EFFECTS OF ROTATION ON COOLING PERFORMANCE OF AN IMPINGING JET ROW

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ABSTRACT

This paper presents the result of an experimental study of impingement cooling from a row of five jets striking a concave surface, in a semi-cylindrical cooling passage that rotates about an axis parallel to that of the jets. This configuration is used to cool internally the leading edge of rotating gas-turbine blades. The jets are symmetrically placed along the centre-line of the flat surface of the passage, spaced 4 diameters apart, with the third jet positioned at the mid point along its length. Tests have been carried out at a mean flow Reynolds number, based on jet diameter, of 15,000 and for rotation numbers ranging from 0 to 0.18 for both clockwise and anti-clockwise rotation. The working fluid is water, with a Prandtl number of 6.09 at the operating temperature.

Local Nusselt number measurements using the liquid crystal technique show that, as expected, under stationary conditions a high Nusselt number region develops around each impingement point, with secondary Nu peaks half-way between impingement points. Ran important discovery is that rotation reduces overall heat transfer levels, leads to the eventual disappearance of the secondary peaks and also to the disappearance of some of the primary peaks in Nusselt number associated with impingement.

Flow visualization tests suggest that these changes in thermal behavior are caused because rotation increases the spreading rate of the jets. Theoretical considerations suggest that the increase in spreading rate occurs because the Coriolis force raises the turbulent shear stress at the jet exits. Future work that includes CFD predictions and LDA measurements will help develop a clearer theoretical understanding.

INTRODUCTION

The leading edge region of modern gas-turbine blades experiences particularly high temperatures due to the normal impingement on the blade of the hot gas stream leaving the combustion chamber. To preserve the integrity of the blades they must be cooled both internally and externally, with protection being especially needed in the stagnation-point region. Using relatively cool by-pass air, effective strategies are being sought to achieve as high heat transfer coefficients as possible on the interior surface of the blade. The most popular route to achieve this is to adopt "impingement cooling" in which a row of jets is directed to the inside of the blade surface just opposite the external stagnation point.

Until now the design of the interior of the blade has been based on measurements of mean heat-transfer coefficients beneath an impinging jet row. These data are usually obtained on a plane (rather than a concave) surface and invariably in a stationary rig. Thus, the contributions of blade rotation to the heat-transfer coefficient are unexamined as are, likewise, the detailed effects of the coolant flow, particularly the character of the fluctuating velocity field. Experimental information on impingement cooling under rotating conditions has only recently started to emerge with studies such as those Akella and Han (1998) and Parsons and Han (1998) and Hsieh et at (1999). These studies focused on impingement cooling in rotating rectangular channels and provided measurements of the side-averaged Nusselt number. They showed that rotation can reduce the cooling effect of impingement, by as much as 20%.

Here we report the first detailed measurements in a simplified model of the impingement-cooling cavity obtained in UMIST's unique rotating facility. The data cover local Nusselt number and also flow-field visualizations over the full range of Rotation numbers encountered in blade cooling. The experimental results will help to directly guide the blade designer and also serve to provide the detailed data that are required to validate CFD codes that aspire to provide predictions of such complex flows.

APPARATUS AND INSTRUMENTATION

The measurements have been undertaken in the rotating flow test rig described in Iacovides et al (2001). The particular test section to be examined is mounted on a horizontal circular table that may be driven over a range of rotational speeds up to 250 rpm by an electric motor. The table is housed within a stationary circularl 2m diameter tank to which water, to be used as the

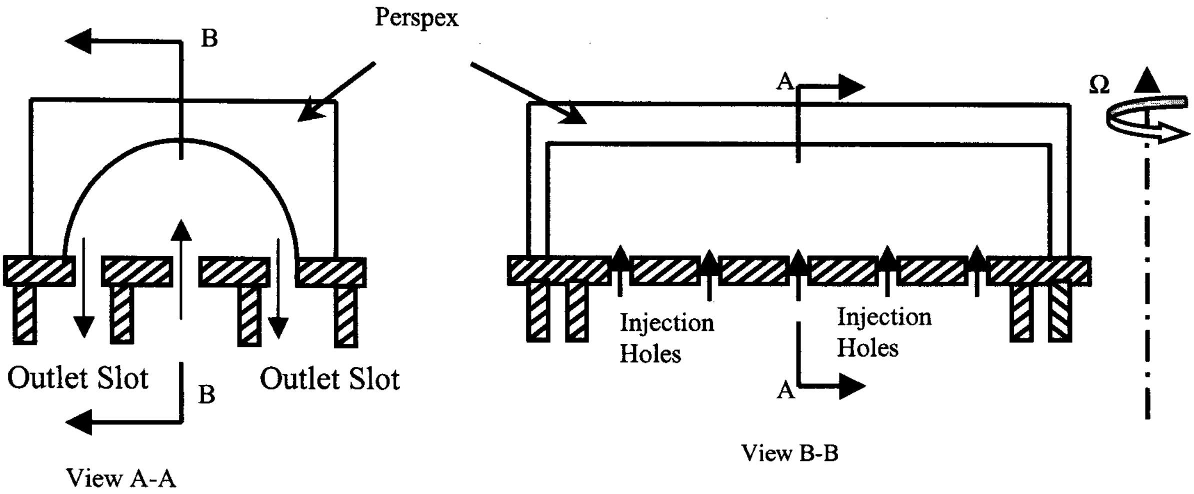


Figure 1. Experimental model.

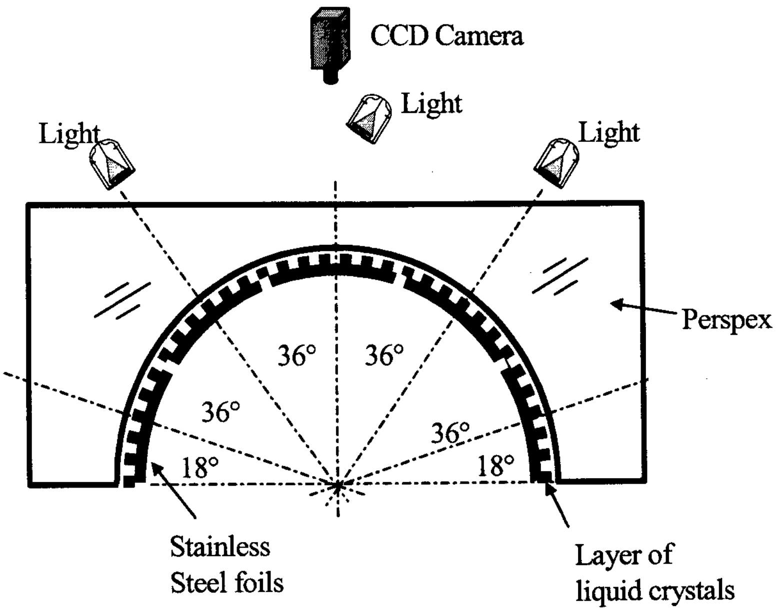


Figure 2. Heating and viewing arrangements for heat transfer tests.

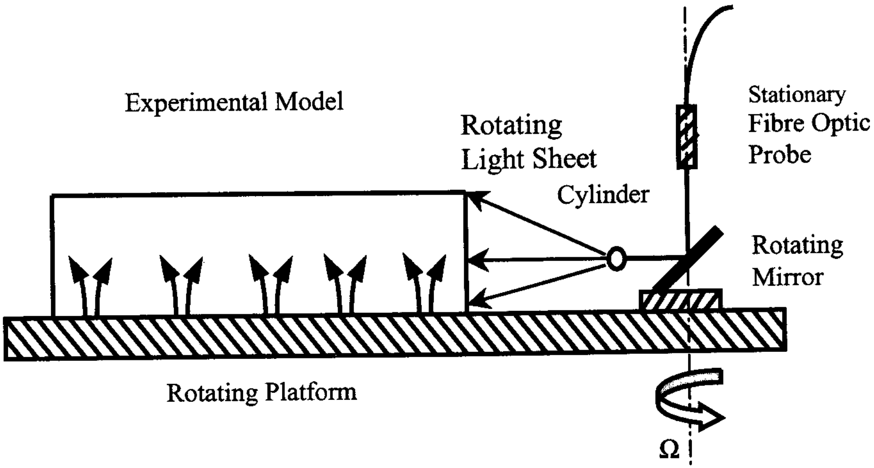


Figure 3. Flow visualization set-up.

working fluid, is fed. Electrical power is supplied to the rotating test section through slip rings as are likewise the data-output channels providing details of the electrical power supply.

A sketch of the test section under examination is shown in Figure 1. It comprises a transparent perspex chamber, semi-circular in cross-section beneath which is a horizontal plate with five holes each 11.2mm in diameter and spaced 45mm apart. Water flows through the holes forming circular jets, which, for zero rotation, symmetrically impinge on the curved surface 35mm above the holes. The jet fluid leaves the semi-circular cavity as shown. Two identical test sections have been made, one for heat transfer and the other for measuring the velocity field. As shown in Figure 2, in the former, the semi-circular surface has first been coated with thermo-chromic liquid crystals (TLCs) which are then covered by double-sided sellotape. In turn, five thin steel foil strips were affixed to the other side of the Sellotape. By passing electrical current through these, they provided the heat input to the cavity surface, under uniform-wall-heat-flux thermal boundary conditions. The temperatures on the curved surface were determined by recording the colour play of the TLCs on a video camera mounted externally to the cavity but rotating with it, as documented in Iacovides et al (2001). In order to transform the liquid crystal data to Nusselt numbers a considerable amount of image and data processing was necessary to identify the co-ordinates of the contour line of the selected colour (yellow), which is also a contour of a constant heat transfer coefficient, to correct for the effects of the surface curvature and to combine the information from different heating rates to produce a set of Nusselt number contours. This was done through Matlab.

The gathering of flow field data has so far been confined to flow visualizations to establish qualitatively how the jet trajectories are modified by rotation. As shown in Figure 3, a stationary fibre optic probe was placed above the center of the rotating platform. The vertical laser beam from the stationary probe struck a rotating mirror inclined at 45°. A horizontal rotating beam was thus reflected from the mirror. The rotating beam then passed through a glass cylinder fixed on the rotating platform, which generated a rotating light sheet. This light sheet was used to illuminate the central plane of the rotating passage that dissects the five jet holes. The trajectory of seeding particles within the illuminated plane could then be monitored. Still pictures were recorded using a high-resolution digital camera and moving pictures using a CCD camera, both of which rotated with the experimental model. The digital camera was operated through a remote control unit. The CCD camera was connected to a transmitter fixed on the rotating platform. The transmitter signal was sent to a stationary receiver that was connected to a TV monitor and also a video recorder.

RESULTS

All heat transfer tests have been carried out at a mean flow Reynolds number of 15,000 based on the jet exit velocity V_j and diameter d_j and for rotation numbers ($Ro \equiv \Omega d_j / V_j$) ranging from 0 (stationary) to 0.18, the latter being typical of engine conditions. Both clockwise and anti-clockwise rotation has been considered, with rotation numbers for anti-clockwise rotation denoted as positive and for clockwise rotation as negative. All fluid properties are evaluated at the fluid film temperature, defined as the average between the jet inlet and the wall temperatures. The appropriate wall temperature in this case is the yellow color temperature for the liquid crystals, determined by calibrating the crystals under the same heating, viewing and illumination conditions as in the actual experiment. The Nusselt number is defined in terms of the difference between the wall and the jet inlet temperature.

The local Nusselt number measurements are summarized in the contour plots of Figure 4. For the non-rotating case (Ro = 0.0) it is noted that the imprint of the impingement of the five jets is very clear giving rise to a roughly concentric elliptic rings of uniform Nu. There is only a small difference between the contours created by one jet and the others: in most cases the contour of Nu = 300 is just reached at the impingement point while, for the second jet from the bottom in the figure it is just absent (though the Nu = 250 contour for this jet is similar in size to the others). The major axis of the roughly elliptic contours is horizontal which is probably because the flow around the concave surface is unimpeded while, in the vertical direction the jets form the adjacent holes collide, thus reducing the velocity. (It appears that this is a more likely reason than effects due to surface curvature in the horizontal direction). Weak secondary peaks in Nu are evident midway between the jet impingement zones. These arise from the collision of the radially outward wall jets following the jet impingement.

At the low rotation number of Ro = 0.04 a slight reduction in Nusselt number is evident. Fewer of the jets exhibit a contour for Nu = 300 and the inter-jet peaks have reduced. If the flow were perfectly symmetric, one would expect the effect of a clockwise rotation to be an inverted mirror image of that an anticlockwise rotation of the same magnitude.

As the rotation rate is further raised, besides a continuing reduction in the mean levels of Nu, two notable changes to the contour pattern are evident. Firstly the major axis of the 'ellipses' of the jet-impingement contours are no longer horizontal (or in compass terminology E-W). For anti-clockwise rotation the contours have a distinct NE-SW orientation while for clockwise rotation the orientation is NW-SE. The second notable change is that in each case one of the jets produces a significantly lower level of heat transfer coefficient than the others. For anti-clockwise rotation (positive Ro's) the jet in question is the second from the top while for negative rotation it is the central jet. This selective diminution is quite evident at Ro =± 0.09 while for Ro = ± 0.18 the imprint of the two jets has entirely disappeared. Now, the fact that in each case just a single jet should be so affected is surprising, doubly so since it is a different jet (that is, the location of the jet affected for one rotation rate is not the mirror image of the other case). This strongly implies that what is observed is some sort of instability provoked by very small differences

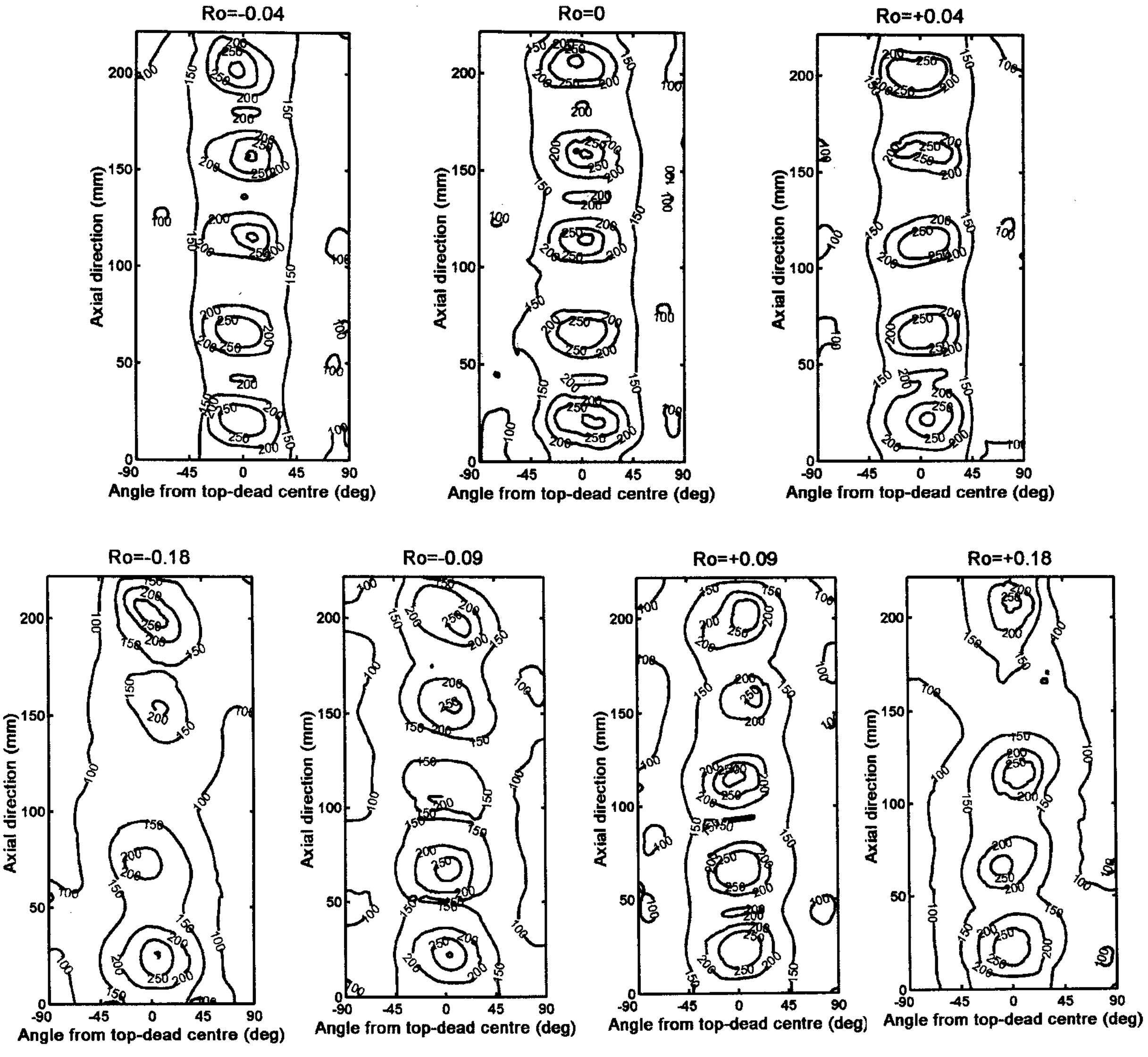
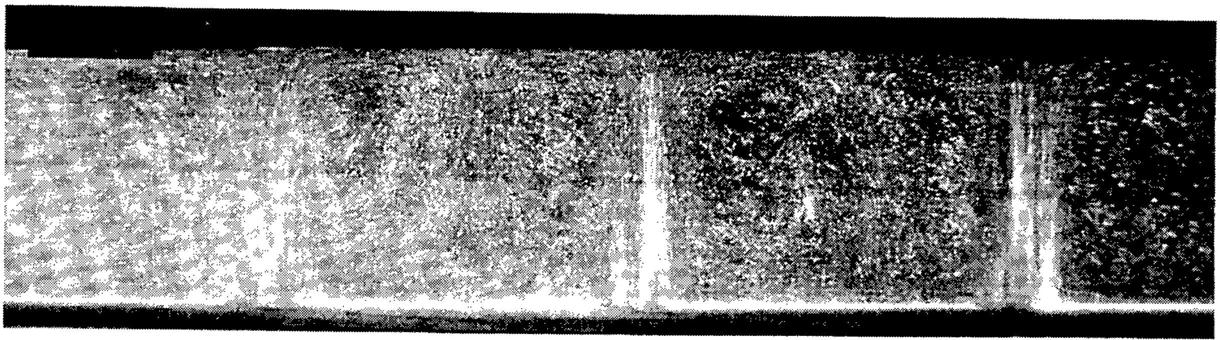


Figure 4. Local Nusselt number contours at Re=15,000 and Pr=6.09

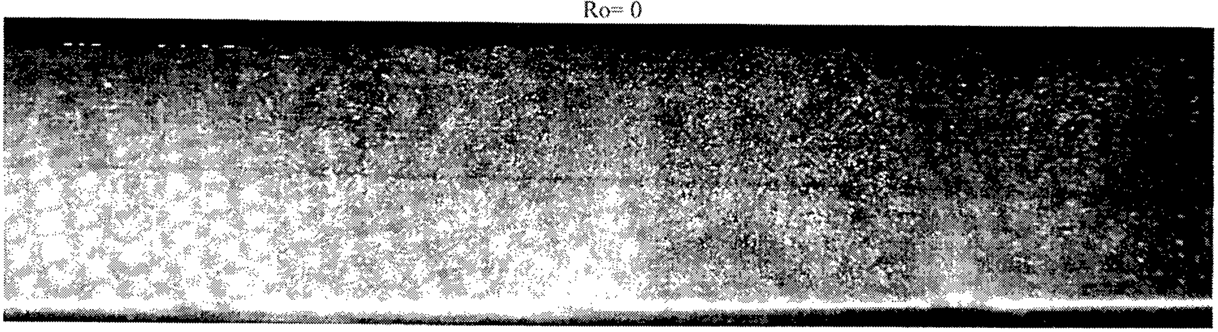
between one jet and another and amplified by equally small differences due to rotation.

It is salutary to note that in an actual turbine blade the manufacturing tolerances will inevitably be much larger than in the present experiment where the hole diameter is an order of magnitude larger than in an actual blade. Moreover, due to the extreme temperature ranges to which it is subjected in use, even if a turbine blade is perfect at the start of its life, it will quickly develop small, imperfections due to depositions etc. Thus, while the mean effects of rotation on overall heat-transfer coefficients uncovered in this exploration are consistent with earlier studies and are thus an expected outcome, the effects on *local* Nusselt number at the levels of blade rotation occurring in an actual gas turbine are found to be quite profound, resulting in changes that lead to local hotspots with serious implications for blade cooling.

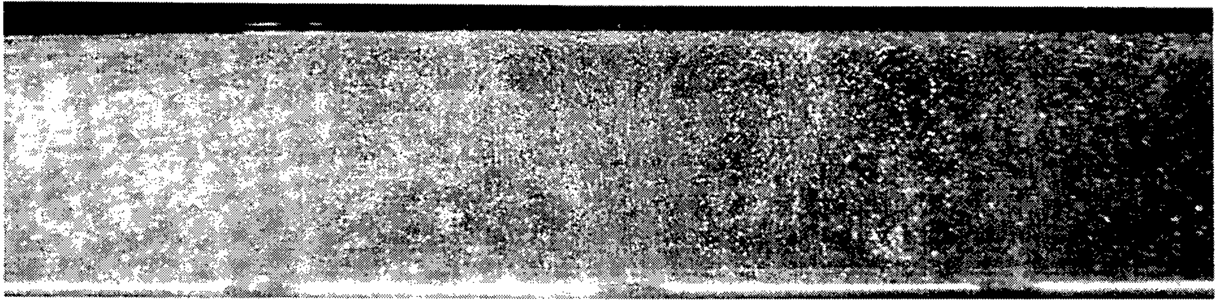
As a start to a longer-term examination of the quantitative effects of the rotation on the flow field, a series of flow-visualization tests have been undertaken. As noted earlier, a sheet of laser light illuminates the flow movement in the plane of the jets axes. Here attention is focused on the three central jets. The comments provided in what follows are based not just on the still photographs reproduced in Figure 5 but also, as noted earlier, on the video recordings of the events. The figure shows clearly that there is a noticeable affect of the rotation on the jets. For the stationary case, the jet core remains intact up to the point of impact (aswould be expected, since the distance from discharge to the impingement surface is only just over three jet diameters) and the resultant radial wall jets collide, giving rise to a noticeable, though highly unsteady, jet 'fountain'. This vigorous unsteadiness where the wall jets collide is what leads to the secondary peaks in Nusselt number noted above. Successively raising the rotation rate appears to make the potential core shrink and disappear while the jets appear to spread more quickly: thus, at their point of impact, they are more diffuse, a development



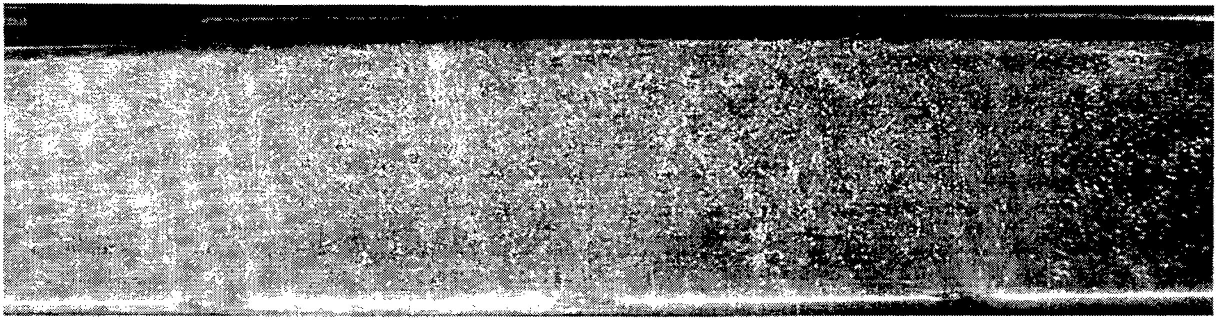
Ro= 0



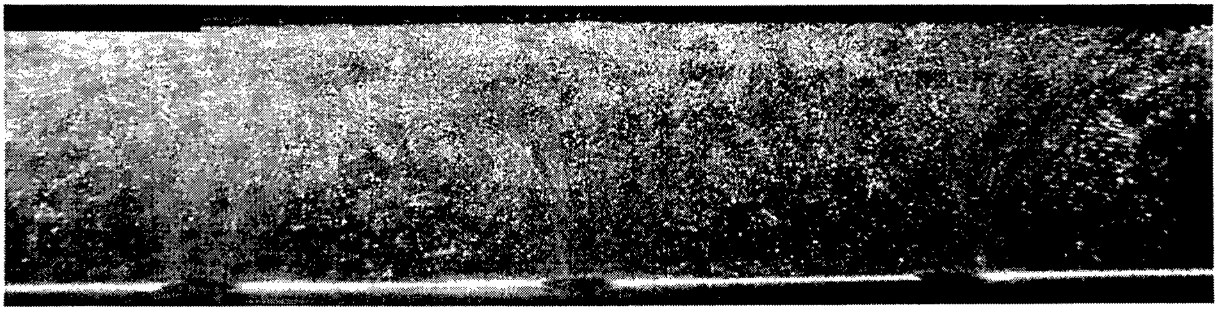
Ro=-0.04



Ro=-0.06



Ro=-0.08



Ro=0.18

Figure 5. Flow visualization photographs for the three central jets

which could be responsible for the diminution in Nu. At the highest rotation rates examined (Ro = -0.08 and –0.18) it appears that the central jet may be spreading more rapidly than the ones on either side. This would seem to be consistent with the heat transfer data that show a complete disappearance of the central jet imprint at Ro = -0.18. It is as well to note, however, that the heat-transfer and flow-visualization studies were made with different test sections and, while they were in principle geometrically identical, if the different behaviour between neighbouring jets arise from *infinitesimal* differences in geometry, it is not certain that those differences were the same between the two models.

While the flow visualization results provide suggestions as to what the effects of rotation on the flow field are, a question left unanswered is how does rotation influence the jet spreading rate. The fact that both clockwise and anti-clockwise rotation increase the jets spreading rate, suggests that rotation does not affect the mean flow directly. In any event the jets' axial velocity is parallel to the rotation axis, Figure 3, and hence will not generate a Coriolis force. The next question to be addressed is thus whether the direct effects of rotation on the turbulence field can account for such an influence. The exact mathematical expressions of the contribution of the Coriolis force to the generation rate of the Reynolds stresses have not been included due to space limitations. They do however show that the shear stress within the axial-radial plane of the jets (which largely determines the spreading rate), is increased by the Coriolis force, for both positive and negative angular velocity, provided that the turbulence intensity in the circumferential direction is greater than that in the radial direction of the jet. This will certainly be the case within the injection holes, since the radial direction is normal to the surface of the hole. Consequently, rotation will increase the turbulent shear stress at the jet exit, providing a possible mechanism for the higher spreading rates. The authors intent to investigate this further through CFD predictions and also through quantitative flow measurements, using laser Doppler anemometry.

CONCLUDING REMARKS

Measurements of the local Nusselt number have been presented which for the first time show in detail the effect of rotation on impingement cooling. As also shown by some recent studies that measured only overall heat transfer levels, rotation has been found to reduce the overall effects of impingement cooling. The local Nusselt number data produced in this study show that rotation can lead to strong non-uniformity in wall heat transfer, with some regions of high Nusselt number, due to impingement, disappearing completely. This feature has strong practical implication for the design blade cooling passages.The local thermal data also show that reversing the direction of rotation does not lead to a mirror-image Nusselt number distribution.

The flow visualization studies suggest that rotation increases the spreading rate of the cooling jets and that at the higher rotation numbers also leads to variations in the spreading rates of different jets. These flow observations are consistent with the thermal measurements. Initial theoretical considerations suggest that a possible reason for the increase in the spreading rates of the jets is that the Coriolis force raises the level of the turbulent shear stress at the jet exit.

The investigations will continue with LDA measurements and CFD analysis.

ACKNOWLEDGEMENTS

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