. All these investigations were performed without the rotor, which was replaced by an aluminum body of revolution. Recently Pasin and Tabakoff (1992a) investigated the flow field inside the inlet guide vane of the radial inflow turbine with the rotor. The effect of the rotor on the upstream inlet guide vane flow field was investigated through measurements using a three component LDV system and a rotary encoder. They presented the flow field contours for various rotor positions and observed the periodicity of the flow field in the inlet guide vane passage with the rotor revolution. Later Pasin and Tabakoff (1993) performed flow measurements inside the rotor of the radial turbine.

The radial turbine exit flow field has been observed by some investigators such as Kofskey et al. (1972), Mclallin et al. (1980) and Szewczuk (1989b), who obtained some picture of the flow field at the exit plane of the radial turbine by traversing a 3-hole probe. Researchers like Rohlik et al. (1970) and Japikse et al. (1979) have done valuable investigations on the radial turbine exhaust diffusers. Zangeneh et al. (1988) obtained flow measurements at the radial turbine exit plane with hot-wire anemometry. In their paper, Zangeneh et al. (1988) have recommended the use of non-intrusive measurement technique like LDV for the complex turbine exit flow field investigation. In high specific speed radial turbines, the flow discharges with high exit velocities and large swirl at off-design conditions. The swirl and turbulence in the exit flow field significantly contribute to the generation of noise and vibration of the unit.

In the present investigation, detailed flow measurements in the downstream region of a radial inflow turbine were obtained at off-design condition using a three component Laser Doppler Velocimetry (LDV). The velocity components, flow angles and some pertinent turbulent stresses within one passage are reported at different cross-sectional planes along the exit duct as well as in the meridional plane. The measured parameters are also correlated to various rotor blade positions. This investigation will help us in understanding the influence of swirl and turbulence on the radial-inflow turbine exit flow and contribute to the control of turbine exit losses as well as noise and vibration.

**Experimental Set-Up**

The experimental set-up consists of the test turbine, the 3-dimensional LDV & Data acquisition systems and the air supply systems as shown schematically in Fig. 1.

**Experimental Radial Turbine**

The test turbine assembly shown schematically in Fig. 2, is an aluminum-cast full scale model of a typical auxiliary power turbine unit used in aircraft. The turbine scroll has a nearly square, unsymmetric cross-section at the inlet and over most of the circumference. The details of the scroll geometry can be found in reference [Malak et al. (1986)]. The scroll is followed by 18 slightly cambered guide vanes and then a vaneless space of 0.13" (3.3 mm) downstream of these vanes. The details of the geometry of the inlet guide vane can be found in references [Eroglu et al. (1989) and Pasin et al. (1992a)]. The rotor has an inlet radius of 3.22" (81.8mm). The exit hub and tip radii are 0.87" (22.1 mm) and 1.7" (43.2 mm) respectively. The rotor has 8 full blades and 8 splitter blades. The splitters start at the rotor tip and end at 86% of the length of the full blades. The rotor blade span at the inlet and at the exit are 0.50" (12.7 mm) and 0.83" (21.1 mm) respectively. The rotor blades are radially straight all along the rotor with blade angles of 90° with respect to the tangential direction at inlet and exit. Hence, the rotor does not incorporate an exducer and so the rotor blades are axially straight at the rotor exit. The overall axial length of the rotor including the hub-end is 2.74" (69.6 mm). The rotor is keyed to a shaft of diameter 0.7" (17.8 mm) and it is supported with two thrust ball bearings located at the backwall end of the rotor. The exit duct wall has an inner radius of 1.75" (44.5 mm). The rotor hub at the exit of the rotor is smoothly rounded to guide the flow into the exit duct.

**Measurement Window**

The exit duct wall was machined sufficient enough on the outside to fit a transparent window for laser penetration. The width of the measurement window was sufficient enough to cover one blade passage at the rotor exit. The window was fixed so that it follows the curvature of the duct wall in order to keep the actual geometry intact. Since a curved window would cause laser distortion problems, different methods were tried to tackle the curvature effects on the test rig installation. One possible solution to this window-curvature problem is to fix a mirror-image window in front of the installed window to nullify the laser beam distortions. However, this is difficult to install and further complicates the laser alignment in the test set-up. Hence, different window materials in varying thicknesses were tested to investigate the optical effects of these materials on the laser beam. Finally Lexan with 0.05" (1.3 mm) thick proved to be the best window material. Lexan window material has good transmitting properties. Since the Lexan material was thin, only 0.05" thick (1.3 mm), it was easily possible to fit the window over the required portion of the duct wall conforming to the shape of the exit duct. The width of the fixed window was sufficient enough to gain access into one rotor blade passage. Then the molded
window was tested with the laser beam and magnifier optics at various beam incidence angles to investigate the amount of distortion of the laser beam caused by the curved window. The highest distortion was found to be well within the uncertainty of the traverse table, which is 0.001" (0.025 mm). Since the distortion of the laser beams was within the uncertainty of the traverse table, it was decided to carry out the experiments with a thin, 0.05" thick (1.3 mm) Lexan window.

Flow Seeding

A commercial six-jet atomizer, TSI 9306 model was used to seed the flow with two micron mean diameter propylene glycol particles. It has been reported by Rudoff and Bachalo (1991) that seed particles of size up to 5 µm are found to be adequate for low velocity air flows of up to 50 m/s. The atomizer is capable of generating particle concentrations of $10^5$ particles/cm$^3$. The atomizer was connected to the bottom of the settling chamber through which the air enters into the turbine as shown in Fig. 1.

LDV System

The measurements were accomplished with a three component LDV system as shown in Fig. 1. A five watt argon-ion Spectra Physics, model 164-09 laser was used as the light source. The optics for the three component LDV were arranged in off-axis backward scatter mode. The laser beam leaving the tube is separated into several components of different wavelengths in the dispersion prism. The first three highest intensity beams are used for the three velocity components. These beams are green with a wavelength of 0.5145µm, blue with a wavelength of 0.48811µm and purple with a wavelength of 0.4765µm. The first two are sent through the optical train in the axial direction, while the third beam passes through a second optical train whose beam expander and focusing lens are inclined at 30° to the axial direction. Blue and green components are used to measure the horizontal and vertical components of the velocity respectively. The purple component measures the non-orthogonal velocity component that is inclined at 30° to the blue but in the same plane as that of the blue component. Each beam is polarized and split into two equal intensity beams by the beam splitter. The six laser beams from the 3-D LDV were focused into one common measuring volume to form three sets of fringes. The focal length of the transmitting lenses was 480 mm. Beam expanders were used to reduce the measuring volume diameter 3.75 times and to improve the signal-to-noise ratio. Frequency shifters were used to remove the ambiguities in the flow direction and to reduce the fringe bias. Further detailed information on the LDV system can be found in references [Malak et al. (1986), Eroglu and Tabakoff (1989), Lakshminarasimha et al. (1989a), Pasin and Tabakoff (1992a, 1993)]. The entire LDV system with the bread-board was mounted on a milling machine table, which can traverse 254 mm, 457.2 mm and 558.8 mm in the axial, transverse and vertical directions respectively with an accuracy of 0.001" (0.025 mm) in all the three directions. The characteristics of the LDV system used are given in Table 1.

Table 1. LDV Characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Blue</th>
<th>Green</th>
<th>Purple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength in µm</td>
<td>0.488</td>
<td>0.5145</td>
<td>0.4765</td>
</tr>
<tr>
<td>Fringe Spacing in µm</td>
<td>2.851</td>
<td>3.0</td>
<td>2.784</td>
</tr>
<tr>
<td>Diameter of measuring volume at $e^{-2}$ intensity location in mm</td>
<td>0.053</td>
<td>0.056</td>
<td>0.052</td>
</tr>
<tr>
<td>Length of measuring volume at $e^{-2}$ intensity location in mm</td>
<td>0.617</td>
<td>0.651</td>
<td>0.603</td>
</tr>
<tr>
<td>Number of stationary fringes</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
</tbody>
</table>
Data Acquisition System

Three counter type signal processors (TSI Model 1990) were used to process the LDV signals coming from the photo-detectors mounted on the receiving optics of the LDV system. These processors send the processed data to a TSI MI-990 multi-channel interface, which is housed in one of the processors. This interface combines the data from all the processors according to the coincidence requirement set through the data acquisition software. The multi-channel interface also tags the information coming from the rotary encoder to the acquired data. The rotary encoder, model TSI 1999 was used to identify the rotor blade position at the time of each velocity data measurement. The combined data is sent from the MI-990 to an IBM P/C through an IBM 6260 DMA card.

The TSI 1999 Rotary encoder operation is based on phase-locking of the voltage-controlled oscillator. The oscillator runs 'n' times (selected by the user) faster than the input frequency of the pulse train, which is fed into the encoder as analog reference input. A 14-bit counter starts at the arrival of each input pulse and counts up to the selected number 'n'. Whenever a velocity data is received by the MI-990 interface, the current running number on this counter is latched and sent to the P/C together with the velocity information. The rotary encoder can also adjust the oscillator so that the counter can follow small changes in the input pulse frequency and hence the rotor speed. If the difference is too large as to affect the fixed testing turbine speed condition, the oscillator circuit becomes out-of-lock and prohibits data acquisition. For generating the analog reference input pulse frequency, a circuit was locally designed. Since the rotor at the exit has 8 blades, a disc with 8 teeth was machined to generate 8 pulses for each revolution. This disc was mounted directly on the turbine shaft with a light emitting diode (LED) and a light detector assembly. Whenever a tooth passes, the LED with the light detector assembly produces a signal. This signal is then processed by a circuit to generate a clean pulse signal with constant width. This pulse is fed into the rotary encoder as the reference input signal. When this disc is synchronized with the rotor, each tooth would correspond to one rotor blade. In this way, the data were collected from all the passages continuously at corresponding locations to represent the velocity data in one blade passage. This procedure was followed to minimize the time of data acquisition, since all the blade passages are geometrically similar.

Measurement Methodology

In the experimental set-up, it was possible to rotate the turbine rig about its inlet duct axis to a convenient angle in order to gain access into the exit region of the rotor as well as to synchronize the rotary shaft-angle encoder. The horizontal (blue) and vertical (green) components were measured directly by the LDV system. In the inclined arrangement of the second optical train, the purple component measures a non-orthogonal velocity component at 30° relative to the blue component on the same plane as that of the blue component. From this, the orthogonal on-axis component was calculated through a transformation relation as shown in the following equation:

\[ W = \frac{V_b \cos \theta - V_p}{\sin \theta} \]

where \( V_b \) and \( V_p \) are the horizontal (blue) and non-orthogonal (purple) components of velocity respectively and \( \theta \) is the inclination angle between the two optical trains. This angle, \( \theta \) was set to 30° due to the access constraints into the test rig. The measured horizontal, vertical and axial (on-axis) components of velocity were then transformed vectorially by the angle of inclination of the test rig to get the tangential, radial and axial components of the velocity in the exit duct. The mean quantities are the ensemble averaged values or the mean value of the data calculated for a given rotor position as explained in the following expressions. For the rotor position \( j \) and at the measurement point \( i \), the mean value of each component velocity is defined as:

\[ \bar{U}_{i,j} = \frac{1}{N_{i,j}} \sum_{k=1}^{N_{i,j}} U_{i,j,k} \]

where \( N_{i,j} \) is the number of data at the measurement location \( i \) for the rotor position \( j \). In a similar way, the variance of the corresponding velocity component for the same rotor position \( j \) at the measurement location \( i \) is defined as follows:

\[ \sigma_{i,j}^2 = \frac{1}{N_{i,j} - 1} \sum_{k=1}^{N_{i,j}} (U_{i,j,k} - \bar{U}_{i,j})^2 \]

where \( \sigma_{i,j} \) is the standard deviation or the turbulence level of the corresponding velocity component.

In order to identify the rotor blade position relative to the measuring location, the LDV measurement volume was placed first on the axis of the rotor. Then it was moved radially out and the measurement volume was made to fall on the edge of a blade at the rotor exit. Whenever a blade cuts the LDV measurement volume, it produces a strong signal. This laser signal was observed in an oscilloscope along with the pulse coming from the rotary encoder circuit and the delay was adjusted to coincide the pulse with the sharp rise of the laser signal coming from the passing blades. This procedure was repeated at different locations along the blade span to determine the change in the delay setting, if any, at different radial locations of the blade. However, since the blade thickness is constant, there was no change in the delay setting. The LDV measurement volume was then moved to various locations for obtaining measurements with this delay setting.

On the data processors, the number of cycles per burst was set to 4 with a 7% timer comparison in order to validate each set of data. A wide low and high filter range was set so as to collect data on either side of the mean without any cut-off. Suitable gain on the processors was used to have a low data rate during data collection, so that the particle arrival rate was less than the particle sampling rate to reduce the velocity bias.

Uncertainty Analysis

Like any other technique, the LDV measurement introduces some fixed bias errors, called systematic uncertainties as well as some random errors, called statistical uncertainties. The statistical uncertainties in the measured mean velocities were estimated using the procedures described by Orloff and Snyder (1981,1982,1984).
The uncertainty interval of a measured quantity can be related to the sample size as shown in the following relation by Snyder et al. (1984):

\[
\Delta U = \frac{z \cdot S_u}{\sqrt{N}} \tag{4}
\]

where \(S_u\) is an estimator for the true standard deviation and \(N\) is the sample size. The value of \(z\) is 1.96 for 95% confidence level. A large population of data (9000 data) was initially collected to determine the value of true standard deviation. This value was then used to calculate the variation in the uncertainty limits with sample size for 95% confidence level. The uncertainties of the measured mean velocities increased with turbulence in the flow field for the same sample size. The uncertainty analyses performed on the total velocity and flow angle (\(\alpha_{zt}\)) near the exit of the rotor are shown in Fig. 3 and Fig. 4 respectively. As shown in these figures, the improvement in the uncertainty was not significant, when the sample size was more than 400. Hence, the sample size was chosen as 400 for each position of the rotor blade at a measurement point. With a sample size of 400, the statistical uncertainty in the total velocity was found to be \(\pm 2.5\%\) (Fig. 3) and the uncertainty in the flow angle in the meridional plane (\(\alpha_{zt}\)) was found to be \(\pm 3^\circ\) (Fig. 4). The velocity data at each point within one passage were collected for eight circumferential positions of the blade. Therefore, 3200 data were collected at each measuring point in the turbine exit measurement zone. The systematic uncertainties were also calculated as described by Snyder et al. (1981). The relative uncertainties associated with the measurements are summarized in Table 2.

### Table 2. Measurement Uncertainties

<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal, transverse &amp; vertical traverses</td>
<td>(\pm 0.001^\circ (0.025 \text{ mm}))</td>
</tr>
<tr>
<td>Optical axis or turbine rig angular orientation</td>
<td>(\pm 0.5^\circ)</td>
</tr>
<tr>
<td>Horizontal Velocity Component ((\Delta V_{h}/V_{hm}))</td>
<td>(\pm 1.63%)</td>
</tr>
<tr>
<td>Vertical Velocity Component ((\Delta V_{v}/V_{vm}))</td>
<td>(\pm 1.63%)</td>
</tr>
<tr>
<td>On-axis Velocity Component ((\Delta W/W_m))</td>
<td>(\pm 12.92%) ((\phi = 0^\circ))</td>
</tr>
<tr>
<td></td>
<td>(\pm 11.87%) ((\phi = 45^\circ))</td>
</tr>
<tr>
<td></td>
<td>(\pm 3.86%) ((\phi = 90^\circ))</td>
</tr>
</tbody>
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**FIG. 3.** RELATIVE STATISTICAL VARIATION IN TOTAL VELOCITY ABOUT THE POPULATION MEAN AS A FUNCTION OF SAMPLE SIZE (AT THE NEAR EXIT OF ROTOR)

**FIG. 4.** RELATIVE STATISTICAL VARIATION IN FLOW ANGLE - \(\alpha_{zt}\) ABOUT THE POPULATION MEAN AS A FUNCTION OF SAMPLE SIZE (AT THE NEAR EXIT OF ROTOR)

**FIG. 5.** SKETCH SHOWING THE TURBINE EXIT AND THE MEASUREMENT ZONE

**FIG. 6.** FLOW VELOCITY VECTORS AND FLOW ANGLE NOTATIONS
Results and Discussion

Referring to Fig. 5, the LDV measurements downstream of the radial turbine rotor were obtained with high pressure cold flow in the cross-sectional planes (A, B, C, and D) and also in the meridional plane. All the experimental results reported in this paper were obtained at an off-design operational point with a constant mass flow rate of 0.121 lb/s (0.055 kg/s) and a constant turbine speed of 1000 rpm. The Reynolds number and the Mach number were 0.56x10^5 and 0.04 respectively based on cold air properties at 70°F (21.1°C), the time and passage averaged velocity at the rotor exit and the mean diameter at the rotor exit. The volute inlet total pressure was set to 10 psig (1.703x10^6 N/m^2 absolute pressure) and the total-to-static pressure ratio (scroll inlet total pressure/exit static pressure) across the turbine unit was 1.68. At this off-design condition, the isentropic velocity ratio, namely Ubl(t)/C_s based on the total-to-static pressure ratio was 0.03, where Ubl(t) is the rotor blade velocity at the rotor inlet and C_s is the isentropic discharge velocity, which would result from an ideal expansion of the air over the same pressure ratio as that of the turbine. The results are presented as vector and contour plots of the measured parameters in the cross-sectional planes A, B, C, and D as well as in the meridional plane, shown in Fig.5. The notations of the measured mean flow velocity vectors and flow angles are presented in Fig. 6. The mean velocity components presented in the plots are the absolute velocity components in the tangential, radial and axial directions from mid-passage to mid-passage, covering one rotor blade passage. The turbulent stresses are normalized with the time and passage averaged absolute total velocity at the rotor exit, which was 12.2 m/s for the tested off-design condition.

The results obtained in the first cross-section A, which is located at 0.1" (2.54 mm) downstream of the rotor exit are explained in this paragraph. According to the tangential velocity contour plot shown in Fig. 7, the tangential velocities of the fluid exiting along the pressure surface are higher compared to those near the suction surface. This can be attributed to the pressure field acting between the pressure and suction surfaces, which drives the flow to come into equilibrium behind the trailing edge of the blade. Near the tip region, gross under turning of the flow is observed at the exit of this tested exducerless radial turbine (see also Fig. 10) and hence the degree of swirl is very high near the tip region. This observation is in good agreement with the results of Kitson (1992). The calculation of the work extracted from the fluid by knowing the velocity triangles at the rotor inlet and exit leads to the fact that the high degree of swirl near the tip region drastically reduces the work loading in that region and is hence detrimental to the overall performance. The steep gradients in the contours in the wake region behind the trailing edge of the blade are observed in Fig. 7 and Fig. 8. The radial velocity contours presented in Fig. 8, show that there is a general radially inward movement (towards the rotor hub) of the flow due to the reduction in the centrifugal force as the flow leaves the rotor. This phenomenon is also reported by Kitson (1992). The radial velocities are generally low throughout the cross-section except near the pressure surface tip corner region, which may be due to the possible increased interaction of the tip clearance flow with the main flow near the pressure surface. It is possible that the mixing of the tip clearance flow with the main flow is enhanced near the pressure surface since the streamwise momentum of the flow near the pressure surface is low, which is also evidently seen in the mean velocity vector plot in the meridional plane along pressure surface in Fig. 23(a). The axial velocity contours are shown in Fig. 9 and they are higher along the suction surface than those along the pressure surface. The flow angle in the z-t plane, α_{zt} contours are presented in Fig. 10. A flow angle of 90° would correspond to zero swirl. As shown in the figure, the flow is exiting with minimum swirl only in the lower region above the rotor hub. Near the exit duct wall region, the flow undergoes a large under turning.

The results obtained at the cross-section B, which is stationed at 0.2" (5.08 mm) downstream of the rotor exit are explained in this paragraph. The tangential velocity contours for this cross-sectional plane are shown in Fig. 11. The tangential velocities downstream of the pressure surface continue to be slightly higher than those downstream of the suction surface. However, the difference in the degree of swirl along the blade pressure and suction surfaces is lower compared to that of the previous cross-section A as the flow mixes and is guided downstream. The radial velocity contours are presented in Fig. 12 and they are slightly higher downstream of the pressure surface tip corner region, which may be due to the continued mixing of the tip clearance flow near the pressure surface. The axial velocities, shown in Fig. 13, are still higher along the suction surface. The flow angle in the z-t plane, α_{zt} contours are presented in Fig. 14. The flow with minimum swirl is observed in the lower region of the cross-section above the rotor hub.

The next set of results, Fig. 15 through Fig. 18, were obtained at the cross-section C, which is located at 0.3" (7.62 mm) downstream of the rotor exit. The tangential velocity contours, shown in Fig. 15 exhibit no significant variation from the pressure side to the suction side. This indicates that the flow behind the trailing edge of the rotor blade is completely mixed at this station. In addition, the tangential velocities are reduced compared to their values at cross-sections A and B. The radial velocity contours, shown in Fig. 16 are generally low in the upper half but higher in the lower half of the cross-section, where the flow starts to turn radially inward near the hub-end (also see Fig. 5). The axial velocity contours presented in Fig. 17, indicate they are mostly uniform except in small zones near the tip along the suction surface. The contours of the flow angle in the z-t plane (α_{zt}), shown in Fig. 18, indicate that the smallest swirl exists in the inner radius region.

The results of the cross-section D, which is located at 0.6" (15.24 mm) downstream of the rotor exit are explained in this paragraph. The tangential velocities for this cross-sectional plane are shown in Fig. 19. They are almost uniform along the tangential direction at each radial location and the levels of the tangential velocities are less than those of the cross-section C. The radial velocity contours presented in Fig. 20, are generally low throughout the cross-section. The radial velocities near the hub along mid-passage are slightly negative due to the wake behind the hub-end. The wake generated behind the hub-end completely blocks the flow near the duct centerline and deflects the main flow slightly in the radially outward direction. The axial velocity contours as shown in Fig. 21 indicate slightly higher values in the lower half of the cross-section. There are no major changes in the swirl angle α_{zt} contours, shown in Fig. 22, compared to the previous cross-section (Fig. 18).

The vector plots of the mean velocities in the meridional plane with respect to different rotor blade positions are shown in
Fig. 23(a) through Fig. 23(c). Fig. 23(a) shows the mean velocity vector plot when the blade pressure surface aligns with the meridional plane. Due to the low meridional velocities near the pressure surface, it is possible for the tip clearance flow to penetrate deep in the radial direction and mix with main flow near the tip region. The meridional velocity vector plot when the rotor mid-passage aligns with the meridional plane is shown in Fig. 23(b). The meridional velocity vectors when the blade suction surface aligns with the meridional plane are shown in Fig. 23(c). Comparing Fig. 23(b) and Fig. 23(c) with Fig. 23(a), one can see the reduced influence of the tip clearance flow at the times of passing of the rotor mid-passage and the blade suction surface. From these three figures, we can conclude that the flow field near the rotor exit is highly complex due to the interaction of the tip clearance flow, the wake region behind the hub-end and the boundary layer development on the duct wall. The exit flow velocities increase in the mid-region due to the blockage caused by the wake region behind the hub-end and the boundary layer on the duct wall. Figures 23(a) through 23(c) indicate that the rotor blade influence diminishes further downstream of the straight portion of the hub, after which the flow field is similar for all rotor blade positions.

The turbulent normal stresses in the axial direction are presented in the meridional plane with respect to three different rotor blade positions in Fig. 24(a) through Fig. 24(c). Fig. 24(a) shows the turbulent normal stress contours in the axial direction when the rotor blade pressure surface aligns with the meridional plane. Regions of high turbulent stresses are observed near the tip region and in the wake region behind the hub-end. The levels of turbulent stresses near the tip region may be due to the intensive interaction of the tip clearance flow near the pressure surface. Fig. 24(b) shows the turbulent normal stress contours in the axial direction when the rotor blade mid-passage aligns with the meridional plane. The levels of turbulent stresses near the rotor exit are generally low compared to those shown in Fig. 24(a). Fig. 24(c) shows the normal turbulent stress contours in the axial direction when the rotor blade suction surface aligns with the meridional plane. The levels of turbulent stresses near the rotor exit are generally low compared to those along the pressure surface due to the higher momentum of the flow in the axial direction. However, the zones of high turbulent stresses near the tip region and along the duct wall are broadened, which may be due to the extended mixing of the tip clearance flow with the main flow.
FIG. 11. TANGENTIAL VELOCITY CONTOURS ($U_t$ - m/s) [CROSS-SECTION B]

FIG. 12. RADIAL VELOCITY CONTOURS ($U_r$ - m/s) [CROSS-SECTION B]

FIG. 13. AXIAL VELOCITY CONTOURS ($U_z$ - m/s) [CROSS-SECTION B]

FIG. 14. CONTOURS OF FLOW ANGLE IN THE $z$-$t$ PLANE ($\alpha_{zt}$ - deg.) [CROSS-SECTION B]

FIG. 15. TANGENTIAL VELOCITY CONTOURS ($U_t$ - m/s) [CROSS-SECTION C]

FIG. 16. RADIAL VELOCITY CONTOURS ($U_r$ - m/s) [CROSS-SECTION C]
FIG. 17. AXIAL VELOCITY CONTOURS ($U_z$ - m/s) [CROSS-SECTION C]

FIG. 18. CONTOURS OF FLOW ANGLE IN THE $z$-$t$ PLANE ($\alpha_{zt}$ - deg.) [CROSS-SECTION C]

FIG. 19. TANGENTIAL VELOCITY CONTOURS ($U_t$ - m/s) [CROSS-SECTION D]

FIG. 20. RADIAL VELOCITY CONTOURS ($U_r$ - m/s) [CROSS-SECTION D]

FIG. 21. AXIAL VELOCITY CONTOURS ($U_z$ - m/s) [CROSS-SECTION D]

FIG. 22. CONTOURS OF FLOW ANGLE IN THE $z$-$t$ PLANE ($\alpha_{zt}$ - deg.) [CROSS-SECTION D]
FIG. 23(a). VECTOR PLOT OF MEAN VELOCITY IN THE MERIDIONAL PLANE [ALONG PRESSURE SURFACE]

FIG. 23(b). VECTOR PLOT OF MEAN VELOCITY IN THE MERIDIONAL PLANE [ALONG MID-PASSAGE]

FIG. 23(c). VECTOR PLOT OF MEAN VELOCITY IN THE MERIDIONAL PLANE [ALONG SUCTION SURFACE]

FIG. 24(a). TURBULENT NORMAL STRESS IN THE AXIAL DIRECTION ($u'_x^2/V_R^2$) [MERIDIONAL PLANE - ALONG PRESSURE SURFACE]

FIG. 24(b). TURBULENT NORMAL STRESS IN THE AXIAL DIRECTION ($u'_x^2/V_R^2$) [MERIDIONAL PLANE - ALONG MID-PASSAGE]

FIG. 24(c). TURBULENT NORMAL STRESS IN THE AXIAL DIRECTION ($u'_x^2/V_R^2$) [MERIDIONAL PLANE - ALONG SUCTION SURFACE]
The results of this and the preceding (1993) experimental investigations inside and downstream of the radial inflow turbine rotor at off-design condition provide a database for validating three-dimensional turbomachinery CFD codes. In addition, this investigation identifies the exit loss producing mechanisms, namely the mixing patterns of the tip clearance flow, the wake behind the rotor hub-end and the boundary layer development on the exit duct wall. However, more detailed investigation of the flow field in the tip clearance zone at the radial turbine exit is required to better understand the interaction of the tip clearance flow and its mixing patterns. The main reason to conduct this and the preceding (1993) investigations at a low turbine speed is to visualize the severity of the secondary flow patterns under extreme off-design condition as well as to check the versatility of the CFD codes to predict the flows under such conditions. Computational flow studies are currently being performed for the tested conditions. The obtained computational results will be compared with the presented experimental data.

Conclusions

An experimental investigation of the exit flow field of a radial turbine was conducted at off-design condition. The flow field in the immediate vicinity of the rotor tip is influenced by the tip clearance flow. The mixing of the tip clearance flow with the main flow is revealed at different locations relative to the rotor blade position. The degree of swirl of the flow near the tip region at the rotor exit is very high due to the gross under turning of the flow near this region. The swirl of the flow near the surface pressure was found to be higher than that near the suction surface at the measurement cross-sectional plane nearest to the rotor exit. The degree of swirl reduces as the flow is guided downstream in the exit duct. The wake behind the hub end and the boundary layer development on the exit duct wall are captured in this investigation. The presented results can serve as a database for the development and validation of three-dimensional computational flow codes applicable to radial turbines.

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References


