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Computational Modelling of the Flow and Heat Transfer in Dimpled Channels

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ABSTRACT

The flow and heat transfer characteristics over a single dimple and an array of staggered dimples have been investigated using the Reynolds Averaged Navier-Stokes (RANS) approach. The objective is to determine how reliably RANS models can predict this type of complex cooling flows. Three classes of low-Reynolds number RANS models have been employed to represent the turbulence. These included a linear eddy viscosity model (EVM), a non-linear model (NLEVM) and a Reynolds Stress transport model (RSM). Variants of the $k$-$\varepsilon$ model have been used to represent the first two categories. Steady and time-dependent simulations have been carried out at a bulk Reynolds number of around 5000 with dimple print diameter to channel height ratios of $D/H = 1.0, 2.0$ and ratios of dimple depth to channel height of $\delta/H = 0.2, 0.4$. The linear EVM and the RSM tested both produce symmetric circulations in the dimples, while the NLEVM produces an asymmetric pattern. The mean velocity profiles predicted numerically are generally in good agreement with the data. The main flow characteristics are reproduced by the RANS models, but some predictive deviations from available data point to the need for further investigations. All models report an overall enhancement in heat transfer levels when using dimples in comparison to those of a plane channel.

Keywords: Turbine Blade cooling — Dimples — Turbulence Modelling — RANS

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1.0 Introduction

Gas Turbines are widely used for power generation, aircraft propulsion and various other industrial applications. As the emissions regulations become more stringent, the need for optimized, highly efficient, gas turbine systems becomes more pressing.

The thermal efficiency of gas turbines can be improved by increasing the inlet-to-outlet temperature ratio over the turbine section. However, higher turbine inlet temperatures will also increase heat transfer to the blades and might severely reduce the blade material durability. In reality, turbines operate at temperatures far above those allowed by the blade metal. This has been made possible by using sophisticated cooling techniques to ensure that blade temperatures do not exceed the metal limits, while using as little coolant as possible. Many research efforts in blade cooling thus focus on refining these techniques to allow even higher turbine inlet temperatures\(^1\).

In the context of these efforts, spherical concavities, or dimples, have received increased attention in the past decade as a way of providing a reasonable heat transfer enhancement for a relatively low pressure loss. Dimples enhance heat transfer by aiding large-scale mixing
and breaking the boundary layer development, due to flow separation and reattachment in the cavity and the formation of vortex cells within the dimple.

Kwon et al.\(^{(2)}\) studied, using the naphthalene sublimation technique, the heat/mass transfer over a single dimple in a channel with dimple depth-to-channel height ratio range of \(\delta/H = 0.2 - 0.4\) and for a range of Reynolds numbers, \(Re_H = 500 - 5000\), covering the laminar, transitional and turbulent flow regimes. They used flow visualisation to analyse the flow structures present in the laminar regime, and reported that the main flow separates over the dimple upstream edge and then impinges on the rear rim of the cavity. Following the impingement, the flow splits into two parts, one of which continues moving downstream while the other recirculates upstream along the dimple curvature. The recirculating flow creates a pair of symmetric vortex cells that fill the dimple, which are periodically ejected and re-formed, producing an unsteady cycle of vortex formation, growth and shedding. In the turbulent regime the authors reported that the heat transfer enhancement increased with dimple depth \(\delta\).

In a series of studies, Isaev et al.\(^{(3,4,5,6,7)}\) performed RANS-based simulations of turbulent flow over a single dimple, reporting that heat transfer enhancement increased slowly, almost linearly with Reynolds number, and also increased with dimple depth. For dimple depths below \(\delta/H = 0.62\) (corresponding to \(\delta/D \sim 0.2\)), they reported the existence of a steady double vortex cell structure within the dimple, although for deeper dimples the flow patterns deviated from this in favour of an asymmetric, mono-core vortex cell inclined by \(\pm 45^\circ\) to the flow direction. The existence of asymmetric structures over deep dimples was also reported in a Large Eddy Simulation (LES) by Kornev et al.\(^{(8)}\). They found, in a series of short-term time averaged flow field snapshots, that the vortex structure switched direction periodically between \(-45^\circ\) and \(+45^\circ\). Thus, contrary to URANS of Isaev et al.\(^{(7)}\), the long-term time averaged flow field was nearly symmetric. This conclusion was later confirmed in an experimental study by Voskoboinick et al.\(^{(9)}\).

For the case of a staggered array of dimples, Lin et al.\(^{(10)}\) studied the flow structure using the RANS approach. They identified two ways for the two dimple vortices to convect downstream, a zigzag flow pattern from one cavity to another over the surface, or a jet-like burst from the downstream part of the dimple. These flow patterns were also observed in the Direct Numerical Simulation (DNS) reported by Wang et al.\(^{(11)}\).

Mahmood et al.\(^{(12)}\) conducted an experiment to investigate the heat transfer characteristics over such surfaces for a range of Reynolds numbers. They found that the overall heat transfer enhancement level was fairly independent of Reynolds number. However, as \(Re\) increased the separation area within the dimple decreased, thus shifting the local heat transfer minimum upstream.

Ligrani et al.\(^{(13)}\) found that with increasing Reynolds number, the secondary vortices, at the dimple span-wise edge, stretch farther away from the dimple edge, and thus, are convected to the neighbouring dimples on the diagonal just downstream.

The effect of channel height \((H)\) on heat transfer was investigated by Mahmood and Ligrani\(^{(14)}\). They argued that decreasing \(H\) leads to stronger vortices over the dimples which in turn enhances heat transfer augmentation. However, an earlier study by Moon et al.\(^{(15)}\) found that the normalised Nusselt number and friction factors were relatively independent of channel height.

Burgess et al.\(^{(16)}\) and Burgess and Ligrani\(^{(17)}\) reported, in experimental studies, that increasing dimple depth in an array also creates stronger and intensified vortices, leading to an enhancement in relative heat transfer (i.e. relative to that of a flat plate). However, the friction
<table>
<thead>
<tr>
<th>Case</th>
<th>Domain Type</th>
<th>$\delta/H$</th>
<th>$D/H$</th>
<th>$P/H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>case1</td>
<td>Single dimple</td>
<td>0.4</td>
<td>2.0</td>
<td>N/A</td>
</tr>
<tr>
<td>case2</td>
<td>Dimple Array</td>
<td>0.2</td>
<td>1.0</td>
<td>$\pi/2$</td>
</tr>
</tbody>
</table>

Table 1: Summary of the non-dimensional geometry cases.

<table>
<thead>
<tr>
<th>Modelling Class</th>
<th>Tested Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVM</td>
<td>Launder and Sharma(^{19}) $k$-$\varepsilon$</td>
</tr>
<tr>
<td>NLEVM</td>
<td>Craft et al.(^{21}) cubic $k$-$\varepsilon$</td>
</tr>
<tr>
<td>RSM</td>
<td>Hanjalić and Jakirlić(^{22})</td>
</tr>
</tbody>
</table>

Table 2: Tested models and their modelling classes.

...factor will also increase, creating more pressure losses. Won and Ligrani\(^{18}\) confirmed these conclusion in a RANS simulation.

The present study uses the RANS approach to model the flow and heat transfer over a single dimple and a staggered array of dimples. While the overwhelming majority of the previous RANS studies do not go beyond the linear eddy viscosity modelling approach, the current investigation uses three classes of low-Reynolds-number RANS models to represent the turbulence. The aim is to build on the previous knowledge through exploring to what extent each modelling approach can accurately reproduce the reported flow and heat transfer behaviours. Two cases have been considered in the present work. These include the study of a single dimple and a dimple array on one wall in a channel. A summary of the most important dimple and channel geometry factors is given in Table 1.

### 2.0 Current Modelling Approach

The combination of flow features present in dimples makes for a challenging task, for any turbulence model, to accurately predict the dynamic and thermal fields in these flows. Thus, employing higher order turbulence closures could prove to be beneficial.

A systematic study of three modelling strategies within the RANS approach has been carried out. These include a linear eddy viscosity model (EVM), a non-linear model (NLEVM) and a Reynolds stress transport model (RSM).

As a linear eddy viscosity model, the Launder and Sharma\(^{19}\) $k$-$\varepsilon$ scheme, with the near-wall lengthscale correction term from Yap\(^{20}\), has been used. The cubic non-linear EVM of Craft et al.\(^{21}\) has also been tested, as has the stress transport model of Hanjalić and Jakirlić\(^{22}\). The low-Reynolds number form of each model was exclusively used. Table 2 shows a summary of the tested models and the different modelling classes they belong to.

The simulations have been carried out using the finite-volume-based STREAM code\(^{23}\), with the SIMPLE pressure correction algorithm. The second order accurate UMIST scheme of Lien and Leschziner\(^{24}\) has been used to approximate the convection terms for the velo-
ity and pressure correction equations, while the convection of turbulent quantities has been
discretized using the first order accurate UPWIND scheme. The meshing strategy has been
taken from Wang et al., where a simple structured grid was first created to fit the channel
section and then stretched in the wall-normal direction to fill up the dimple volume. Figure 1
shows the computational grids used for the tested cases. As can be seen from the figure, the
meshes have been refined near walls to ensure a value of $y^+$ less than unity. Grids of up to
around two million cells have been used with 2.4 million cells used for the single dimple case
and 1.8 million cells for the dimple array case. Tests have been carried out to ensure the mesh
density was sufficient to fully resolve the flow field and achieve grid independent solutions.

3.0 Flow over a Single Dimple
The natural starting point for this investigation is to study the flow over a single dimple in
a channel. This serves as a first step in exploring the best way to tackle more realistic and
complex geometry configurations.

The case considered here is that studied experimentally by Kwon et al.. The experimental
data was reported at a Reynolds number, based on bulk velocity and channel height, of $Re_H =
5000$ with a dimple print diameter to channel height ratio of $D/H = 2.0$ and a ratio of dimple
depth to channel height of $\delta/H = 0.4$. The Prandtl number was taken to be $Pr = 0.71$. A
schematic of the tested domain is shown in Figure 2, with $W/H = 8$ and $L/H = 16$.

At the inlet, fully-developed channel flow profiles have been provided for the dynamic
field quantities, whilst a uniform temperature has been assigned. Zero gradient conditions
have been applied to all variables except pressure at the outlet, with a bulk mass-correction
algorithm employed to speed up convergence. The no-slip condition has been enforced on
both walls, with two thermal boundary conditions tested. In the first, a uniform heat flux was
imposed on the dimpled surface, while in the second, the dimpled wall was set at a constant
temperature higher than than that of the fluid. In both cases, the upper wall was treated as
adiabatic. At the spanwise (z-direction) boundaries, periodic conditions have been applied. It
is worth noting that the size of the domain is large enough for the boundary conditions not to
have an effect on the dimple region.

The experiments reported that no dominant frequencies were found in the frequency spectrum which suggests that no large-scale unsteadiness was detected. Thus, the main simulations for this case have been conducted as steady state. To test the validity of this assumption, a time dependent simulation has been carried out using the Launder and Sharma\textsuperscript{(19)} \(k-\varepsilon\) model without the Yap\textsuperscript{(20)} lengthscale correction term. The simulation resulted in a steady state solution, and thus the steady RANS approach has been deemed suitable for this case.

Figure 3 shows the near-wall streamlines predicted in the present study. It can be seen that all models successfully capture the formation of the dimple’s vortices, with the linear EVM and RSM predicting a pair of symmetric vortices. This vortex pair forms due to flow recirculation upstream along the dimple curve, following its impingement on the dimple downstream half. These structures tie in nicely with the flow patterns reported by Kwon et al.\textsuperscript{(2)} and Isaev et al.\textsuperscript{(3)} in the laminar and turbulent flow regimes, respectively.

The NLEVM, on the other hand, predicts a single asymmetric vortex cell that is inclined to the flow direction by nearly 45°. This is similar to the features reported by Isaev et al.\textsuperscript{(6)}, however, for much deeper dimple depths \(\delta/H > 0.628\). To investigate this further, another simulation has been conducted using the NLEVM for a shallower dimple depth of \(\delta/H = 0.2\) with the other geometric factors being the same. In this case, the model does predict a symmetric pair of vortices, in line with other model predictions, which could lead to the conclusion that the non-linear model may have amplified the effect of dimple depth.

One can clearly see from Figure 4 that all models return more or less the same position for the reattachment point within the dimple, with slightly thicker recirculation region predicted by the NLEVM.

Figure 5 shows an iso-surface of the Q-criteria within the dimple. The figure emphasises the previous conclusion with both the EVM and RSM returning symmetric coherent structures within the dimple, while the NLEVM produces an asymmetric one.

The velocity profiles, in Figures 6 and 7, are in general good agreement with the experimental data reported by Kwon et al.\textsuperscript{(2)}. However, in Figure 6, the measured data does not
Figure 3: Stream traces on a curved surface close to the dimpled wall.

Figure 4: Stream traces across the centerline of the dimple at $z = 0.0$. 
Figure 5: Q-criteria iso-surface ($Q=0.2$) for the single dimple case with $\delta/H = 0.4$ and $D/H = 2.0$.

Figure 6: Profiles of the streamwise velocity, $U$, at a point on the centerline in the upstream half of the dimple, $(x,z) = (-0.15D,0.0)$, as indicated by the cross on the schematic, compared to the experimental data reported by Kwon et al.\textsuperscript{(2)}.

Figure 7: Profiles of the streamwise velocity, $U$, at a point on the centerline in the wake of the dimple, $(x,z) = (0.85D,0.0)$, as indicated by the cross on the schematic, compared to the experimental data reported by Kwon et al.\textsuperscript{(2)}.
Figure 8: Contours of the turbulent kinetic energy across the dimple centerline at $z = 0.0$.

Figure 9: Contours of the turbulent kinetic energy in the cross-stream plane at $x = 0.0$. 
extend far into the dimple region where the model predictions start to deviate from each other. The figure shows that all models predict similar velocity profiles over the dimple until just under the dividing surface (between the channel section and the dimple, at $y/H = 0.0$) with a steep velocity gradient above and across the upper part of the dimple. Further in the dimple, the NLEVM shows slightly different behaviour, at least partly as a result of the different flow field (asymmetric vortex) predicted by the model. The differences in prediction between the models become more clear in the wake of the dimple, Figure 7, where the NLEVM asymmetric flow pattern shifts the wake flow away from the dimple centreline and off the sampling point.

The contours of the turbulent kinetic energy over the dimple, in Figures 8 and 9, show that the peak levels of $k$ occur in the shear layer and close to the impingement region around the dimple rear rim. The asymmetric flow pattern of the NLEVM model is clearly visible in the cross-stream plane and the model generally returns lower levels of $k$.

Furthermore, it can be seen from Figure 10 that all models, apart from the NLEVM, predict a high peak $k$ level to occur close to the dividing surface between the dimple and the channel, partly, as a result of the steep velocity gradients occurring across the separated shear layer in this region. The lower levels of $k$ predicted by the NLEVM are also clear in this figure.

After the dimple, Figure 11, the same pattern persists. Tests indicated that this difference in behaviour is mainly due to the form of the $c_\mu$ coefficient used in the turbulent viscosity formulation of the NLEVM, rather than the non-linear terms appearing in its stress-strain relation. In this case $c_\mu$ is taken as a function of local strain rate, and reduces significantly in regions of high strain (such as the separated shear layer), resulting in lower turbulent viscosity and turbulent kinetic energy levels.
Reported $u'$ levels by Kwon et al.\textsuperscript{(2)} suggest that the NLEVM slightly underpredicts, and other models overpredict, $k$ levels in the dimple, while all models underpredict $k$ in the dimple wake region.

Finally, the Reynolds stress anisotropy does not seem to be a major factor in the flow field prediction in this case. Hence, the use of the linear stress-strain relation (Boussinesq approximation) did not hinder the performance of the EVM.

The disparity in flow structures predicted by the models is also reflected in the contours of Nusselt number shown in Figures 12 and 13. These figures show that, for both wall boundary conditions, the symmetric flow field predicted when using the EVM and RSM leads, expectedly, to symmetric distribution of Nusselt number contours, with the highest levels of heat transfer enhancement being located in the dimple downstream half, where the flow impinges on the dimple surface. The NLEVM model, however, shows asymmetric contours of $Nu$ with a peak location that does not coincide with the flow impingement zone. A reduction in heat transfer is also evident in the upstream part of the dimple.

It is worth noting that for a constant temperature wall boundary condition, Figure 12, the contour lines of Nusselt number extend further in the lateral direction when compared to those of the constant heat flux case, Figure 13. This is consistent with experimental findings reported by Kwon et al.\textsuperscript{(2)} (for the constant temperature BC case) and Mahmood et al.\textsuperscript{(12)} (for the constant heat flux case).

Figure 14 shows profiles of the span-wise averaged Nusselt number for the constant temperature case, with the averaging carried out over the area shown in the contour plot, Figure 12, and the resulting averaged $Nu$ normalised by that of a plane channel. The figure shows that the model predictions are generally in good qualitative agreement with the experimental data in the sense that all models reproduce the reduction in the upstream half of the dimple as well as the significant heat transfer enhancement in the downstream part. It can also be seen from Figure 14 that the RSM outperforms the other two models as it provides a qualitative prediction of $Nu$, in the dimple area, that is more inline with the levels reported in the experiment.
Figure 12: Contours of Nusselt number at the dimpled wall normalised by that of a plane channel, for the case of a constant temperature wall thermal boundary condition.

Figure 13: Contours of Nusselt number at the dimpled wall normalised by that of a plane channel, for the case of a constant heat flux wall thermal boundary condition.
Figure 14: Span-wise averaged Nusselt number, normalised by that of a plane channel, compared to the experimental data reported by Kwon et al.\textsuperscript{(2)}.

4.0 Flow over an Array of Dimples

The case considered is based on the DNS performed by Wang et al.\textsuperscript{(11)}. The geometry of the tested channel is shown in Figure 15 where, in this case, $W/H = \pi$, $L/H = 2\pi$. The dimple surface geometry factors were taken as: $P/H = \pi/2$, $D/H = 1.0$ and $\delta/H = 0.2$.

![Figure 15: Schematic of the dimple array.](image)

The flow was driven by a fixed streamwise mean pressure gradient ($\Pi$). The Reynolds number, $Re_\Pi = 0.5u_\Pi H/\nu$, is taken as 180, to match the DNS data, where $u_\Pi$ is a velocity scale defined as $u_\Pi = \sqrt{0.5\Pi H/\rho}$, corresponding to the usual friction velocity in a plane channel case. The Prandtl number is taken as 0.71. Periodic boundary conditions were applied for all transported quantities in both the stream- and span-wise directions. On the walls, the no-slip condition was enforced with a uniform heat flux boundary condition applied on the dimpled surface, while the upper wall was considered adiabatic.

Unlike in the single dimple case, no information about the flow field statistical steadiness, or lack of, can be easily inferred from the study of Wang et al.\textsuperscript{(11)}. Moreover, Ligrani et al.\textsuperscript{(13)} and Won et al.\textsuperscript{(25)} have reported, through flow visualisation in a similar setup to the one described here, that the main vortex pair formed within the dimple is shed periodically from the cavity. This suggests that the presence of a large scale unsteadiness may be likely for this
case. Thus, time-dependent simulations were conducted to investigate the flow in this case, with the time step taken small enough to ensure CFL numbers less than unity. The EVM and the RSM converged to steady state solutions from which the results below are presented. As for the NLEVM, the predicted flow field remained unsteady, and thus, the long-term temporal averages are presented here.

Figure 16 shows the near-wall streamlines, over a curved surface parallel to the dimpled wall. It can be seen (similarly to what was described in the single dimple case) that both the EVM and RSM still maintain the symmetric structures, similar to those of the DNS, in the dimples, while the NLEVM predicts an asymmetric, single vortex cell instead. However, it is worth noting that in the flow field predicted by the non-linear EVM, the inclination of these asymmetric vortices changes direction, from $-45^\circ$ to $45^\circ$ and vice versa, from one row of dimples to the following. This alternating inclination of vortices is also clearly visible in the instantaneous flow field, forcing the flow out of the dimple to follow the side of the vortex inclination. This leads to the formation of neighbouring fast and slow flow lanes where the former appear on the sides of the dimples where shedding occurs and the latter lanes on the opposite sides.

In Figure 17, the profiles of $U^* = U/\bar{u}_e$ are shown at the symmetry point between the dimples. From the DNS data, one can clearly see that the viscous sublayer and a log-law region (albeit below the usual log-law line) remain present near the dimpled wall. However they are separated by a buffer region where the velocity gradient is sharply reduced. The RSM clearly reproduces all three regions in its profile, but significantly overpredicts the $U^*$ gradient in the buffer region. The NLEVM captures the general level of $U^*$ but fails to produce the buffer region. This could be due to the fact that, with the asymmetric shedding described above, the sampling point plotted is no longer in the wake of the dimple shedding. The profiles predicted by the EVM show a slender buffer region, but it also significantly overpredicts the $U^*$ gradient in the buffer region and slightly underpredicts the $U^*$ level in the log-law region.

Through the dimple’s centre, Figure 18, all model predictions are generally in good agreement with the DNS data, particularly in the recirculation region. The NLEVM extends this good agreement further across the shear layer, while the other two models better match the DNS in the remaining part of the channel.

Figure 19 shows profiles of the turbulent shear stress, $\overline{uv}^* = \overline{uv}/\bar{u}_e^2$, at the symmetry point between the dimples. Results from all the models show an increase in the value of $\overline{uv}^*$ near the dimpled wall compared to that of a plane channel. The EVM tends to over-predict the values of $\overline{uv}^*$ in this region, while the results from the NLEVM and RSM better match the levels reported by the DNS across most of the channel. However, near the wall, the NLEVM slightly under-predicts the peak $\overline{uv}^*$ magnitude, while the RSM overpredicts it.

In Figure 20, the profiles of the turbulent shear stress through a dimple centre are shown. It can be seen that the NLEVM returns significantly lower levels of turbulence within the dimple area and across the shear layer compared to the other two models. The EVM and RSM give similar peak levels of $\overline{uv}^*$ and, in general, predict increased turbulence levels within the dimple.

Figures 21 and 22 show the turbulent normal stresses at the symmetry point between dimples predicted by the NLEVM and the RSM, respectively. Both models return the correct stress distribution with the RSM, expectedly, outperforming the NLEVM when it comes to quantitative comparison with DNS. The EVM predictions were not included here since the model produces a nearly isotropic normal stress distribution in this case. This stems from a well-known deficiency in the Boussinesq approximation which underpins all linear eddy
Figure 16: Stream traces on a curved surface close to the dimple array. DNS data reported by Wang et al.\cite{11}.

Figure 17: Profiles of the streamwise velocity, $U^+$, at the symmetry point between dimples, compared to DNS data reported by Wang et al.\cite{11}.

Figure 18: Profiles of the mean streamwise velocity, $U^+$, through dimple centre, compared to DNS data reported by Wang et al.\cite{11}.

Figure 19: Profiles of the turbulent shear stress, $\overline{u'v'}$, at the symmetry point between dimples, compared to DNS data reported by Wang et al.\cite{11}.

Figure 20: Profiles of the turbulent shear stress $\overline{u'v'}$ through dimple centre.
viscosity models.

Contours of Nusselt number over the dimpled wall, normalised by that of a plane surface at the same Reynolds number, are shown in Figure 23. Similarly to the discussion in the single dimple case, the models predict increased values of Nusselt number in the downstream half of the dimples, where the flow impinges on the dimpled wall. Moreover, all models show reduced levels of \( \text{Nu} \) in the upstream part of the dimple due to flow separation. Following their predicted flow fields, the EVM and RSM report a symmetric distribution of Nusselt number on the dimple surface, while the NLEVM returns an asymmetric \( \text{Nu} \) distribution, due to the inclined vortex structure predicted in the dimple. On average, all models report an enhancement in Nusselt number levels, up to twice or more that of a plane channel in parts of the dimpled wall. However, reduction in heat transfer over the upstream part of the dimples is also evident.

### 5.0 Conclusions

The Reynolds-Averaged Navier Stokes approach has been used to investigate the flow over a single dimple and an array of dimples. A number of RANS models have been tested spanning different closure approaches.

The EVM and RSM predicted the formation of symmetric vortex cells that fill the separation zone in the upstream part of the dimple, while the NLEVM showed a single, asymmetric, vortex in the separation area of the dimple with much lower levels of turbulence predicted in general. Table 3 gives a summary of flow patterns predicted by all models.

Comparison with the experimental and DNS data shows that low-Re RANS models of three different types have been able to reproduce the main features of the flow over dimpled sur-
Figure 23: Contours of Nusselt number across the dimple array normalised by that of a plane channel.

<table>
<thead>
<tr>
<th>Case</th>
<th>EVM</th>
<th>NLEVM</th>
<th>RSM</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>case1</td>
<td>Symmetric vortex pair</td>
<td>Asymmetric mono-vortex</td>
<td>Symmetric vortex pair</td>
<td>Symmetric vortex pair</td>
</tr>
<tr>
<td>case2</td>
<td>Symmetric vortex</td>
<td>Asymmetric mono-vortex</td>
<td>Symmetric vortex</td>
<td>Symmetric vortex</td>
</tr>
</tbody>
</table>

Table 3: Flow characteristics as predicted by all models and data.
faces. Nevertheless, from the presented analysis, one can conclude that using a relatively advanced RSM, such as the Hanjalić and Jakirlić\(^{(22)}\) model, results in the most reliable predictions. This, however, comes at the price of an increased computational cost as well as a deterioration in the numerical stability of the simulation since RSM’s can be more difficult to converge, compared to eddy viscosity models.

On the other hand, using an eddy viscosity model, in either the linear or non-linear variety, may seem to yield a reasonable compromise between accuracy, stability and computational cost. However, with EVM’s, there will always be a risk of the simulation arriving at a flow pattern other than the one physically expected (e.g. established through an experiment or a high fidelity simulation) as is the case with the NLEVM predictions in the present work. The NLEVM predictions (the asymmetric flow patterns), while they deviate from those reported in the literature for the tested configurations, do remain a viable physical and numerical solution to the dimple flow problem, and have been reported by Tay et al.\(^{(26)}\) in a flow visualisation study. Moreover, other RANS-based studies (e.g. Isaev et al.\(^{(6)}\) with the \(k-\omega\) SST linear EVM) have also reported asymmetric dimple vortices in dimple configurations where they are not expected. This is particularly interesting since both the chosen NLEVM (Craft et al.\(^{(21)}\) cubic \(k-\varepsilon\)) and the \(k-\omega\) SST EVM are formulated to reduce the turbulent viscosity at regions of high strain rates\(^{(27,28)}\). Thus, both models tend to reduce the turbulent diffusion in the dimple region, where high strain rates are prevalent, and the computed flows are more likely to become unstable and give rise to the asymmetric dimple vortices.

All models tested were able to reproduce the general heat transfer characteristics associated with the flow over dimples, namely, the reduction in heat transfer in the upstream half of the dimple and the significant heat transfer enhancement in the downstream part.

Further explorations are required to fully understand the flow patterns predicted by the models and how these models would react to changes in the geometrical factors, such as the dimple depth and channel height, as well as how they would perform in more complex cases (e.g. arrays of dimples on both walls with rotation).

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