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DOI: 10.1016/j.expthermflusci.2021.110594

Document Version
Accepted author manuscript

Citation for published version (APA):

Published in:
Experimental Thermal and Fluid Science

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Effect of Porous Blocks on Flow Development through a Serpentine Cooling Passage under Stationary and Rotating Conditions

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Abstract

This study investigates how the inclusion of porous block influences the flow development in a serpentine passage, which consists of two straight square-sectioned ducts connected with a square-ended bend. Aluminium porous foam blocks have been attached to two opposite walls of the straight sections normal to the bend in a staggered manner, used as turbulence promoters. The investigation considers flows in the passage in stationary conditions, and in orthogonal rotation. Particle image velocimetry (PIV) is used to map out the flow development. The wall static pressure distribution along two sides of the passage (the leading and trailing under rotating conditions) is also provided. Tests are carried out at Reynolds numbers of 16,000, 26,000 and 36,000 and rotation numbers of 0.32 and 0.64. Preliminary tests, in a smooth (without porous blocks) passage of identical geometry, establish the reference conditions and enable the identification and quantification of the effects of the porous blocks on the flow development. PIV results show the meandering manner of the flow both upstream and downstream of the bend region, due to the presence of the porous blocks. Within the bend, in contrast to the case with a smooth upstream section, a single vortex dominates the flow. While rotation does not change the overall flow character, it does force more fluid through the blocks along the trailing (pressure) side of the duct. For both stationary and rotating conditions, the upstream section is long enough for the flow to become periodic over successive rib intervals, which produces very attractive data for CFD validation. These data include mean flow as well as second-moment profiles. The pressure coefficient is found to decrease linearly along the channel, due to the high blockage by the porous blocks. Rotation does not change the shape of the pressure coefficient profile but causes a greater reduction along the passage.
1. Introduction

Serpentine passages with sharp U-turns and turbulence-promoting ribs on opposite walls [1, 2] are widely used for the internal cooling of engine components, which can be either stationary or rotating. Over the past decade, many studies conducted experiments on the rotating serpentine passages and studied the effect of parameters such as the strong bend curvature [3, 4], and the rib-roughness and rotation [5, 8] on the turbulent flow and thermal developments.

The use of porous metal foams in serpentine 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. Also, porous blocks, while generating turbulence, cause a more moderated drop in pressure than solid blocks. Most research in introduction of porous material serpentine passages has emphasised the use of porous baffles in stationary passages. Hwang [9] 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. Jeng et al. [10] 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. [11] 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. [12] 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. Acoustic Doppler velocimetry ADV measurements obtained by Leu et al. [13] to investigate the turbulent flow in an open channel with the presence of porous structure mounted on the bottom wall. It was indicated that all the flow velocity, turbulent intensities and turbulent shear stress in the downstream direction were decreased with increasing porosity.
This was due to the decrease in the resistance of the porous material. These experimental studies have been instrumental in advancing understanding of flows through porous media but have all been confined to flows through stationary passages.

When it comes to the numerical modelling of such flows, turbulent flows inside rectangular channels with staggered porous baffles have been numerically predicted by Yang and Hwang [14], Li et al. [15] and Zhang et al. [16]. A meandering 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. It was also found that as the permeability increased much of the fluid passes through the baffles the recirculation bubbles become weaker and are shifted downstream. As also confirmed by a recent numerical study from the authors’ group, Al-Aabidy et al [17], the development of reliable RANS models for turbulent flow through passages with porous regions, depends on the availability of reliable local flow data. This means that to extend the effective use of RANS models to the prediction of cooling flows through rotating passages with porous regions, there is a need for local flow experimental data.

To address these knowledge gaps, this paper focuses on the rotational effects on flows through rotating passages with porous blocks. PIV measurements 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 for both stationary and rotating conditions. The main objectives of this study are to improve the understanding of the effects of porous metal foams on the flow development in cooling passages in general and, for the first time, to explore the effects of orthogonal rotation. Such data are believed to provide a useful reference for the validation of CFD codes and the development of suitable turbulence models. The effect of porous metal forms on the thermal development of the same channel flow with porous blocks will be published in another paper.

2. Experimental Apparatus and Data Processing

2.1 Test rig

The experimental facility which has been used in this study is shown in Figure 1. It is a rotating water flow facility, consisting 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 clockwise and anti-clockwise 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. 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 (\( \text{Re} = U_b D/\nu \)) can be achieved at lower velocities, and consequently the rotational speed required to produce rotation number (\( \text{Ro} = \Omega D/U_b \)) value relevant to those of 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. Since this study focuses on only the flow development, as long as it produces the appropriate values of the relevant dimensionless numbers (Reynolds and rotation) the resulting dimensionless flow field will be the same, irrespective of what the working is.

2.2 The Test Section

A square-ended U-bend test section, as shown in Figure 2, has been made of 10 mm thick transparent acrylic (Perspex) and mounted on the turntable. Such passage is often used as an idealised representation of the serpentine cooling passages in the middle part of the turbine blade, Fu et al [18]. The reasons for using Perspex are the good optical access that allows detailed flow and heat transfer measurements to be performed, and high thermal insulation due to its low thermal conductivity. The total length of the test section is 768mm with a constant square cross-section of 50×50 mm. Measurements have been obtained 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 (\( \varepsilon \)) of 0.93 and pore density of 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 a staggered configuration, whereas the block spacing \( S/D \) is fixed at 1.0. These dimensions result in an \( S/h \) ratio of 1.67 and \( h/D \) of 0.6. These values are not typical of cooling passages with solid ribs, but because porous ribs offer a lower resistance to the flow, they tend to occupy a greater proportion of the duct cross-section. In the investigation of Jeng et al [10] for example, \( S/h \) is about 2. In the subsequent measurement presentations, the origin of the coordinate system is set at the centre of the splitting plate tip. To treat the streamwise velocity (\( U \)) positive along the main-stream direction, the upstream of the turn is negative to zero in X-coordinates while the downstream is positive in X-coordinates.
As can also be seen in Figure 2, in this experimental setup, the axis of rotation is in the middle of the channel. Because this investigation focuses on isothermal (uniform density) flows, under rotating conditions, only the Coriolis force influences the flow development. Since the Coriolis force is independent of the distance from the axis of rotation, the location of the latter, while having an effect on the hydrostatic pressure, does not influence the flow field.

### 2.3 Instrumentation

A Dantec Dynamics PIV system is used in these measurements, which consists of a double cavity Nd:YLF laser, which provides maximum output energy of 15 mJ with pulsed light sheets at a wavelength of 527 nm. 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 thickness of the laser sheet was approximately 1 mm. The laser head was kept normal to the flow direction to enter the window on the side of the channel.

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 velocity field mapping is generated from the displacement of particles seeded into the flow. These particles should be small enough to follow the flow but large enough to generate bright light scattering for imaging. In addition, the density of the seeding particles should be close to that of the fluid so that the particles will not float to the top or sink down to bottom of the flow. Considering the need of seeding a relatively large volume of water, aluminium flakes with a nominal size of 5 μm are selected for the current PIV measurements. The size of these particles and their neutral density enable the trace particles to follow the flow correctly for accurate, high-resolution recording at a small interrogation area of PIV images. It is important to synchronise the laser pulses with the camera for the acquisition of the imaging in correct timing. Thus, Q-switch lased delay is used to control the light pulse emission after each laser trigger. The separation time between pulses (200 μs) is set to have the maximum mean displacement in the plane of interest with a minimum loss of particles out of the plane.

Data were obtained from 1000 to 2000 pairs of images related to measurement planes in order to obtain the averaged velocity field and the relevant statistics. The recorded images have been processed by commercial software (DANTEC Dynamics, Dynamic Studio) using the 2D cross-correlation algorithm to calculate the velocity field for the plane under investigation. The image
of the flow is divided into small areas called interrogation windows. The interrogation window of the first image should correlate its correspondent in the second image of the pair and show a correlation peak at the most likely displacement location of the particles in each interrogation window. The size of each interrogation window was 32x32 pixels with 50% overlap to enhance the overall resolution. Each instantaneous image (900×600 pixels) produced 79x49 instantaneous velocity vectors.

Obtaining PIV measurements for the rotation cases, with a stationary camera mounted outside the rotating platform, required further data processing, because 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. A new method proposed by Zhang et al [19] to de-rotate the PIV images before a standard cross-correlation process can be performed to produce PIV velocity vectors was performed in this study.

Pressure drop measurements across the test channel for both stationary and rotating conditions are individually measured at the isothermal conditions. A total of 12 pressure taps are located at intervals of 50 mm along both the upstream and downstream sidewalls, and on the turn, as shown in Figure 2. Several differential pressure transducers by Huba Control with a pressure range of 0 – 1000 mbar were connected to the taps and used to measure the differential pressure between the fluid and the atmospheric pressure. A dedicated data acquisition system has been assembled to transmit data from the pressure sensors to the PC remotely for both stationary and rotating tests. It consists of a microprocessor (raspberry pi 3B) connected to 16 analogue channels input card (Custard Pi 3A).

2.4 Static Pressure Data Reduction

The pressure drop measurements along the smooth and porous roughened ducts are performed under both stationary and rotating conditions. This section aims to present further calculations after the pressure measurements have been acquired. The voltages recorded by the pressure sensors are converted into absolute pressure values, using a linear function obtained from the sensors’ calibration process. The distributions of the local pressure drop along the locations of the pressure taps were normalized by the fluid dynamic pressure as:
where $P_x$ is the local pressure at a given location and $P_{in}$ is the reference pressure which is chosen at the inlet of the passage. The average inlet velocity $U_b$ is calculated using the duct mass flow rate measured from the orifice plate and $\rho$ is the density of water. As indicated in equation (1), for the rotational measurements, the hydrostatic pressure variation due to the centrifugal force has been removed, in order for $C_p$ to reduce the effects of viscous losses.

2.5 Experimental Uncertainty

The uncertainty in the PIV velocity includes contributions from the uncertainties in the magnification $M = 0.085\text{mm/pix}$, time separation $\Delta t$ and of displacement of the particles. Among them, the final item makes the dominant contribution in the overall uncertainty. Based on $U = 0.8\text{m/s}$ and $\Delta t = 200\mu\text{s}$, the displacement is 0.16 mm (about 1.9 pixels), the uncertainty in the camera domain displacement is about 0.05 pixels (2.6%). Following the uncertainty analysis of Kline and McLintock [20] the maximum uncertainty in the total velocity magnitude is found to be $\pm 0.02 \text{ m/s}$. This amounts to $\pm 5\%$, $\pm 3.4\%$ and $\pm 2.6 \%$ of the bulk velocity for Reynolds number values of 16000, 26000 and 36000 respectively.

According to ISO 5167-2 Orifice Plates, the uncertainty of the mass flow rate through the orifice plate is about 1% induced by the uncertainty of the direct measurements of pressure and temperature.

The differential pressure transducer by Huba Control has a tolerance of $\pm 0.1 \text{ mbar}$. For the range of the pressure drop in the channel, the uncertainty of pressure measurement is well below 0.5% for most measurements. The propagation of uncertainty of $C_p$ is dominated by that of the mass flow rate and is about 2%.

3 Results

3.1 Flow Development in Stationary Upstream Section

The effect of inserting porous blocks inside the first pass of the test section on turbulent flow is first examined. Figure 3a shows the mean velocity vector field in the upstream duct. It shows that the mean flow follows a meandering path, since most of the fluid is deflected around the
staggered porous blocks and only some of it penetrates through them. As mentioned in Suga et al. [12] and Yang and Hwang [14], the flow around the porous and solid type blocks is entirely different, to that observed around solid blocks. 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 then 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. Moreover, as evidenced by a) the direction of the velocity vectors over the top surface of each rib and b) the fact that the mass flow rate entering the upstream side of each rib seems to be higher than that leaving the downstream side, the flow within each porous rib is not one-dimensional and has a significant wall-normal component.

The contours of the normalized turbulent kinetic energy for flow around the porous blocks are shown in Figure 3b. High turbulent kinetic energy is generated, which corresponds to the flow’s meandering path, around the porous blocks, which in turn generates strong mean flow shear in the passage core, leading to strong generation of turbulence. Comparisons with the mean velocity vector plots of Figure 3a, confirm that the regions of higher turbulence levels around each block coincide with the locations of strong mean flow shear.

The difference in the magnitude of the turbulent kinetic energy and that of the turbulent shear stress shown in Figure 3c, is like that reported in the LDA study of Iacovides et al [5], for flows in cooling passages with solid ribs. The turbulent shear stress levels reported here are lower than those in passages with solid ribs, possibly because of the reduction in the turbulent length scales imposed by the porous blocks. The highest value of the turbulent shear stress is located at the front edge of the blocks due to the contribution of streamwise and wall-normal velocity gradients. As the flow approaches the bend, the turbulent shear stress starts to increase due to the increase in the turbulence levels there, because the bend entry generates a strong mean flow shear. The shear stress and turbulence intensity levels have similar magnitudes to those reported by Suga et al. [12].
3.2 Flow Development in Stationary Bend

Figure 4a illustrates the vortical structure of the flow in the bend region, for the “smooth” passage case, in which there are no porous blocks in the straight sections. Along the top wall at the upstream half of the turn, as the incoming flow impinges on the end wall and starts to turn downwards, a strong vortex is generated at one side of the bend, while at the opposite corner a counter-rotating vortex is beginning to form. As the flow moves downwards toward the middle of the bend, a second, weaker, vortex starts to grow. As a result, the planes at the middle of the bend and also at the middle of the second half of the turn, show evidence of the well-known two-vortex structure, caused by the bend centrifugal pressure gradient, though here it is highly asymmetric. As also found in an earlier experimental study, Iacovides et al. [4], flow in a square-ended U-bend tends to be highly unstable and minor perturbations in the upstream flow are sufficiently strong to cause non-symmetries within the bend. The results of the present study agree well with the experimental data, measured by Kelemenis [21] and Servouze et al. [8]. Figure 4b shows the flow field characterization in the bend region after inserting the porous blocks in the straight passages. The flow becomes more stable than that for the smooth channel. This is due to the fact that the presence of the porous blocks on the one hand increases the levels of turbulence, and on the other hand generates a strongly non-symmetric velocity distribution at the bend entry. Starting again from the top wall in the upstream half of the turn, one strong vortex is formed along the left side, which is the side with a porous block closest to the bend entry, with a very weak vortex appearing at the right side corner. This is due to the location of the porous blocks before the entrance and after the exit of the bend. Over the upstream half of the turn, because of the upstream porous block on the left side, the fluid is faster on the right side, then following impingement on the end wall, causes the strong vortex on the left side. Over the downstream turn half, the downstream porous block on the right side accelerates the fluid exiting the turn from the left side, thereby continuing to strengthen the dominant vortex on the left side.

Turbulent kinetic energy contours for the bend region are presented in Figure 5. In the straight upstream section, as also shown in Figure 3b, turbulence levels are generally lower than those in the turn, especially immediately after each porous block. The strong vorticity within the bend causes stronger generation rates of turbulence. A comparison with Figure 4b confirms that the regions of stronger vorticity coincide with the regions of higher turbulence.
3.3 Flow Development in Stationary Downstream Section

Figure 6a shows the average main flow velocities and the corresponding vector plots measured over the mid-plane of the second pass of the serpentine passage with metal foam blocks. Between the 8th pair of blocks, which is the first after the bend, the levels of velocity are high because of the bend, which seems to accelerate the flow along the mid-plane. The flow features are like those for the first pass with a meandering flow path, guided by the staggered blocks and the fluid accelerated and decelerated according to the location of the blocks. The flow between the 9th and the 10th pairs is starting to develop towards a periodic state. The distribution of the turbulent shear stress in the downstream section, shown in Figure 6c, tends to mirror that in the upstream section, which confirms that the porous blocks dominate the flow development. The effects of the bend are nevertheless still evident, with the overall levels of the uv component of the shear stress being higher over the block interval closest to the bend and then gradually coming down over each successive interval.

3.4 Flow Development in Rotating Upstream Section.

The effects of rotation on the mean velocity vector field for the upstream section of the rotating duct is presented in Figure 7a. The flow behaviour with rotation indicates a flow path similar to that for the stationary case, shown in Figure 3a, underlying the dominant influence of the porous blocks. A more detailed comparison between the flow along the trailing (pressure) and leading (suction) sides, shows that the high momentum regions along the trailing side have expanded, extending further across the duct, and those along the leading side have contracted, not extending as far into the duct as the corresponding high momentum regions along the trailing side. This also becomes apparent when the vector plots of Figure 7a (under rotating conditions) are compared with the corresponding plots of the stationary case, of Figure 3a. As was also the case with the rotating smooth duct, even with the presence of the porous blocks, the Coriolis effect (at Ro = 0.32) is strong enough to push the high momentum fluid towards the trailing (pressure) side. Figures 7b and 7c present the development of the turbulent kinetic energy and turbulent shear stress respectively, over the mid-plane of the upstream section, under rotating conditions. Comparison with the corresponding contour plots for stationary conditions, Figures 3b and 3c, shows that the turbulence field undergoes a similar development, which underlines the dominance of the porous blocks, but under rotating conditions overall turbulence levels are lower, which suggests that rotation has a stabilising effect.
3.5 Effects of Rotation on Flow Development in Bend Region

We begin the examination of the effects of the bend on the rotating flow, by first looking into the case of a rotating turn for the smooth passage, in the absence of porous blocks in the upstream and downstream sections, in Figure 8a. The streamlines reveal, in contrast to the two asymmetric vortices for the corresponding stationary case, a single curved spinning vortex, which starts along the leading side of the rotating passage in the upstream half of the turn and then moves towards the trailing side in the downstream half. This is due to the interaction between the Coriolis and the curvature forces, when the rotation and curvature axes are normal to each other. It was first observed by Iacovides et al. [4], who provide a more detailed explanation, and was subsequently reported in corresponding CFD simulations by Nikas and Iacovides [22]. The vortex starts near the leading edge and as the flow moves downwards, the vortex extends diagonally towards the trailing side. The location of the vortex is consistent with the Coriolis-induced secondary flow within the bend region. The streamlines of Figure 8b, show the effects of the inclusion of porous blocks in the upstream and downstream sections on the flow development in the rotating bend. The flow development within the bend shows stronger similarities with that of the stationary case with the porous blocks, rather than with the rotating case without any porous blocks in the straight sections. This comparison suggests that the effect of the porous blocks is the dominant one. Nevertheless, there is one notable difference between the rotating and stationary cases, namely that the single vortex which is normal to the 90° plane of the turn, while still close to the left (now also the leading) side, it is now displaced further upstream, at a greater distance from the end wall. The centre of the vortex in the case of flow through a smooth rotating passage, is also similarly displaced further away from the end wall. The probable cause is the transfer of high momentum fluid towards the trailing side, through the action of the Coriolis force. In general, the flow becomes more stable than that for the smooth channel, due to the increase in the levels of turbulence within the bend region.

Figure 9 shows the turbulent kinetic energy contours in the bend region for the rotating passage. As was also the case in the corresponding stationary comparisons of Figures 4b and 5, the rotating flow comparisons of Figures 8b and 9 also show that the regions of high turbulence levels coincide with the regions of strong vorticity. In the rotating bend, turbulence levels are generally lower than those in the stationary case. This is consistent with the comparisons in the upstream section. Rotation appears to stabilise the flow, by reducing large-scale instabilities and consequently turbulence levels.
3.6 Effects of Rotation on Flow Development in the Downstream Section.

The effects of rotation on the development of the mean flow along the second pass of the passage is shown in Figure 10a. The overall flow development is similar to that noted earlier for the stationary case in Figure 7, once again confirming the dominance of the porous blocks. There is nevertheless a noticeable effect of rotation, with the flow being faster along the trailing than along the leading side. This is consistent with the expected effects of the Coriolis force in a flow through an orthogonally rotating duct, as discussed by, among others, Iacovides and Launder [23]. As can be seen from the comparison between the turbulent shear stress contours in the downstream section for stationary and rotating conditions (Figures 6c and 10c respectively), the effects of rotation are even more noticeable on the turbulence field, where the high shear stress regions are pushed towards the trailing side.

3.7 Periodic Flow Region

To study the development of the flow in the section upstream of the bend, the measured profiles of the streamwise velocity at three positions (P1, P2 and P3) over each pair of blocks are presented in Figure 11. 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. At each of the three monitoring positions, the velocity profiles for the third and the fourth intervals between pairs of blocks are similar, especially above the block. It is consequently concluded that the flow is periodically fully developed by the fourth pair of porous blocks. In the second half of the fifth interval, the flow starts to accelerate, due to the presence of the bend at the end of the first pass of the channel. 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 provide detailed mean flow and turbulence data, which can be used for the validation of CFD codes and the development of turbulence models of flow through passages with porous regions. As established earlier, the flow is considered to have reached repeating conditions in the interval between the fourth pair of porous blocks. From the velocity profiles in Figure 12, it can be seen that as a consequence of the resistance that each block provides to the flow, there is a low momentum region downstream of each block, and, as some of the fluid is deflected around each block, a high momentum region across the gap between the top of each block and the opposite wall. There is still, however, enough fluid passing through 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. As also noted in earlier comparisons, for the rotating case, when the high velocity fluid switches to the trailing side, the high momentum region extends further into the duct. Profiles of the velocity fluctuations in the streamwise and cross-duct directions, and also of the turbulent shear stress, are presented in Figures 13 to 15, for both stationary and rotating conditions. As noted earlier, the staggered porous blocks lead to the meandering of the flow and high strain rates, which in turn cause the strong generation of turbulence. This is evident in the normal stress profiles of Figures 13 and 14. Turbulence levels are especially high over the top of each block and in the regions downstream of the gap between the top of each block and the opposite wall, where the mean velocity profiles of Figure 12 exhibit the strongest gradients. The profiles of the cross-duct normal turbulent stress in Figure 14, show generally lower levels than the corresponding profiles for the streamwise component in Figure 13. The difference in the levels of the two components is, not surprisingly, greater at the near-wall regions, where the wall damping is stronger for the wall-normal component. At the top surface of the porous block, on the other hand, which is parallel to the flow direction, both the streamwise and the cross-duct normal stresses reach high levels. Under rotating conditions, the levels of the turbulent normal stresses are consistently lower than those for the stationary case. As suggested earlier, rotation appears to have a stabilising effect on the flow. Comparing with the earlier study of Iacovides et al. [5], 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 downstream of each rib, where there is flow separation. The distribution of the turbulent shear stress is shown in Figure 15. The higher levels of the shear stress occur near the porous walls, especially over the top of the blocks, where there is a strong shear and non-zero velocity at the porous wall. Low levels of turbulent 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.

3.8 Pressure Distribution in the Smooth and Porous Blocked Ducts

The distribution of the wall static pressure is measured for this serpentine passage, with and without the porous blocks attached in the upstream and downstream sections, at three Reynolds numbers (16,000, 26,000 and 36,000) for the stationary and rotating conditions (Ro = 0, 0.32, 0.49, 0.65, 0.8 and 1.3). All results show the variation of the wall pressure coefficient $C_p$ with the axial distance $X/D$. The effects of both the Reynolds number and the Rotation number are presented.
The local pressure distribution along the stationary smooth channel is shown in Figure 16. Measurements are presented along only one of the two flat sides, since for a stationary passage the two sides are symmetric. The pressure coefficient distributions are similar for all Reynolds numbers. The pressure losses in the straight smooth sections are relatively low, with the dimensionless pressure loss decreasing with the Reynolds number. Within the bend, the pressure first shows a modest rise, most likely caused by the end-wall impingement, seen in Figure 4a, followed by a much stronger reduction at the bend exit, related to the presence of flow separation at the bend exit. After the bend, a modest pressure recovery is also noted, probably related to the flow re-attachment along the inner wall, downstream of the bend exit. It is also observed that the reduction in the pressure coefficient is stronger at the lower Reynolds numbers, due to the stronger influence of viscosity.

Figure 17 shows the static pressure distribution along the leading and trailing sides at three Reynolds numbers (16000, 26000 and 36000), for a smooth passage at a rotation number of 0.65. The pressure coefficient variation in the rotating cases has some similarities with that in the stationary ones, such as gentler distributions in the straight sections and stronger pressure drop across the bend, but there are also important differences. Under rotating conditions, the drops in pressure coefficient in the straight sections are stronger, which a) make the drops in pressure coefficient across the bend less dominant and b) lead to substantially greater overall reductions in pressure coefficient in comparison to the stationary cases. Again, effects are stronger at lower Reynolds numbers. The rotating flow pressure measurements also show that there is practically no difference between the leading and trailing side pressures in the upstream section, while downstream of the bend the pressure is higher along the leading side.

As shown in Figure 18, the inclusion of the porous blocks in the two straight sections increases pressure losses along these sections, and the overall drop in pressure coefficients, by an order of magnitude. Overall, the pressure coefficient decreases linearly along the channel, due to the high blockage by the porous blocks. Over the bend region, the decrease in the pressure coefficient is now a lot less significant in terms of the overall change over the entire passage. As also noted in the smooth passage comparisons, there is a small but noticeable increase in the drop in \( C_p \), as the Reynolds number is reduced.

The effect of rotation on the pressure distribution in a passage with porous blocks attached in the straight sections, is shown in Figure 19. The trend of the pressure distribution is similar to that for the stationary case with porous blocks attached, Figure 18, but with orthogonal rotation.
at $Ro = 0.65$ increasing the overall pressure loss by about 20%. The effects of rotation on pressure loss are consistent with the ones observed for the smooth passage.

Finally, Figure 20 compares the pressure variations along the sidewall of the ducts with and without porous blocks under rotation of $Ro=0.32$ for a Reynolds number of 36000. At this speed of rotation, the differences between leading and trailing edge pressure coefficients are negligible for the duct with porous blocks. The drops in pressure coefficients along the two straight paths, on the other hand, are quite substantial. For the duct without porous blocks, variations in pressure coefficient are not as strong and are confined to the bend and downstream sections.

4 Concluding Remarks

This experimental investigation has examined flow through cooling passages in which blocks of porous metallic foam are attached to the walls to enhance wall heat transfer. Particle Image Velocimetry has been used to map the flow field and a set of pressure taps has been used to monitor the wall static pressure.

For the stationary case, the resulting data show how the inclusion of the porous blocks in the straight sections dominates the flow development upstream of, within and downstream of the bend. The porous material used allows enough fluid to pass through to prevent flow separation downstream of each block, but also diverts sufficient fluid around each block to generate regions of high momentum in the gap between the top of each block and the opposite passage wall and regions of low momentum downstream of each block. The resulting strain field leads to the generation of turbulence levels far higher than those in a smooth duct, especially over the top of each block and in the region downstream of the gap between the top of the block and the duct wall. Comparisons with earlier studies also show that the measured turbulence levels are not as high as those reported in cooling passages with solid blocks. The staggered porous blocks in the straight sections also dominate the flow development within the turn, favouring the formation of a strong single vortex, while in the downstream section the flow development is largely similar to that upstream of the turn.

The influence of the porous blocks on the flow development is so dominant, that the main flow characteristics remain largely the same under rotating conditions, even at a rotation number as high as 0.64. There are nevertheless some noticeable effects of orthogonal rotation. For the mean flow, the regions of high momentum flow, which originate along the trailing side of the
rotating duct, extend further across the duct. For the turbulence field, orthogonal rotation is found to stabilise the flow, leading to generally lower levels of turbulence.

Moreover, it has been demonstrated that the upstream section is divided into enough repeating intervals, for flow conditions to eventually become periodic over successive rib intervals. The present study is thus able to provide profiles of the mean velocity and of two normal and one shear stress component of the Reynolds stress tensor, over a porous block interval for which the flow is periodic, under both stationary and rotating conditions. Such data are especially useful for the validation of physical models suitable for the simulation of turbulent flow through passages with porous regions.

The extensive set of wall static pressure measurements makes further contributions to our understanding of these phenomena and also to the calibration of turbulence models. Porous blocks increase the drop in pressure coefficient by more than an order of magnitude. While orthogonal rotation has a stronger effect on the pressure variation in passages with smooth walls, it also causes a modest increase in pressure loss for flow through rotating passages with porous blocks. In all cases (stationary, rotating, with and without porous blocks), as the Reynolds increases there is a gentle reduction in the dimensionless pressure drop.

In summary, this experimental study has provided data on the development of turbulent flow in stationary and, for the first time, also rotating cooling passages with porous blocks, which have advance current understanding over a range of conditions and which greatly facilitate the further development of reliable numerical models.

REFERENCES


Figure 1. The water Rotating Rig

Figure 2 The configuration of the test section with porous metal foam blocks
Figure 3. Contours on (a) Mean axial velocity (b) normalized turbulent kinetic energy (c) turbulent shear stress along the symmetry plane of the upstream pass for $Re = 36,000$ and $Ro= 0$. 
Figure 4. Streamlines and vorticity contours of flow within the bend for a passage with (a) smooth straight sections (b) porous blocks in the straight sections for $\text{Porosity}(\varepsilon)=0.93$, $S/D=1$, $Re=36,000$ and $Ro=0$

Figure 5. Normalised turbulent kinetic energy within the bend for a passage with porous blocks in the straight sections for $\text{Porosity}(\varepsilon) = 0.93$, $S/D = 1$, $Re = 36,000$ and $Ro=0$
Figure 6. (a) Mean velocity field (b) normalized turbulent kinetic energy (C) turbulent shear stress along the symmetry plane of the second pass for Porosity(ε)=0.93, S/D =1, Re = 36,000 and Ro= 0
Figure 7. (a) Measured mean velocity field (b) normalized turbulent kinetic energy (c) turbulent shear stress along the symmetry plane of the first pass for porous blocks for Porosity(ε)=0.93, S/D =1, Re = 36,000 and Ro = 0.32
Figure 8. Vortical structure of flow within the bend for a passage with (a) smooth straight sections (b) porous blocks in the straight sections for Porosity(ε) = 0.93, S/D =1, Re = 36,000 and Ro = 0.32

Figure 9. Normalised turbulent kinetic energy within the bend for a passage with porous blocks in the straight sections for Porosity(ε) = 0.93, S/D =1, Re = 36,000 and Ro = 0.32
Figure 10. (a) Measured mean velocity field (b) normalised turbulent kinetic energy (c) turbulent shear stress along the symmetry plane of the second pass for porous blocks for Porosity(ε) = 0.93, S/D =1, Re = 36,000 and Ro= 0.32
Figure 11. Streamwise velocity profiles over successive porous block intervals along the symmetry plane of the upstream of the turn at Re = 36,000 and Ro= 0.

Figure 12. Streamwise velocity profiles along the symmetry plane for the fourth porous block interval of the upstream section at Re = 36,000 and Ro= 0 or 0.32.
Figure 13. Comparison of streamwise turbulence intensity $v'/U_b$ along the symmetry plane for the fourth porous block interval of the upstream section at $Re = 36,000$ and $Ro = 0$ or $0.32$.

Figure 14. Comparison of cross-duct turbulence intensity $u'/U_b$ the symmetry for the porous block interval of the upstream section at $Re = 36,000$ and $Ro = 0$ or $0.32$. 
Figure 15. Comparison of turbulent shear stress along the symmetry plane for the fourth porous block interval of the upstream section, at Re = 36,000 and Ro= 0 or 0.32.
Figure 16 Static pressure variation along the sidewall of the smooth duct, at Re = 16,000, 26,000 and 36,000 and Ro = 0.

Figure 17 Static pressure variation along the sidewall of the smooth duct, at (a) Re = 16000, (b) Re = 26000 and (c) Re = 36000 for Ro = 0.65.
Figure 18 Static pressure variations along the sidewall of the ducts with porous blocks at Re = 16000, 26000 and 36000 and Ro = 0.

Figure 19 Static pressure variation along the sidewall of the ducts with porous blocks under rotation at Re = 16000, 26000 and 36000 and Ro = 0.65.

Figure 20 Static pressure variation along the sidewall of the ducts with and without porous blocks under rotation at Re = 36000 and Ro = 0.32.