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Heat Transfer in a Two-Pass Internally Ribbed Turbine Blade Coolant Channel With Cylindrical Vortex Generators

Author:

R. Hibbs
S. Acharya
Y. Chen
D. Nikitopoulos
T. A. Myrum

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two dimensional rectangular geometry. The present investigation will study the effect of this vortex generator geometry in a square-sectioned, ribbed duct over a range of Reynolds numbers. The flow in this geometry is three dimensional with secondary flows expected to have some effect on the flow structure. To the authors' knowledge, no studies on the effect of cylindrical vortex generators in a square-sectioned duct have been made.

The Experiments

The experiments are performed in a test apparatus designed for the study of mass transfer (sublimation of naphthalene) in a rotating duct that simulates the coolant channels of a turbine blade. Mass transfer measurements permit the acquisition of detailed local distributions of the Sherwood number which can then be converted to Nusselt numbers using the heat-mass transfer analogy.

An overall schematic of the experimental setup is shown in Figure 1. Compressed air is used as the working fluid for all experiments in order to more closely simulate the operational parameters in a turbine engine. The air is taken from large, exterior reservoirs in order to minimize flow disturbances caused by the compressor. A concentric bore orifice plate is used to measure the mass flow rate in the meter run. A regulator is used to maintain a constant supply pressure in the meter run. Test section and meter run pressures are measured using mechanical pressure gauges that have a 2.5 psi resolution, and are controlled independently with gate valves located downstream of both the meter run and test section. Naphthalene laden exhaust air is directed through flexible tubing to a fume hood.

Figure 1. Schematic of Experimental Apparatus

Apparatus

The aluminum alloy test section consists of a 2.75 in. tapered settling chamber; a frame that supports eight removable, hollow plates; and a removable 180 degree bend. These major components are secured in a flange-like manner, using O-rings between all parts to prevent air leakage. When assembled, the test section forms 1 x 1 x 12 in. long inlet and outlet sections 1.5 in. apart that are connected by the 180 degree, 1 x 1 in. square cross-section bend. The aluminum ribs are 0.1 x 0.1 x 1.0 in. long and have holes on either end for mounting (Figure 2). Steel, 0.025 in. diameter music wire is inserted into these holes to secure them to the side walls of the test section. The ribs are mounted only on opposite walls and are not coated with naphthalene. The vortex generators (rods) are made from 0.078 in. diameter steel music wire. The rods are positioned in the test

Figure 2. Schematic of Test Section Showing Geometrical Notation

section by means of small aluminum brackets that allow for variation of rib-rod spacing.

Detailed surface profiles of the cast surfaces are required for local mass transfer results. These profiles are obtained by moving the walls under a fixed, linear variable differential transducer (LVDT) type profilometer. A bi-directional traversing table is securely mounted to the platform of a milling machine. The plates are secured to a 0.625 in. thick tooling aluminum plate which is fixed to the traversing table. This mounting plate has been machined with an assortment of pin supports and machine screw taps to ensure the walls not only lie flat on the plate, but also are mounted in the same location for all scans. A custom written program run on a personal computer is used to control the motion of the traversing table through micro-step drive motors with a 0.00005 in. step size.

Procedure

Fresh, 99% pure naphthalene crystals are melted in a heavy-walled glass beaker with an electric heating element. The clean test section walls are clamped to stainless steel plates which have been polished to a mirror-like finish. Molten naphthalene is quickly poured into the hollow cavity of the plate frame to fill completely the region between the walls. The cast plates stand for at least eight hours in a fume hood to attain thermal equilibrium with the laboratory.

Each wall is then separated from the casting plate and mounted to the mounting plate for scanning. After scanning, the plates are stored in an air-tight container, saturated with naphthalene vapor, to hinder natural sublimation until the test section is assembled.

Test section assembly is begun by first inserting the two inner side walls and then attaching the bend. Any ribs or vortex generators are then attached to these walls and the two outer side walls are mounted. The alignment of all ribs and vortex generators is checked before the four top and bottom walls are assembled. After the experiment is over, the test section is disassembled and the walls are placed in the storage container until they are scanned again.

Data Reduction

Mass flow rate in the meter run is calculated from measurements of temperature, pressure, and differential pressure using standard equations for concentric bore orifice meters (Stearns, et al., 1951 and Miller, 1989).

Naphthalene sublimation depth is calculated from the two surface profiles for each wall. Each profile is normalized with respect to a reference plane computed from

three points scanned on the aluminum surface of the walls. The difference between the normalized profiles gives the local sublimation depth.

The local mass flux $\dot{m}''$ at each location is calculated from the following expression:

$$\dot{m}'' = \rho_s \delta / \Delta t \quad (1)$$

where ρ_s is the density of solid naphthalene, δ is the local sublimation depth, and Δt is the duration of the experiment. Vapor pressure at the wall p_w is calculated from the following equation (Sogin, 1958):

$$\log_{10}(p_w) = A - B/T_w \quad (2)$$

where A and B are constants and T_w is the absolute wall temperature. Wall vapor density ρ_w is then calculated using the perfect gas law. Bulk vapor density of naphthalene $\rho_b(x)$ is obtained by mass conservation balances of naphthalene from the inlet ($x = 0$) to the streamwise location (x).

The local mass transfer convection coefficient h_m is then calculated as follows.

$$h_m = \dot{m}'' / (\rho_w - \rho_b(x)) \quad (3)$$

The binary diffusion coefficient D_{n-a} for naphthalene sublimation in air is taken as the ratio of the kinematic viscosity of air ν to the Schmidt number for naphthalene-air ($Sc = 2.5$). The local Sherwood number Sh is then calculated by:

$$Sh = h_m D / D_{n-a} = h_m D Sc / \nu \quad (4)$$

where D is the hydraulic diameter of the test section. Sherwood number results presented in this study have been scaled with a correlation

adapted from McAdams for fully developed smooth wall pipe flow.

$$Sh_o = 0.023 Re^{0.8} Sc^{0.4} \quad (5)$$

where Re is the duct Reynolds number.

Comparison of heat transfer and mass transfer results is done through the use of the heat-mass transfer analogy (Sogin, 1958).

$$Nu = Sh(Pr/Sc)^{0.4} \quad (6)$$

where Nu is the Nusselt number and Pr is the Prandtl number of air. An augmentation number N is used to compare mass transfer augmentation for tests involving vortex generators. It is defined as follows:

$$N = Sh_{rib-rod} / Sh_{rib} \quad (7)$$

where $Sh_{rib-rod}$ is the Sherwood number with the vortex generators installed and Sh_{rib} is the Sherwood number for the baseline. Both local and area-averaged results are compared in this manner. Area-averaging is performed over the cross stream width of the wall.

Uncertainty

Uncertainties for all computed values are estimated using the second-power equation method (Kline and McClintock, 1953). The estimates for these experiments are comparable to previously reported values for both heat transfer and mass transfer studies, but are believed to be conservative.

Volume flow rate and duct Reynolds number (Re) uncertainties are estimated to be less than 10 percent for $Re > 6000$. The reported resolution of the LVDT is 0.00005 in. while the A/D board is reported to have an accuracy of 0.000078 in. in a 12 kHz acquisition rate, 16 bit resolution mode.

Experimental tests of accuracy and repeatability for the entire acquisition system indicate a sublimation depth uncertainty of 0.00015 in. Sublimation depths are maintained at about 0.006 in. by varying the duration of the experiment. This target depth was selected to minimize uncertainties in both depth measurement and changes in duct cross section area. These uncertainties were found to be 1 and 3 percent, respectively. The resulting experimental duration was between 90 minutes for $Re=30,000$ and 180 minutes for $Re=5,000$.

Vapor density uncertainty based on measured quantities is negligible for both wall and bulk values. Overall uncertainty in Sherwood number calculation is about 8 percent and varies slightly with Reynolds number (<1 percent).

Experimental Results

The experiments reported in this paper were performed with ribbed top and bottom walls and smooth side walls. Measurements were made for the following parameters (see Figure 2 for notation): rib height-to-hydraulic diameter ratio, $e/D = 0.1$ and vortex generator (rod) diameter-to-rib height ratio, $d/e = 0.78$. Rods are placed above all the ribs for $P/e = 21$, and over every other rib, beginning with the first one in the duct, for rib pitch-to-rib height ratio, $P/e = 10.5$. For $s/e=0.55$, rods are placed in both the inlet and outlet sections, but for $s/e = 1.0$ and 1.5 , rods are placed only in the inlet section. Three different Reynolds numbers: 5,000, 10,000, and 30,000 were investigated for the rib only baseline and each of the three rod clearance ratios.

Along the centerline of each plate, 120 points are measured and these are used for the calculation of the bulk naphthalene vapor density. To obtain more detailed measurements in

both the developing and fully developed regions of the walls, profile measurements on a 30 x 28 (streamwise x transverse) uniform grid are made in selected inter-rib modules.

Rib-Only Baseline Measurements

Figure 3 shows the centerline Sherwood number ratio in the inlet (radially inward leg) and the outlet (radially outward leg) sections for the rib-only baseline case at a Reynolds number of 30,000. Along the ribbed top and bottom walls (Figure 3a) periodic fully developed profiles are obtained after only a few inter-rib modules. Asymmetry between the top and bottom walls is present for most of the inlet, and is due to the asymmetry in the inlet flow profile. The asymmetry diminishes significantly in the last three inter-rib modules of the inlet duct and essentially vanishes in the outlet section. Peak Sherwood number ratios are typically between 3.0 and 3.25 in the inlet and between 2.75 and 3.0 in the outlet. These values remain nearly constant throughout the length of the section. The profiles typically have two peaks, one that occurs nearly 5-6 rib heights downstream of the rib and corresponds to reattachment, and the other that occurs just upstream of each rib and corresponds to a corner eddy upstream of the rib. These observations are consistent with those reported in the literature (e.g. Acharya et al., 1995a).

The centerline profiles for the smooth side walls qualitatively resemble the asymptotically decaying profiles (to fully developed values) observed for a smooth surface. However, a careful inspection shows small periodic undulations in the profile with the peaks in the vicinity of the ribs. These peaks appear to correlate directly with the peaks in the turbulence intensity profiles reported by Acharya et al. (1994). Sherwood number ratios for the

Figure 3. Centerline Sherwood Number Ratio Distribution for the Rib-only Baseline Case: $Re = 30,000$, $P/e = 10.5$

inlet are in the range of 1.5 - 2.0 over most of the plate. This nearly two-fold enhancement of centerline mass transfer over the purely smooth walls can be attributed to an increase in the turbulence levels caused by the ribs. The profiles in the outlet section show that immediately past the bend the Sherwood numbers along the outer wall are higher than those along the inner wall. This is presumably due to the effect of secondary flows induced by the bend and leads to a noticeable asymmetry between opposing walls in the first inter-rib module past the bend.

Detailed contours of Sherwood number ratio in the inlet section of the duct for the baseline case are shown in Figure 4. The developing region is depicted by the first two inter-rib spaces and the fully developed region is depicted by the last four inter-rib spaces. The asymmetry between opposing walls in the developing region, noted earlier in the centerline profiles, is quite evident in the contours. Asymmetry is dampened downstream indicating that the flow field induced in a rib-roughened duct quickly overwhelms the history of the inlet field. The fully developed mass transfer on the top and bottom walls clearly shows regions of separation, reattachment, redevelopment, and recirculation that, as noted earlier, have been previously reported in the literature based on centerline values. Sherwood number ratio in most of the separated region downstream of a rib is in the range of 1.0 to 2.0. A peak value in the vicinity of 3.0 occurs near the point of flow reattachment, and in the fully developed region, this peak is relatively uniform in the spanwise direction. Sherwood number ratios expectedly decrease downstream of reattachment. Just upstream of the rib appears to be a small but energetic eddy that, in the transverse direction, spans most of the rib and extends about one rib height upstream of the rib.

Sherwood number ratios as high as 4 are noted in this region.

The Sherwood number ratios for the smooth side walls show similar asymmetry in the developing region, but this asymmetry persists throughout the duct. Contours in the fully developed region clearly show a periodically fully developed distribution on the outer wall. Local mass transfer near the ends of the ribs is very high ($Sh/Sh_0 = 4$), but is restricted to the near vicinity of the rib. These localized regions of high mass transfer near the ribs correlate spatially with the peaks in the streamwise turbulence intensity measured in the vicinity of the ribs (Acharya et al., 1993, Acharya et al., 1994, Acharya et al., 1995a). Sherwood number ratios in the mid-span regions of the smooth walls are of the order of 2. This mass transfer enhancement on the side walls extends up to nearly 4 rib heights toward the mid-span of the plate, and is believed to result from an increase in turbulence levels caused by the ribs.

Local mass transfer for the baseline case in the outlet section is shown in Figure 5. As was suggested from centerline values, overall mass transfer is lower in the outlet section than in the inlet section. Top and bottom wall symmetry is excellent. Comparison of the inner and outer walls clearly shows the effects of the bend. Higher Sherwood numbers are observed on the outer surface relative to the values on the inner wall. Secondary flows induced by the bend are expected to drive the flow toward the outer wall resulting in higher Sherwood numbers along these walls as observed here.

Mass transfer distributions in the fully developed region of the outlet duct resemble those from the inlet duct, except that the peak values along the ribbed walls are 15-25%

Figure 4. Detailed Sherwood Number Ratio Contours in the Inlet Section for the Baseline Case: $Re = 30,000$, $P/e = 10.5$

Figure 5. Detailed Sherwood Number Ratio Contours in the Outlet Section for the Baseline Case: $Re = 30,000$, $P/e = 10.5$

lower. The mass transfer distribution on the side walls is also similar to that in the inlet, but the region of augmentation ($Sh/Sh_0 > 1$) is restricted to only about two rib heights.

Rib-Vortex Generator (Rod) Measurements

Centerline mass transfer distribution for both the rib only baseline and the $s/e=0.55$ rib-vortex generator spacing at $P/e = 21$ and $Re=5,000$ is shown in Figure 6. Mass transfer in the inlet duct is noticeably enhanced by the presence of vortex generators. In particular, the peak value upstream of each rib is consistently 1.5-2 times greater than the baseline rib-only values. In the first two inter-rib spaces, the profiles are similar in shape to the baseline profile, with the reattachment location appearing to be roughly at the same location (5-6 rib heights downstream of the rib). From the third inter-rib module onwards, the inter-rib Sherwood number profiles for the rib-rod cases appear to be more uniform, and suggests a delayed reattachment (10-15 rib heights downstream of the rib). However, these more uniform Sherwood numbers are generally higher than the rib-only values, and particularly so in the later regions of the inter-rib module. Presumably the rods enhance the inter-rib turbulence intensities and provide an overall increase in the mass (heat) transfer from the ribbed surface.

The outlet centerline Sherwood number distribution indicates that the enhancement of local mass transfer is not as pronounced as in the inlet. However, the same trends of generating a more uniform Sherwood number distribution in the inter-rib modules can be observed.

Centerline mass transfer distribution along the side walls in both the inlet and outlet sections show that vortex generators induce considerable enhancement (nearly 2-2.5 the

rib-only value). It is believed that this enhancement is due to the horseshoe vortices shed behind the base of the rods and the associated increases in the turbulence levels. Overall, the presence of the rods seems to merely shift the mass transfer distribution upward, without altering the trends. Similar mass transfer behavior is seen in the outlet section.

Figure 7 presents the results at the lowest and highest Reynolds numbers studied ($Re=5,000$ and $40,000$) and for the same P/e and s/e values in Figure 6. Only the fully developed region (the last inter-rib module in each section) is shown. The results, in the form of a mass transfer augmentation number, $N=Sh_{rib-rod}/Sh_{rib}$, are presented for each of the four walls in the inlet and outlet sections. At the lower Re value, mass transfer enhancement of the order of 50% is obtained along the smooth walls with peak enhancement as high as 80%. Along the ribbed top wall, there is an initial degradation for up to six rib heights followed by a substantial increase in mass transfer with peak N -values reaching 1.75. For $Re=40,000$, the behavior is similar, with centerline mass transfer along the smooth side walls enhanced by nearly 50% due to the presence of the vortex generators. Along the ribbed bottom wall of the inlet passage, the centerline N -values show about a 20% average increase in mass transfer, with a peak increase of nearly 40%. It is worth noting that these increases are primarily downstream of 8 rib heights from the rib, and that the maximum enhancement generally occurs just ahead of the rod-rib pair downstream. Along the top ribbed wall enhancement levels are similar to those along the bottom ribbed wall. In the outlet passage, enhancement in the ribbed wall mass transfer is observed over most of the stream-wise extent of the inter-rib module, with a peak enhancement of nearly 50% for the bottom ribbed wall.

Figure 6. Comparison of Centerline Sherwood Number Ratio:
 $Re = 5,000$, $P/e = 21$, $s/e = 0.55$

**Figure 7. Fully Developed Centerline Mass Transfer Augmentation Number:
 $P/e = 21$, $s/e = 0.55$**

To highlight the effects of the spanwise variations in the enhancements induced by the vortex generator, spanwise-averaged augmentation numbers are also presented for $Re = 40,000$. Spanwise averaged profiles of the mass transfer augmentation number expectedly have a smoother appearance than the centerline profiles. Spanwise averaged values for the side walls are consistent with the centerline, with average enhancements along the side walls that are typically of the order of 50% except for the inner wall of the inlet duct where the enhancements are somewhat lower. For the ribbed walls, the enhancement levels are somewhat lower in the outflow passage.

Contours of the local mass transfer augmentation numbers in a fully developed inter-rib module for all the walls is shown in Figure 8 for $Re = 5,000$, $P/e = 21$, and $s/e = 0.55$. As seen in Figure 6, there is enhancement in the second half of the inter-rib module, and degradation in the first half. It is clear from Figure 8, that on the top wall the enhancement (peak value of N is nearly 2) is greater than the degradation (minimum value is around 0.6), and that the spanwise profile is fairly uniform. Near the outer and inner walls, high values of N are noted. Along the bottom ribbed wall, the enhancement levels are lower. The side walls show significant enhancements (values of N as high as 2.75 can be seen) with the peak values centered in the wake of the vortex generator. The traces of N in the two wakes behind the vortex generators show that they are deflected away from the rib as the flow emerges from the rib-rod inter-space. The two wakes appear to merge downstream (at approximately 10 rib heights downstream of the rod); the wake effect on the mass transfer can be seen to persist through the entire inter-rib module.

Figure 9 shows the behavior at the lower $P/e = 10.5$. Observations similar to those

noted above can be made. Along the ribbed walls local regions of mass transfer degradation and enhancement can be seen, but overall the enhancement levels and coverage exceed the degradation. Mass transfer degradation levels are typically 20% while enhancements levels are typically in the 20-40% range.

Mass transfer contours for the side walls again clearly show the effect of vortex shedding behind the rods. In the wake region behind the rods, significant mass transfer enhancement is present. The inner wall seems to benefit more from the rods than the outer wall. This behavior may be explained by the scaling of local Sherwood numbers by those for the baseline. The "distinct" wake regions behind the rods on the outer wall seem to extend to about five rib heights and show enhancement of up to 100% before the two wake regions combine. In the region after the two wakes have combined, mass transfer enhancement is about 20 - 40%. The contours for the inner wall indicate that the wakes combine later and that enhancement is much greater--up to over 300%. Mass transfer near the centerline of both side walls is enhanced, even in the region between the wakes. Average enhancement for the side walls is approximately 40% over the entire inter-rib space.

Local mass transfer contours for $s/e = 1.5$ and $Re = 10,000$ and $30,000$ are shown in Figure 10. Enhancement at higher Reynolds numbers is somewhat smaller than the enhancement at the lower Reynolds numbers. It is believed that the shear layers formed by the ribs and rods are much thinner at higher Reynolds numbers and thus do not influence the flow as much as they do at lower Reynolds numbers. For the ribbed walls, degradation up to 20% is observed while enhancement levels up to 40% are noted. The surface area with enhancement is again much larger than the area where degradation occurs. Along the side

Figure 8. Detailed Mass Transfer Augmentation Numbers in the Fully Developed Inlet Section: $Re = 5,000$, $P/e = 21$, $s/e = 0.55$

Figure 9. Detailed Fully Developed Mass Transfer Augmentation:
 $Re = 5,000$, $s/e = 0.55$

Figure 10. Effect of Reynolds Number on Fully Developed Mass Transfer Augmentation: $s/e = 1.5$

walls maximum enhancement levels are in the range of 2-2.8, but they are much more localized. Unlike the flow at lower Reynolds numbers, the merging of the two wakes is not apparent along the smooth walls of the inlet passage. In fact, in the midspan regions the augmentation number is typically 1, indicating no enhancement. Along the inner wall of the outflow passage, some wake interference can, however, be observed.

Concluding Remarks

An experimental study is made to measure the local Sherwood numbers in the internally ribbed passages of a square turbine blade coolant channel with a radially outward flow leg and a radially inward flow leg. The primary objective of the study is to examine if cylindrical vortex generators placed above the ribs can be used to enhance mass transfer from the surfaces. Measurements of the mass transfer include centerline and spanwise averaged profiles of Sherwood number ratios and corresponding contours in the developing and periodically developed regions. The following main conclusions are obtained.

1. Baseline rib-only results confirm the reported peaks in the Sherwood number in the vicinity of reattachment and just upstream of the rib where a strong corner vortex is formed. Along the smooth side walls, significant enhancement is obtained with the peak occurring in the vicinity of the rib. This peak correlates with the measured location of maximum turbulence intensity.

2. For the higher pitch case ($P/e=21$), significant enhancement due to the vortex generators is obtained along the ribbed walls in the developing region of the inflow passage. In the periodically developed region, the profile is more uniform, with degradation in

the initial separated region and enhancement in the later regions of the inter-rib module. The enhancement levels and coverage substantially exceed the corresponding degradation quantities. Along the smooth walls, the horseshoe vortices in the wake of the vortex generator are associated with high levels of mass transfer enhancement. The wakes from each vortex generator are deflected away from the rib, and appear to merge downstream. The wake effect is seen to decrease somewhat with Reynolds number.

3. Spanwise average profiles in the developed regions indicate an average 50% increase in the mass transfer from the side walls due to the vortex-generators. Along the ribbed walls the average enhancement levels are lower. Local enhancement levels can be substantially higher--reaching values in the vicinity of 300% along the side walls.

4. For the lower pitch ($P/e=10.5$), the general behavior is the same as that for $P/e=21$. Enhancement levels are somewhat lower and the wake interference and merging effects along the side walls are weaker.

5. Future studies are directed at optimizing the vortex generator geometry and making measurements under rotating conditions.

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