Numerical Calculation of Internal Blade Cooling Using Porous Ribs

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ABSTRACT

The study of flow and heat transfer around and through porous ribs is promising in many industrial applications that require high cooling rates, such as gas turbine blade cooling, or require noise reduction. Turbulent flow in porous media is usually investigated by using macroscopic transport equations, which are obtained by applying double (both volume and Reynolds) averaging to the Navier-Stokes equations. In this study turbulence is represented by using the Launder-Sharma low-Reynolds number $k - \varepsilon$ turbulence model [1], which is modified via proposals by Nakayama and Kuwahara [2] and Pedras and de Lemos [3], for extra source terms in turbulent transport equations to account for the porous structure. Additional refinements are introduced to account for effects close to the porous media/clear fluid interface. In order to investigate the validity of the extended model, two types of porous channel flows have been considered, for which there is available DNS and experimental data. The first case is a fully developed turbulent porous channel flow, where the results are compared with DNS work conducted by Breugem et al. [4] and experimental work conducted by Suga et al. [5]. The second case is a turbulent porous rib channel flow to understand the behaviour of flow through and around the porous rib, which is validated against experimental work carried out by Suga et al. [6]. Cases are simulated covering a range of porous properties, such as permeability and porosity. Through the comparisons with the available data, it has been found that the extended model shows generally satisfactory accuracy, except for some predictive weaknesses in regions of either impingement or adverse pressure gradients.

Keywords: turbulence in porous media, interface porous-fluid region, turbulent flow around a porous rib.

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NOMENCLATURE

\( b \) Constant
\( c_F \) Forchheimer coefficient
\( c_{\epsilon 1}, c_{\epsilon 2}, c_k \) Non-dimensional turbulence model constant
\( c_{\mu} \) Coefficient in the eddy-viscosity
\( Da \) Darcy number, \( Da = K/H^2 \)
\( D_p \) Pore diameter
\( f_{\epsilon}^\phi, f_{k}^\phi, f_{\epsilon}^d \) Damping functions for source terms of porous media
\( H \) Channel height
\( h \) Rib height
\( G_k \) Generation rate of \( k \) due to porous media
\( G_{\epsilon} \) Generation rate of \( \epsilon \) due to porous media
\( K \) Permeability of porous media
\( k \) Turbulent kinetic energy
\( N_\phi \) Constant
\( P \) Pressure
\( P_k \) Production term
\( Re_b \) Bulk Reynolds number
\( R_t \) Turbulent Reynolds number
\( U_D \) Darcy or superficial velocity
\( U \) Velocity vector
\( \nabla V \) Total volume
\( \nabla V_f \) Fluid volume
\( y' \) Normal distance from the nearest porous surface

Greek Symbol

\( \epsilon \) dissipation rate of the turbulent kinetic energy, \( k \)
\( \nu \) kinematic viscosity
\( \nu_t \) kinematic turbulent viscosity
\( \phi_\infty \) Porosity of homogeneous porous media
\( \delta_{ij} \) Kronecker delta unit symbol
\( \varphi \) General quantity
\( \phi \) Porosity of inhomogeneous porous media (\( = V_f/V \))
\( \rho \) Fluid density

Acronyms/Abbreviations

\( DNS \) Direct Numerical Simulation
\( LES \) Larg Eddy Simulation
\( LSMPL \) Launder Sharma Modified by Pedras and de Lemos [7]
\( LSMNK \) Launder Sharma Modified by Nakayama and Kuwahara [2]
\( PPI \) Pore Per Inch
\( REV \) Representative Elementary Volume
\( RANS \) Reynolds-Averaged Navier-Stokes
\( SIMPLE \) Semi-Implicit Method for Pressure-Linkage Equations
\( TCL \) Two-Component-Limit
\( UMIST \) Upstream Monotonic Interpolation for Scalar
\( VAT \) Volume Averaging Theory
1.0 Introduction

To improve combustion efficiency, gas turbines are being designed to operate at increasingly higher temperatures. As a consequence, the air flowing over the blades can exceed the permissible temperature level of materials. Protecting gas turbine components and increasing thermal efficiency therefore require more efficient internal and external blade cooling strategies to meet the demands of the modern gas turbine applications. One of the more effective strategies in internal blade cooling is the use of roughened internal serpentine passages with ribs in different configurations, to increase the mixing of the flow that in turn enhances the blade cooling. As a result of the attractive thermal characteristics of metal foams in a variety of applications in industry, the use of porous metal foams within these passages has been investigated for turbine cooling applications [8, 9, 10, 11, 12].

The porous foams contain highly tortuous flow paths that can significantly intensify the mixing of fluid flow and enhance the heat transfer as a result of extensive surface areas that permit the fluid to be in contact with a large extended area. However, because of the complex flow paths, treating the flow through such media at the pore level requires huge computer power and cost, and even when possible it is limited to simple cases. As a result, the Volume Averaging Theory (VAT) is a common approach for the numerical modelling of flows in porous media [13, 14].

In many traditional engineering applications the flow in porous media is almost laminar, as a result of the small voids and high resistance that cause relatively low velocities [15]. Turbulence may become appreciable at the pore level, however, if the flow within or around the porous structure is at very high speed, or if the pore scale is larger than the turbulence length scale, i.e. when the pore Reynolds number \( Re_p \), defined as \( Re_p = u_p D_p / \nu \) where \( u_p \) is pore velocity scale (intrinsic velocity) and \( D_p \) is the pore diameter, is sufficiently high [16]. This is what was visualized by Dybbs and Edwards [17] who conducted an experimental investigation and found that the flow in the porous media became turbulent when the pore Reynolds number was greater than a few hundreds.

Numerical modelling of turbulent flow in porous media is mainly based on a macroscopic approach in which the double-averaging (volume and Reynolds averaging) is used. Macroscopic Navier-Stokes equations can be derived by two different methodologies: either using time-averaging of volume-averaged Navier-Stokes equations, or volume-averaging of Reynolds-averaged Navier-Stokes equations. Lee and Howell [18] and Getachew et al. [19] used the first methodology to obtain macroscopic \( k-\varepsilon \) transport equations for treating the turbulence in a porous media. However, since a highly porous medium was considered by Lee and Howell [18], no additional terms were included related to porosity in the turbulence equations. The second methodology, which is based on using the Reynolds averaging first, has been more widely used in dealing with turbulent flows, for example in the studies of Ma-suoka and Takatsu [20], Nakayama and Kuwahara [16], Finnigan [21], Pedras and de Lemos [3] and Nikora et al. [22].

Pedras and de Lemos [3] proved that the momentum equation is not affected by the order of averaging, although the two approaches do lead to different definitions of the turbulent kinetic energy. Nakayama and Kuwahara [16] believed that the Reynolds averaging should be performed first in order to detect the turbulence level at the porous scale, since this level of turbulence is unlikely be detected in the case of starting with volume averaging. The final forms of macroscopic turbulent transport equations obtained by Pedras and de Lemos [3] and Nakayama and Kuwahara [16] shared similar terms to those found for the non porous media, but also contained extra production and dissipation rate terms due to the presence of porous
Kuwata and Suga [23] used a sophisticated turbulence model for treating three unknown elementary second moment terms that appear in the Navier-Stokes equations after applying double (both volume and Reynolds) averaging. These terms are namely the dispersive covariance and the volume averaged Reynolds stress, which is decomposed into the macro-scale and micro-scale (sub-filter scale) Reynolds stress. The TCL (two-component-limit) second moment closure and a one-equation eddy viscosity model were used for modelling macro-scale and micro-scale Reynolds stresses, respectively, while the dispersive covariant was modelled via a form based on the Smagorinsky scheme typically used to represent sub-grid-scale stresses in Large Eddy Simulation (LES). In addition to this model they proposed an economical multi-scale $k-\varepsilon$ model for industrial applications. Mößner and Radespiel [24] used Reynolds averaging of volume-averaged Navier-Stokes equations, justifying its use in their study by showing good agreement with DNS data from Breugem et al. [4].

In this study, the double-decomposition technique has been used to model the flow through a porous media, with surrounding clear fluid. The Launder and Sharma low-Reynolds number $k-\varepsilon$ turbulence model [1] has been used, with modifications proposed by Nakayama and Kuwahara [2] and Pedras and de Lemos [3, 7] to mimic the flow inside the porous media. To improve predictions close to the clear fluid/porous media interface, additional damping terms are introduced to the porous source terms in this region, to relax the resistance of the porous media from the homogeneous porous region to the clear fluid zone across the distance of the mean pore diameter. These damping functions are modified forms of those proposed by Kuwata and Suga [23]. Results from the use of the current extended turbulence models are compared with DNS data by Breugem et al. [4] and experimental data by Suga et al. [5, 6] to validate the models.

2.0 Macroscopic Mathematical Formulation

2.1 Macroscopic Navier-Stokes Equations

The turbulent flow over porous walls or around porous blocks/ribs/baffles is described by the conventional RANS equations, while the flow through porous regions is described by the Brinkman-Forchheimer-extended Darcy model. This latter formulation accounts for viscous effects (Darcy term), form drag (Forchheimer term) and the Brinkman term (viscous diffusion), Vafai and Tien [25]. The continuity and mean momentum equations can be written as:

$$\frac{\partial U_{D_i}}{\partial x_i} = 0$$

$$\frac{\partial U_{D_i}}{\partial t} + \frac{\partial}{\partial x_j} \left( U_{D_j} U_{D_i} \right) = -\frac{1}{\rho} \frac{\partial \phi(P_f)}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \nu \left( \frac{\partial U_{D_i}}{\partial x_j} + \frac{\partial U_{D_j}}{\partial x_i} \right) - \phi \langle u_i u_j \rangle_f \right] -$$

$$f_U \sqrt{\nu K} U_{D_i} + c_F \phi \sqrt{K U_{D_i} U_{D_k}}$$

(2)

where the symbol $K$ is the permeability of the porous media, which is defined as a measure of the ability of the porous medium to permit fluid flow through it, and $c_F$ is the Forchheimer coefficient, $\phi(P_f)$ is the superficial average pressure of the fluid, and $\phi$ is the porosity of the porous media, which is defined as the pores' volume fraction. $K$, $c_F$ and $\phi$ are unique properties of the porous media. $U_{D_i} (= \phi(U_i))$ is the Darcy velocity which is superficial velocity. When the porosity and permeability are extremely high (and the porous matrix effectively disappears), the generalized model Equation 2 reverts to the traditions RANS equations. The relationship between the superficial $\langle \phi \rangle$ and intrinsic $\langle \phi \rangle_f$ property is $\langle \phi \rangle = \phi \langle \phi \rangle_f$. 
The macroscopic Reynolds stress tensor, $\phi(u_\ell u_\ell)\ell$, appearing in Equation 2 has been modelled in analogy with the Boussinesq concept for clear fluid (non-porous), as follows [7]:

$$
\phi(u_\ell u_\ell)\ell = -\nu_{\phi} \left( \frac{\partial U_{Dk}}{\partial x_j} + \frac{\partial U_{Dj}}{\partial x_i} \right) + \frac{2}{3} \phi(k)\ell \delta_{ij}
$$

(3)

where $\langle k \rangle\ell$ is the intrinsic turbulent kinetic energy, and $\nu_{\phi}$ is the macroscopic turbulent viscosity, modelled similarly to that in the clear fluid as:

$$
\nu_{\phi} = f_\mu C_{\mu} \frac{\langle k \rangle^2}{\langle \epsilon \rangle\ell}
$$

(4)

where $c_\mu$ is a constant with the usual value of 0.09 and $f_\mu$ a near-wall damping term, here taking the form proposed by Launder and Sharma [1] of $exp \left[ -3.4/ (1 + Re_\ell/50)^2 \right]$.

### 2.2 Macroscopic equations for $k$ and $\epsilon$

Nakayama and Kuwahara [16] and Pedras and de Lemos [3] conducted numerical experiments for turbulent flow through periodically arranged square rods and circular rods, respectively. The final forms they adopted for the macroscopic turbulent kinetic energy and its dissipation rate equations, after applying the volume-averaging operator for microscopic $k - \epsilon$ equations inside a Representative Elementary Volume REV, can be written as follows:

$$
\frac{\partial \phi(k)\ell}{\partial t} + \frac{\partial \left( U_{Dj} \langle k \rangle\ell \right)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu_\phi \frac{\partial \phi(k)\ell}{\partial x_j} \right] + P_k + f_1^2 G_k - \phi(\epsilon)\ell
$$

(5)

$$
\frac{\partial \langle \epsilon \rangle\ell}{\partial t} + \frac{\partial \left( U_{Dj} \langle \epsilon \rangle\ell \right)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu_\phi \frac{\partial \langle \epsilon \rangle\ell}{\partial x_j} \right] + c_{\epsilon f} f_1 \frac{\langle \epsilon \rangle\ell}{\langle k \rangle\ell} P_k + c_{\epsilon \Delta} \left[ f_2 \sqrt{\nu_{\phi}} G_\epsilon - f_2 \frac{\langle \epsilon \rangle\ell}{\langle k \rangle\ell} \right] \langle \epsilon \rangle\ell
$$

(6)

where $P_k = -\phi(u_\ell u_\ell)\ell \frac{\partial u_\ell}{\partial x_j}$ is defined as the production rate of $\langle k \rangle\ell$, $f_1$ and $f_2$ are viscous damping terms for low-Reynolds-number $k - \epsilon$ Launder and Sharma [1] model, and they are, respectively, 1.0 and 1.0 - 0.3 exp(-$Re_\ell^2$). $G_k$ and $G_\epsilon$ represent respectively the extra generation rate of $\langle k \rangle\ell$ and the extra production rate of $\langle \epsilon \rangle\ell$ due to the presence of the porous media. These extra source terms were derived in different forms in the two studies, as shown in the Table 1 where $c_k$ and $c_D$ are constants equal to 0.28 and 0.09 respectively, and $b = c_F/\sqrt{K}$.

### Table 1:

<table>
<thead>
<tr>
<th></th>
<th>$G_k$</th>
<th>$G_\epsilon$</th>
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</thead>
<tbody>
<tr>
<td>Pedras and de Lemos</td>
<td>$c_k \sqrt{U_{Dk} U_{Dk}}$</td>
<td>$c_k \sqrt{U_{Dk} U_{Dk}}$</td>
</tr>
<tr>
<td>Nakayama and Kuwahara</td>
<td>$b (U_{Dk} U_{Dk})^{3/2}$</td>
<td>$b \sqrt{c_F/2K} (U_{Dk} U_{Dk})^2$</td>
</tr>
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</table>
2.3 Modification for Porous-Fluid Interface Regions

The equations introduced in the previous section are valid for the porous media, whilst in the clear fluid region the additional terms in the momentum and turbulence terms clearly vanish. However, the additional terms are based on spatially uniform porous media properties, whilst there will be a thin layer at its interface with the clear fluid where the effective porosity will increase as the clear fluid region is approached. This is accounted for in the present model by relaxing the porosity and additional source terms in the macroscopic Reynolds averaged Navier-Stokes equations across a thin transitional layer at the edge of the porous region. The porosity across this layer is taken as:

\[ \phi = \phi_\infty + (1 - \phi_\infty) \exp \left(-N_\phi y'/D_p\right) \]  

(7)

where \( \phi_\infty \) is the porosity of the homogeneous porous media and \( y' \) is the normal distance from the nearest porous surface. The coefficient \( N_\phi \), which is taken as 4, is chosen so that the porosity varies within the distance of the mean pore diameter \( D_p \). The drag terms, in the momentum Equation 2, and other additional terms in the turbulence transport Equations 5 & 6, are respectively multiplied by the following functions:

\[ f_{\phi U} = 1 - \exp\left(-1.03 \left(y'/\max\left(0.004, \sqrt{K}\right)\right)^{1/2}\right) \]  

(8a)

\[ f_{\phi k} = 1 - \exp\left(-1.21 \left(y'/\max\left(0.004, \sqrt{K}\right)\right)^{5/2}\right) \]  

(8b)

\[ f_{\phi \varepsilon} = 1 - \exp\left(-\left(1.0 + R_t/58.51\right) \left(y'/\max\left(0.004, \sqrt{K}\right)\right)^2\right) \]  

(8c)

where \( R_t = (\phi k^2) / (\nu \phi \varepsilon) \) is the turbulent Reynolds number. These functions are modified forms of those suggested by Kuwata and Suga [6], re-optimized for use within the present \( k - \varepsilon \) framework, and also designed to vary between 0 and 1 within the distance of the mean pore diameter to relax the effect of porous resistance from the homogeneous porous region to the homogeneous clear fluid region.

3.0 Results and Discussions

The calculations presented in this study have been carried out by using an in-house finite volume code STREAM developed in Manchester by Lien and Leschziner [26]. It employs a non-orthogonal and body-fitted grid system in which all transported properties are stored in a fully collocated manner. The SIMPLE pressure-correction algorithm of Patankar and Spalding [27] is used to evaluate the pressure field in addition to Rhie and Chow interpolation [28] to avoid pressure oscillations. Advection volume-face fluxes are approximated using the second order-accurate UMIST scheme [29]. Results are presented from the use of the current extended turbulence models, referred to as LSMNK in case of that based on the Nakayama and Kuwahara turbulence model [2] and LSMPL in case of that based on the Pedras and de Lemos model [3, 7].

3.1 Turbulent Porous Channel Flows

The case considered is that of a fully developed plane channel flow over a porous media, which was examined using DNS by Breugem et al. [4] and experimentally by Suga et al. [5]. Such flows are encountered in a wide range of engineering and environmental problems such as metal foam heat exchangers, catalytic converters, flows in oil wells, flows over forests and porous river beds.
Figure 1 shows the channel geometry, with a solid top wall and a permeable lower layer. The total channel height is H, and the bottom impermeable wall covered by a porous layer of half the channel height. Simulations have been performed covering a range of porosity, permeability and Reynolds numbers, matching the available DNS and experimental data. Due to space limitation reasons, only a selection will be presented here, with the results below concentrating on three cases: the DNS study at $Re_b = 5500$ with porosity $\phi = 95\%$, $c_F = 0.295$, $Da = 4.75 \times 10^{-5}$ and $D_p/H = 0.011$, the experimental studies are at $Re_b = 5259$ and $Re_b = 10200$ with porosity $\phi = 81\%$, $c_F = 0.1$, $Da = 9.93 \times 10^{-6}$ and $D_p/H = 0.048$, where Da is the dimensionless permeability. For simplicity, in these cases, the porosity and Reynolds number are used to distinguish them, and they will be referred to below as E95, E81L and E81H, respectively.

For illustration, Figures 2a and 3a show the mean streamwise velocity across both porous layer and fluid region, normalized by bulk velocity in the clear channel for the lower Reynolds number cases E95 and E81L. Figures 2b & 3b and 2c & 3c show corresponding profiles of turbulent kinetic energy and Reynolds shear stress, normalized by friction velocity $U_\tau$ at the (impermeable) top wall for both cases. Since fluid, and some turbulence structures, can penetrate across the porous boundary, there is less of a wall-blocking effect there (particularly on the wall-normal velocity component) than would be found at a solid wall. As a result, Suga et al. [5] noted that the flow becomes turbulent at a lower Reynolds number than would be expected in a clear plane channel.

As can also be seen in Figures 2 and 3, the measurements show higher turbulence levels in the clear fluid near the porous interface than near the solid wall, with the peak levels increasing as the porosity increases, together with a highly asymmetric mean velocity across the clear fluid part of the channel. These features can be explained by noting that, since the flow is fully developed the momentum equation implies that the total shear stress must increase linearly across the clear fluid part of the channel (as it would for a purely clear fluid channel flow), and the results show the turbulent shear stress doing so across the core region. Clearly, the mean velocity and turbulent shear stress must both fall to zero at the solid wall, however, they do not do so at the porous interface. Consequently, there is not a rapid growth of viscous shear stress as the interface is approached, and the velocity gradient here is lower than near the solid wall, leading to the asymmetric profile seen in the data.

Considering first the predictions of the higher porosity case 2, the original form of the Pedras and de Lemos [3] model (without the near-interface damping terms described in Section 2.3) clearly returns too high levels of turbulence around the porous/clear fluid interface, with consequent high levels extending out into both regions. The addition of the proposed near-interface damping terms brings the predicted levels down to closely match the DNS data. Although not shown, the additional terms have a similar effect when incorporated within the Nakayama and Kuwahara [2] model, and the modified form again shows good agreement with the DNS data.

A similar level of agreement to that shown above was found from both modified model forms in most of the other cases examined. However, when the porosity (and permeability) was reduced in the case E81L, as in Figure 3, the LSMPL scheme does produce a reduction in turbulence levels near the interface, again broadly matching the data. The LSMNK model,
on the other hand, predicts a significant increase and overprediction of near-interface turbulence levels, resulting in a more asymmetric mean velocity profile, as seen in Figure 3a. In attempting to understand this discrepancy in LSMNK model behaviour, it is worth noting that the results shown are at fairly low bulk Reynolds numbers; simulations at higher Reynolds
numbers and similar porosity (and permeability) levels gave quite close agreement between both models and available data. An example of this can be seen in Figure 4, where LSMNK
model does generally produce better predictions than in the lower bulk Reynolds number case $E81L$. The cause of the difference in model behaviour at low Reynolds numbers would appear to lie in the forms adopted for the modelled source terms $G_k$ and $G_\varepsilon$. Based on arguments of how terms in the turbulent kinetic energy equation should scale, Nakayama and Kuwahara [2] formulated their additional source terms to depend primarily on the mean Darcy velocity, whereas the forms proposed by Pedras and de Lemos [3] are dependent on both the Darcy velocity and the local turbulent kinetic energy and its dissipation rate levels. From the results here, it would appear that the latter responds better to the flow changes seen as permeability (or porosity) is decreased at quite low Reynolds numbers, whereas the former shows too great a sensitivity to the permeability (or porosity).

### 3.2 Turbulent Porous Rib Channel Flows

As a further test of the present models, flow along a channel again half-filled with a porous layer, but now with a porous square rib, of half the clear channel height, mounted on top of this layer, as shown in Figure 5, has been considered. The porous layer and rib are made of the same material, and fluid can both penetrate through the rib, and by-pass through the layer underneath it, as a result of the low pressure behind the rib. Such flows can be encountered in the chip cooling of electronic packages and vegetative canopies. The two cases considered have been studied experimentally by Suga et al.[6] and numerically by Kuwata et al. [30]. The first is at $Re_b = 9800$ with $PPI = 20$, $\phi = 82\%$, $c_F = 0.17$, $Da = 6.2 \times 10^{-4}$ and $D_p/H = 0.03$, whilst, the second is at $Re_b = 10600$ with $PPI = 6$, $\phi = 80\%$, $c_F = 0.095$, $Da = 2.6 \times 10^{-5}$ and $D_p/H = 0.065$, where $PPI$ denotes Pores Per Inch and is used to characterize the permeability of porous meal foams. Because the two cases have almost the same porosity, $PPI$ (characterising, but inverse to, permeability) is used to distinguish them, denoting as Case #20 and Case #6 the former and latter cases, respectively.

To ensure sufficient upstream and downstream flow development lengths, the computational domain extends from 12$h$ upstream of the porous rib to 51$h$ downstream of the rib. Fully developed flow profiles (from a separate calculation) are imposed at the inlet, with zero streamwise gradients applied at the outlet, and no-slip conditions at the impermeable walls. A block-structured grid of around $275(x) \times 240(y)$ cells was used, with grid nodes concentrated towards the porous-fluid interfaces and solid wall. Tests with more refined grids confirmed the distribution adopted to be sufficient.

Streamlines from LSMPL model predictions of flow over and through the porous rib mounted on the porous layer are shown in the Figure 6. Figures 7a and 8a show predicted profiles of the mean streamwise velocity, turbulent kinetic energy and Reynolds shear stress for the flow within and around the porous rib with low and high permeability, Case #20 and Case #6 respectively, compared with the experimental measurements carried out by Suga et al.[6]. From Figure 6 it can be clearly seen that, due to the resistance of the porous rib, some of the flow is directed towards the upper wall. However, the permeability of the rib and lower channel layer permit a certain amount of fluid to pass through them (not surprisingly, to a greater extent as the permeability is increased), and some of that through the latter subsequently bleeds back into the clear fluid layer behind the rib. As a result of the fluid travelling through and under the rib, little or no flow separation and recirculation is in the clear fluid immediately behind the rib in these cases.

Although there is now no significant flow separation immediately behind the rib, the fluid seeping back into the clear fluid region downstream of the rib does result in an adverse pressure gradient in the porous layer, which together with the fluid being entrained into the clear fluid.
region leads to a weakly recirculating area (starting at around \( x/h = 5 \) in the lower permeability *Case #20*). As the permeability increases (*Case #6*), the fluid bleeds back into the clear channel more slowly and the recirculation within the porous region is weaker and occurs further downstream. Such a feature was also deduced to be present by Suga et al. \(^6\) from analysing their measured mass flow rates in the clear fluid and the streamwise pressure variation.

![Streamlines of Case #20](image1)

![Streamlines of Case #6](image2)

Figure 6: Streamlines of flow over and through a porous rib-mounted porous layer layer with different permeabilities, as predicted by the LSMPL model. Note that non-uniform stream-function step sizes are displayed, in order to make the distribution within the porous media visible.

The vertical distributions of turbulent kinetic energy and turbulent shear stress normalized by the bulk velocity are shown in Figures 7b & 7c and 8b & 8c, it can be seen that high levels of turbulent kinetic energy generally occur close to the upstream edge of the porous rib, and then in the shear layers downstream, corresponding to the regions where the mean strains will result in significant turbulence generation.

In the low permeability case, *Case #20*, Figure 7, the predicted turbulence profiles are generally in satisfactory agreement with the measured data, although rather too high levels of turbulent kinetic energy are predicted by both models ahead of, and around, the rib (slightly more so by the LSMPL variant). Since it is well-known that the Launder-Sharma model (and most other linear EVMs) tend to overpredict turbulence levels in normally strained and impingement flow regions, the high levels of predicted turbulent kinetic energy just ahead of, and around, the rib are perhaps not unexpected. The higher levels predicted by the LSMPL variant within, and immediately beneath, the rib are then a result of that model’s porous source terms depending on the (already high) turbulence levels, whereas the LSMNK schemes source terms depend purely on the mean Darcy velocity, as noted earlier. Further downstream of the rib, both models tend to slightly underpredict the peak turbulent kinetic energy levels in the clear fluid region, although peak shear stress levels are slightly overpredicted. The LSMPL model does also rather overpredict turbulence levels around the interface between porous and clear fluid regions between \( 5 < x/h < 8 \), and returns higher turbulence levels than the LSMNK variant within the porous media here. This region corresponds to the area
Figure 7: Comparison between the current predictions for the low permeability Case #20 and the Experimental data [6] for turbulent porous rib channel flows. Red lines represent LSMPL model, broken black lines represent LSMNK model and symbols represent Experimental data.
Figure 8: Comparison between the current predictions for the high permeability Case #6 and the Experimental data [6]. Red lines represent LSMPL model for turbulent porous rib channel flows, broken black lines represent LSMNK model and symbols represent Experimental data.
of flow recirculation seen in Figure 6 as a result of the fairly weak, though non-negligible, adverse pressure gradient in this region, as fluid bleeds from the porous media back into the clear flow stream. The same mechanisms as above can then lead to a slight overprediction of turbulence levels by linear EVMs, with the LSMPL scheme magnifying this effect because of its additional source terms being directly dependent on $k$ and $\varepsilon$.

For the higher permeability case, Case #6, Figure 8, the agreement in the turbulent quantities is generally satisfactory. The much weaker impingement around the rib in this case means that turbulence levels are not so overpredicted here (although the LSMPL variant does again produce higher turbulent kinetic energy levels than the LSMNK version within the rib, for the same reasons as noted above). The profiles downstream of the rib are also generally better captured than in the lower porosity case and the weaker recirculation in the porous region, which now occurs further downstream at around $x/h = 8$, does not result in a noticeable increase in turbulence levels here.

4.0 Conclusions

Two different modifications of the Launder-Sharma model, those proposed by Nakayama and Kuwahara [2] and Pedras and de Lemos [7] have been tested, representing widely-used schemes for turbulent flow in porous media applications. These have been combined with re-optimised forms of near-interface damping terms for the modelled porous source terms, which have been shown to improve significantly the predictions around the porous/clear fluid interface region. The results of the turbulent porous channel flows show that the prediction accuracy of both modified models is generally satisfactory, although at low Reynolds number and low permeability the LSMNK results become poorer, with turbulence levels quite significantly overpredicted. In the porous rib channel flows the prediction are generally satisfactory, especially in the higher permeability case. In the lower permeability case both models tend to overpredict turbulence levels around the impingement region at the front of the porous rib, as a result of the underlying weakness in the linear eddy-viscosity formulation in such flows. The form of the modelled porous source terms then leads to the LSMPL scheme returning higher turbulence levels within and beneath the rib than the LSMNK model. The LSMPL scheme also predicts higher near interface turbulence levels further downstream, where a weak recirculation occurs, for similar reasons.

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