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Turbulent Flow Development inside a Rotating Two-Pass Square Duct with Porous Blocks

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ABSTRACT

This paper presents an experimental investigation of turbulent flow inside square-sectioned channels connected with a square-ended bend using particle image velocimetry (PIV). Aluminium porous foam blocks of aspect ratio of 1.5 with 0.93 porosity and pore density per cm of 2, are attached to two opposite walls of the straight section normal to the turn axis, in a staggered manner. The spacing ratio of the blocks \((S/D)\) is 1; whereas the height ratio \((h/D)\) is 0.6. Water is used as the working fluid at Reynolds number of 36,000. The duct is either stationary or rotates orthogonally about an axis normal to that of the turn at a rotation number of 0.32. Results show the serpentine manner of the flow in the upstream and downstream channels due to the presence of the porous blocks. While in the straight sections there is no flow separation downstream of each block, turbulence levels are raised by the blocks’ presence. Within the bend, in contrast to the case with a smooth upstream section, a single vortex dominates the flow. For the first time, the effects of orthogonal rotation are also highlighted. While rotation does not change the overall flow character, it does force more fluid through the blocks on the duct trailing (pressure) side.

**Keywords:** PIV measurements, Strong curvature, Orthogonal rotation, Turbulent flow, Porous metal foam.
NOMENCLATURE

\[ D \] hydraulic diameter
\[ h \] porous block height
\[ Re \] Reynolds number \( = \frac{U_b D}{\nu} \)
\[ Ro \] rotation number \( = \frac{\Omega D}{U_m} \)
\[ S \] porous block spacing
\[ t \] porous block thickness
\[ U_b \] bulk velocity
\[ u' \] Streamwise turbulent intensity
\[ v' \] Cross-duct turbulent intensity

Greek Symbol

\[ \nu \] kinematic viscosity
\[ \varphi \] Porosity
\[ \Omega \] angular velocity of rotation

1.0 INTRODUCTION

Turbine inlet temperatures in modern gas turbines are higher than the allowable point of the blade material. Therefore, turbine blades need to be cooled to protect them from excessive thermal damage. Various cooling techniques have been developed, where relatively cool air from the high-pressure stage of the compressor is ducted to internal cooling passages within the turbine blades. Moreover, the blade surface is covered with a thermal barrier coating. The middle part of the blade is cooled through serpentine passages with sharp U-turns and heat-transfer-enhancing ribs on opposite walls [1]. Over the past decade, many studies conducted experiments on the rotating cooling passages and studied the effect of parameters such as the strong bend curvature [2], and rib-roughened passages [3, 4] and rotation number [5], on the turbulent flow features inside the cooling channels.

The use of porous metal foam in blade cooling passages instead of ribs, is one promising and exciting alternative recently proposed. The reason for this approach is that the large surface area over a confined volume, greatly facilitates the transfer of thermal energy from the walls of the cooling passage to the coolant. Most research in internal cooling has emphasised the use of porous baffles in stationary passages. Hwang [6] studied turbulent fluid flow and heat transfer inside a channel with staggered porous baffles mounted along the top and the bottom walls. It was shown that the flow around the baffles was different than that for the solid baffles and flow reversal around the porous baffles disappeared, because some flow penetrates through the porous baffle. The thermal performance for the porous baffled channel was better than that for solid baffled channels at the same pumping power. Turbulent flow inside a rectangular channel with staggered porous baffles was numerically predicted by Yang and Hwang [7] and Li et al. [8]. A serpentine flow pattern was observed as the flow partly passed through the baffle and the flow reversal behind the solid baffle was not present. The friction factor for the porous baffles was lower than that for the solid baffles because of less channel blockage. Jeng et al. [9] used a flow visualisation technique to observe the characteristics of the fluid flow through a channel with a bend and with porous aluminium blocks inserted along the upper and the lower walls. It was noticed that the flow behaviour was affected by the arrangement of the foam blocks and that, due to the presence of the aluminium blocks in the bend section, there were no recirculating vortices in that region. Suga et al. [10] employed PIV to study experimentally the effects of the wall permeability on turbulent flow near a porous wall; experiments were performed in a channel with a porous bottom wall. It was observed that the flow becomes more turbulent over the porous wall and that as the permeability was increased, the normal to wall velocity fluctuation component was higher near the porous wall. Suga et al. [11] conducted measurements for turbulent flow over solid and porous square ribs mounted in a channel, whose bottom side was made of a porous layer. For the porous rib case,
the recirculation and the reattachment points were displaced and turbulence became weaker due to the flow penetration through the ribs.

In this study the focus is on the so far unexplored case of flows through rotating passages with porous blocks. Here experiments are carried out to investigate turbulent local flow characteristics through a serpentine cooling passage with a square-ended U-bend with porous metal foam blocks attached to the passage walls. Tests are performed for both stationary and rotating conditions. The main objectives of this study are to improve the understanding of the effects of porous metal foam on flow development in cooling passages in general and for the first time to explore the effects of orthogonal rotation. This is done by generating detailed local flow data, using Particle Image Velocimetry (PIV). Such data are also highly suitable for the validation of CFD codes and the development of suitable turbulence models.

2.0 EXPERIMENTAL SETUP

2.1 Experimental Apparatus

Figure 1 shows the rotating water rig which has been used in this study. The reason for using water as the working fluid is that due to the low kinematic viscosity, \( \nu \), of water compared to that of air, a high Reynolds number \( (Re = U_b D/\nu) \) can be achieved at lower velocities, and consequently the rotational speed required to produce a rotation number \( (Ro = \Omega D/U_b) \) value relevant to blade cooling applications is also lower than that for air. This in turn, enables the use of transparent materials, Acrylic, for instance, to build large-scale test sections which allow the use of particle image velocimetry for flow field measurements. The water rig consists of a rotor driving system and a water recirculation system. The rotor system consists of a motor-driven turntable mounted in a 1.22- m diameter water tank. The turntable can be driven by an A.C. motor driving a D.C. generator, which in turn drives a variable speed D.C. motor at any needed speed up to 250 rpm in positive and negative directions. In a closed loop water recirculation system, the water is driven by a pump (with an AC motor) through a strainer, then to an orifice plate (to measure the mass flow rate) through a horizontal pipe. The distance from the strainer to the orifice plate is 38 times the duct hydraulic diameter. To control the flow rate and to ensure fine flow adjustment, two valves (6” and 3”) are installed in parallel. The water then arrives through a vertical pipe and flows to the centre of the turntable through a settling chamber, then enters the test section mounted on the turntable. Finally, it discharges to the water tank through a bell mouth and returns to the pump.

Figure 1. Schematic diagram of rotating flow water rig.
2.2 Test Section and Conditions

A square-ended bend test section, as shown in Figure 2, has been made of 10 mm thick transparent acrylic (Perspex) and mounted on the turntable. The reason for using Perspex was the good optical access that allows detailed flow measurements to be performed. The total length of the test section is 768mm with a constant square cross-section of 50x50 mm. Two geometries have been tested; one with smooth walls and the other with porous metal foam blocks. Measurements have been taken at a Reynolds number of 36,000 and rotation numbers of 0 and 0.32. For the porous roughened case, the aluminium-foam blocks are used in this study with porosity (\(\phi\)) of 0.93, and its pore density is 2 PPC (pores per centimetre, supplied by ERG Materials and Aerospace Corporation. The porous blocks, height h=30 mm and thickness= 20mm, are attached to opposite walls in staggered configuration, whereas the block spacing \(S/D\) is fixed at 1.0.

2.3 Flow Field Measurements

The principal flow velocity measurements instrument to be used in this research is a Particle Image Velocimetry (PIV) system. The Dantec Dynamics PIV system consists of a double cavity Nd:YLF laser that provides maximum output energy of 15mJ with pulsed light sheets at a wavelength of 527nm. The system generates a light pulse of short duration and the time duration between pulses can be set according to the velocity range at different test planes. The light sheet thickness can be set by adjusting the distance between built-in lenses. The flow is seeded with small particle sized (\(= 5 \mu m\)) aluminium flakes. The small size of particles and their neutral density allows for accurate, high-resolution recording and enables the tracer particles to follow the flow correctly. The laser head was kept normal to the flow direction to enter the window on the side of the channel horizontally. Recording of the seeding images on double frames has been undertaken by using a high-speed camera (Phantom V310) running at 3250 frames per second at full resolution and a full screen at 1280 x 800 resolution using a Nikon AF Micro 60 f/2.8D lens. The camera is mounted on a traverse system above the test section.

The thickness of the laser sheet was approximately 1mm and the time delay between pulses of 200 \(\mu s\) depending on flow conditions. Data were obtained from 1000 to 2000 pairs of images related to measurement planes. The recorded images were processed by commercial software (DANTEC Dynamics, Dynamic Studio) using a cross-correlation algorithm to calculate the velocity field for a 32x32 pixels interrogation window size with 50% overlap to enhance the overall resolution. Each instantaneous image( 900x600 pixels) produced an instantaneous 79x49 vectors.
For the rotation cases, due to the fact that the laser could not be fired below 200Hz and the relatively low rotational speed (below 1Hz) of the channel in the current experiments, the PIV camera did not run at the external triggered mode. Instead it ran continuously at a higher repetitive rate of 1450Hz without synchronization with the rotation of the channel. Later, one pair of images per rotation was manually chosen at the same angular location to conduct PIV cross-correlation and generate velocity information. Roughly 100 image pairs were used to compute the statistics of the flow field. In the postprocessing, the movement caused by the rotation of the channel was removed by subtracting the mean velocity of channel at different radial positions from PIV results to produce averaged fluid flow field information.

The error of the PIV measurement is estimated according to the approach outlined in Westerweel [12], in which the error measured within a small displacement (0.1 pixel unit), is proportional to the displacement based on measurements of the particle image displacement. For the main flow along the symmetry plane, the magnification factor of 0.07 pix/m with a mean velocity of about 0.8 m/s. This indicated that the error of the instantaneous velocity is about 4.5% of the mean velocity. The uncertainty of the mass flow rate associated with the orifice plate is about 1%.

3.0 RESULTS AND DISCUSSION

3.1 Upstream and Downstream Passes

Figure 3 shows the mean velocity vector field for porous-type blocked channels. It indicates that the manner of the flow is serpentine in behaviour, guided by the staggered blocks and impinges on the side walls of the channel. When the fluid flows over the porous blocks, some of the fluid penetrates through them, and the rest is deflected around them. As mentioned in [11] and [7], the flow around the porous and solid type blocks is entirely different. The recirculation bubble present behind the solid-type either becomes weaker, or even disappears in the corresponding region of the porous-type blocks. This weakening or disappearance of the bubble depends on the properties of the porous metal foam (porosity and permeability) and the entry conditions of the fluid. Along each half of the duct, the flow accelerates as it passes through the gap between the near wall and the block on the wall opposite. The fluid then decelerates as it first approaches and passes through the porous block on the near side. Due to the staggering of the blocks, the flow along the opposite half of the duct undergoes the opposite changes at the same locations.

Figure 3. Measured mean velocity field along the symmetry plane of the first pass for porous blocks for $\phi = 0.93, S/D = 1, Re = 36,000$ and $Ro= 0$.

To study the development of the flow in the pass upstream of the bend, the measured profiles of the streamwise velocity for three positions (P1, P2 and P3) in each pair of blocks are presented in Figure 4. It can be seen that the velocity profile in the clear regions is smoother than that after the porous blocks. This is due to the random passes formed inside the porous metal foam blocks where the fluid passes through. For the three positions of measurements,
the velocity profiles for the third and the fourth pair of blocks are entirely similar, especially above the block. So it is concluded that the flow is periodically fully developed before the 4th pair of porous blocks. In the second half of the 5th pair region, the flow has started to accelerate due to the presence of the bend at the end of the first pass of the channel.

Figure 4. Streamwise velocity profiles along the upstream section.

Figure 5 shows the velocity vector field measured in the mid-plane of second pass, downstream of the bend, with metal foam blocks inserted. At the 8th pair of blocks, the levels of velocity are high due to the acceleration of the flow at the bend exit. The flow features are similar to those for the first pass, where the flow again follows a serpentine path, guided by the staggered blocks and the fluid accelerated and decelerated according to the location of the blocks. The flow at the 9th and the 10th pair of blocks reaches the stage where it becomes periodic. Finally, as the flow approaches the exit of the channel, it is accelerated at the second half of the last pair of the porous blocks.

Figure 5. Measured mean velocity field along the symmetry plane of the second pass for porous blocks for $\varphi = 0.93$, $S/D = 1$, $Re = 36,000$ and $Ro = 0$.

3.2 Bend Region

Figure 6 illustrates the flow field characterization in the bend region, for the case in which there are no porous blocks in the straight sections. As the flow approaches the bend, the flow impinges on the end wall generating two counter-rotating asymmetric vortices. This
asymmetry is due to minor flow perturbations in the upstream section being amplified inside the bend because of the instabilities of the flow caused by the corner separation bubbles. These vortices are developed due to the pressure gradient associated with the strong centrifugal forces in the bend. As the flow moves downwards toward the bend exit the two vortices appear to become more equal in size and strength. The results of present study agree well with the experimental data, measured by [13] and [5]. Figure 7 shows the flow field characterization in the bend region after inserting the porous blocks in the straight passages. It can be seen that the flow becomes more stable than that for the smooth channel. This is due to the presence of the porous blocks which on the one hand increase the levels of turbulence, and on the other hand generate a strongly non-symmetric distribution of the velocity of the fluid entering the bend region. As the flow approaches the bend, two counter-rotating asymmetric vortices are formed, the left side vortex is considerably larger than the right-hand side vortex. This is due to the location of the porous blocks in the entrance and the exit of the bend, where the flow is accelerated in the gap between the side wall and the blocks. Consequently the vortex that is dominant in size and strength at the bend entry, remains so until it disappears at the downstream end of the turn.

3.3 Periodic Flow Region

In this section, a detailed study of the flow features in the region of the straight upstream section where the flow reaches periodically repeating conditions is presented. The intention is to generate detailed mean flow and turbulence data, which can be used for the validation of CFD codes and the development of turbulence models. As established earlier, the flow is considered to have reached repeating conditions in the interval between the 4th pair of porous blocks.

Figure 8 shows the flow patterns around the porous blocks. It can be established that the flow decelerates as it approaches each block, and accelerates as it flows through the clear space between the top of each block and the opposite channel wall. The porous metal blocks allow the fluid to go through the cells of the structure and the behaviour of the flow behind these blocks is similar to that of jet flows which in turn removes the reverse flow that appears behind solid structures as found in [7] and [11]. From the velocity profiles in Figure 9, it can be seen that at each porous block the fluid going through it is slowed down and consequently most of the fluid is deflected over the top of each block and is strongly accelerated. There is still, however, sufficient fluid passing through the each block to prevent downstream flow separation. Because of the staggering of the blocks, the high momentum fluid continuously alternates its location from one side of the duct to the other.
Profiles of the velocity fluctuations streamwise and cross-duct directions and also of the Reynolds shear stress for both smooth and porous roughened channels are presented in Figures 10 to 12. Due to the alternating acceleration and deceleration flow pattern, the turbulence levels along the porous roughened channels are higher than those for the smooth channels, especially just upstream of each block, where the flow decelerates. However, the levels of turbulent intensities behind the blocks are lower than those infront of the blocks because of the damping effect of the blocks which severely reduce the size of the turbulent eddies. Generally, intensities in the cross-duct direction are weaker than the corresponding streamwise ones and the structure of turbulence of the flow behind the porous blocks seems to be anisotropic. Comparing with the earlier study done by Iacovided et al. [15], where the passages were roughened with square sectioned solid ribs, it is found that the levels of turbulence along the porous roughened channels are lower than those along the ribbed channels, especially over ribs, and near the wall downstream the rib, where the flow was separated. The distribution of the turbulent shear stress is shown in Figure 12. The higher levels of the shear stress occur at the interface region between the porous blocks and the fluid especially over the top of the blocks, where the penetrated fluid velocity is high and the mixing layer is increased. Low levels of Reynolds shear stress occur after 0.2D of each block where the turbulence levels are low due to the high permeability of the porous blocks and the consequent disappearance of the reverse flow there.

Figure 8. Measured mean velocity field along the symmetry plane of the 4th pair of porous blocks for $\varphi = 0.93, S/D = 1, Re = 36,000$ and $Ro = 0$.

Figure 9. Streamwise velocity profiles along the symmetry plane of the 4th pair of porous blocks for $\varphi = 0.93, S/D = 1, Re = 36,000$ and $Ro = 0$.

Figure 10. Comparison of streamwise turbulence intensity along the symmetry plane for the smooth and porous roughened channel with $\varphi = 0.93, S/D = 1, Re = 36,000$ and $Ro = 0$. 
Figure 11. Comparison of cross-duct turbulence intensity along the symmetry plane for the smooth and porous roughened channel with $\varphi = 0.93$, $S/D = 1$, $Re = 36,000$ and $Ro = 0$.

Figure 12. Comparison of Reynolds shear stress along the symmetry plane for the smooth and porous roughened channel with $\varphi = 0.93$, $S/D = 1$, $Re = 36,000$ and $Ro = 0$.

3.4 Effect of Rotation

Figures 13 and 14 show the vector field and the streamlines for the PIV flow measurements along the symmetry plane at the 4th pair of porous blocks region with a rotation number of $Ro = 0.32$. It can be seen that the flow is faster near the trailing side of the duct (pressure side), while along the leading side (suction side) the flow is slower. This is consistent with the presence of Coriolis-induced secondary motion, as explained by, among others, Iacovides and Launder [14], Iacovides et al. [15] and Iacovides [16], which, along the symmetry (in relation to the rotation axis) plane of the duct, transports the faster fluid to the trailing side. Orthogonal rotation, consequently forces more fluid to pass through the porous blocks attached to the trailing (pressure) side of the rotating duct. This is more clearly illustrated by the streamline plots of Figure 14.

4.0 Conclusions

Detailed mappings of the flow development has been obtained for a cooling passage of square cross-section consisting of two long straight sections connected by a tight square-ended U-bend. Rectangular blocks of Aluminium foam of porosity of 0.93 and pore density per cm of 2, are attached to two of the opposite walls of the straight sections in a staggered arrangement. Some initial indications of the effects of orthogonal rotation have also been provided. These data are suitable for CFD validation purposes, especially since the straight sections are long enough for the flow between successive blocks to become periodic. The resulting data also advance our understanding of flows through cooling passages with heat transfer enhancing porous blocks and for the first time reveal the effects of orthogonal rotation.
The main findings are:

1. The staggered porous blocks force fluid to take a meandering path through the straight sections with most of the fluid being deflected around the blocks. Enough fluid passes through blocks, however, to prevent downstream flow separation.
2. The presence of the porous blocks also raises overall turbulence levels, though these are not as high as the turbulence levels generated by solid ribs, and increases the anisotropy of the turbulence field.
3. In the bend region, the presence of the porous blocks upstream appears to stabilise the flow and to cause the development of one dominant vortex.
4. Orthogonal rotation, while not changing the overall character of the flow through the straight passages with porous blocks, it nevertheless forces more flow through the blocks on the pressure side of the rotating duct.

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