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INVESTIGATION OF DISCRETE-HOLE FILM COOLING PARAMETERS USING CURVED-PLATE MODELS

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ABSTRACT

Computations have been conducted on curved, three-dimensional discrete-hole film cooling geometries that included the mainflow, injection hole, and supply plenum regions. Both convex and concave film cooling geometries were studied. The effects of several film cooling parameters have been investigated, including the effects of blowing ratio, injection angle, hole length, hole spacing, and hole staggering. The blowing ratio was varied from 0.5 to 1.5, the injection angle from 35° to 65°, the hole length from 1.75D to 6.0D, and the hole spacing from 2D to 3D. The staggered-hole arrangement considered included two rows. The computations were performed by solving the fully elliptic, three dimensional Navier-Stokes equations over a body fitted grid. Turbulence closure was achieved using a modified k-ε model in which algebraic relations were used for the turbulent viscosity and the turbulent Prandtl number. The results presented and discussed include plots of adiabatic effectiveness as well as plots of velocity contours and velocity vectors in cross-stream planes. The present study reveals that the blowing ratio, hole spacing, and hole staggering are among the most significant film cooling parameters. Furthermore: (1) the optimum blowing ratios for curved surfaces are higher than those for flat surfaces, (2) a reduction of hole spacing from 3D to 2D resulted in a very significant increase in adiabatic effectiveness, especially on the concave surface, (3) the increase in cooling effectiveness with decreasing hole spacing was found due to not only the increased coolant mass per unit area, but also the smaller jet penetration and the weaker counter-rotating vortices, (4) for all practical purposes, the hole length was found to be a much less significant film cooling parameter.

NOMENCLATURE

D diameter of injection hole
DR density ratio = ρ_j/ρ_∞
H plenum height
I momentum ratio = $\rho_j U_j^2/\rho_\infty U_\infty^2$
k turbulent kinetic energy
L length of injection hole
M blowing ratio = $\rho_j U_j/\rho_\infty U_\infty$
P Hole spacing or pitch
T temperature
Tu turbulence intensity level = $\sqrt{k/1.5}/U_\infty$
U gas velocity
X horizontal distance measured from the hole leading edge at hole exit
Y lateral distance measured from hole centerline plane
Z vertical distance from the test surface measured from the hole leading edge

Greek Symbols

α injection angle
ε dissipation rate of turbulent kinetic energy
η local adiabatic film cooling effectiveness
η_c centerline adiabatic film cooling effectiveness
$\bar{\eta}$ laterally averaged film cooling effectiveness
ρ gas density
ξ streamwise coordinate
ζ wall-normal coordinate

Subscripts and Superscripts

j coolant jet
l measured from the hole leading edge
t measured from the hole trailing edge (also turbulent flow)

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w	at the wall
ξ	along the streamwise direction
ζ	along the wall-normal direction
∞	freestream quantity

INTRODUCTION

Over the years, several experimental studies have been conducted on curved-plate geometries to investigate the effects of various parameters on film cooling performance. Schwarz (1986) studied the effect of blowing ratio on cooling effectiveness and found that the optimum blowing ratio depends on the type of surface curvature involved. On convex surfaces representative of suction surfaces of turbine blades, he found that the optimum blowing ratio was of the order of 1.0. On concave surfaces, on the other hand, higher blowing rates always provided higher cooling effectiveness. Cruse et al. (1997) conducted experiments on a curved-plate geometry representative of the leading edge of turbine blades. They found that the optimum blowing ratio was of the order of 1.5. This is higher than the value obtained by Schwarz (1986), indicating that the optimum blowing ratio is higher on strongly curved surfaces.

Kruse (1985) investigated the effects of injection angle and hole spacing on cooling effectiveness of curved surfaces. He considered injection angles of 10° to 90° and found that the smaller injection angles performed better than the larger angles. He also found a strong effect of hole spacing on cooling effectiveness. He showed that, when the hole spacing is small, the counter-rotating system of vortices of adjacent jets interact in such a way that the tendency to re-attach to the wall is intensified and the jet penetration is reduced. Recently, Stone (1992) also studied the effect of injection angle on convex and concave surfaces and found that, at low blowing rates, the effect of injection angle is insignificant. However, at high blowing rates the smallest injection angle (15°) provided the best cooling performance. The larger angles he studied, 25° and 45°, gave nearly the same level of cooling effectiveness.

Hole staggering was also found to play the same role as reducing the hole spacing, i.e., it decreases the jet penetration and enhances the film cooling effectiveness. Ames (1997) studied the effects of hole staggering on the pressure and suction surfaces of turbine blades. He reported elevated levels of cooling effectiveness when the injection holes were staggered. The enhancement in cooling effectiveness was especially high for larger blowing ratios.

Numerical studies have also been conducted on curved surfaces. Many of these studies were, however, conducted on curved surfaces applicable to the leading edge of turbine blades. He et al. (1995) modeled the leading edge of a turbine blade using a semi-circular plate with a flat afterbody and the standard k-ε turbulence model. They reported distributions of velocity, temperature, pressure, kinetic energy, and adiabatic effectiveness following two staggered rows of holes. The spanwise inclined holes they studied resulted in good film cooling coverage at low blowing ratios. However, the coverage deteriorated at high blowing ratios. Lin et al. (1997) conducted a similar study and documented the interaction of the mainstream gases with the coolant jets. Martin and Thole (1997) also studied nearly the same geometry as the preceding two studies and reported flow and effectiveness results following two staggered rows of leading edge holes. Among other things, they found that the film cooling coverage was uneven following the two rows of holes. Garg and Gaugler (1996) modeled the leading edge of an actual turbine blade using an algebraic turbulence model and an assumed velocity profile at hole exit. They reported non-uniform distribution of heat flux in both the streamwise and spanwise directions, resulting in regions of good and bad film cooling coverage.

As already mentioned, the above-cited numerical studies were conducted on curved surfaces specific to the leading edge of turbine blades, as opposed to curved surfaces applicable to the pressure and suction surfaces. In addition, although the surface curvatures involved in these models were very strong, the turbulence models used in these studies did not take the effects of streamline curvature into account. In the present study, we have addressed these issues and investigated the effects of several parameters using curved-plate models applicable to the suction and pressure surfaces of actual turbine blades. The main features of this study are: (1) realistic, curved film cooling geometries have been used that included the mainflow, injection hole, and supply plenum regions, (2) the effects of streamline curvature was taken into account by using a modified k-ε turbulence model in which algebraic relations are used to calculate the turbulent viscosity and the turbulent Prandtl number, (3) the effects of several parameters on film cooling effectiveness have been studied, and (4) the underlying reasons for these effects have been discussed using velocity contours and velocity vectors at several cross-stream planes.

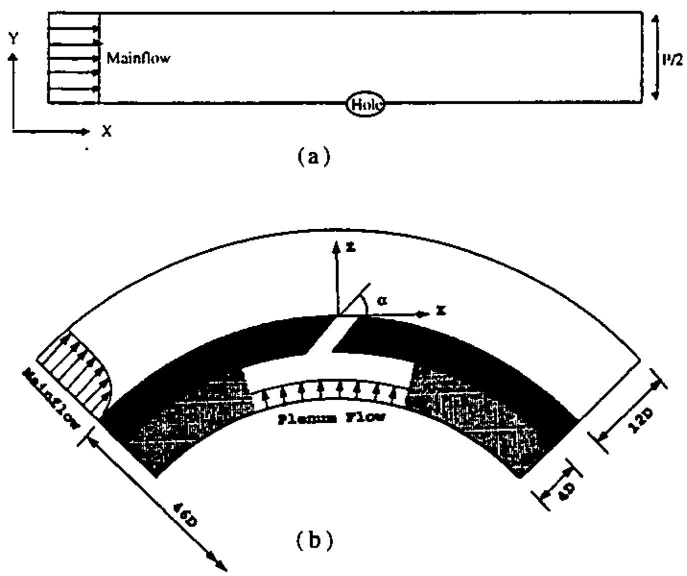

Fig. 1 The film cooling computational geometry, (a) top view and (b) front view

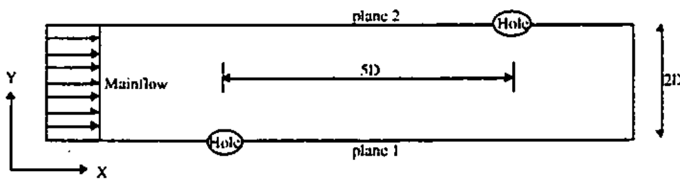

Fig. 2 Top view of the staggered-hole arrangement considered (a partial view)

TEST CASES CONSIDERED

Computations were performed for a wide variety of test cases. The blowing ratio was varied from 0.5 to 1.5, the injection angle from 35 to 65 degrees, the hole spacing from 2D to 3D, and the hole length from 1.75D to 6.0D. The basic film cooling geometry considered in this study is shown in Fig. 1. The flow and geometric variables used are given in Table 1. The effect of hole staggering was studied by considering the geometry shown in Fig. 2 where the lateral spacing bewteen holes is 4D and the streamwise distance between rows is 5D.

Table 1 Values of flow and geometric variables

Variable	Value	Variable	value
U_∞	12 m/s	D	11.1 mm
T_∞	298 K	α	35, 45, 65°
Tu	0.2%	L/D	1.75, 5.0, 6.0
DR	2.0	P/D	2.0, 3.0
M	0.5, 1.0, 1.5	H/D	4.0

COMPUTATIONAL DETAILS

The computational procedure followed in this study is given in the companion paper by Berhe and Patankar (1998). In this paper, the calculation procedure is described, which involves a modified k-ε turbulence model where algebraic relations are used for the turbulent viscosity and the turbulent Prandtl number. Also given are details of the solution methodology, discretization, boundary conditions, initialization, and convergence criteria.

RESULTS AND DISCUSSION

In this section, we discuss the effects of several film cooling parameters on film cooling performance, including the effects of blowing ratio, injection angle, hole length, hole spacing, and hole staggering. The results presented and discussed include plots of adiabatic effectiveness as well as plots of streamwise mean velocity contours and velocity vector for several cross-stream planes. Also given are comparisons between the present results and those of flat-plate studies and their implications to film cooling of pressure and suction surfaces of actual turbine blades.

The Effect of Blowing Ratio

As discussed in the companion paper by Berhe and Patankar (1998), the effect of blowing on film cooling effectiveness is determined by the sum total of the effects of: (1) the coolant mass injected per unit area, (2) the jet penetration into the mainstream, and (3) the strength of the counter-rotating vortices. In general, higher blowing ratios produce increased coolant mass per unit area, greater jet penetration, and stronger counter-rotating vortices. Although the increase in coolant mass per unit area tends to increase the cooling effectiveness, both greater jet penetration and stronger vortices decrease the cooling performance.

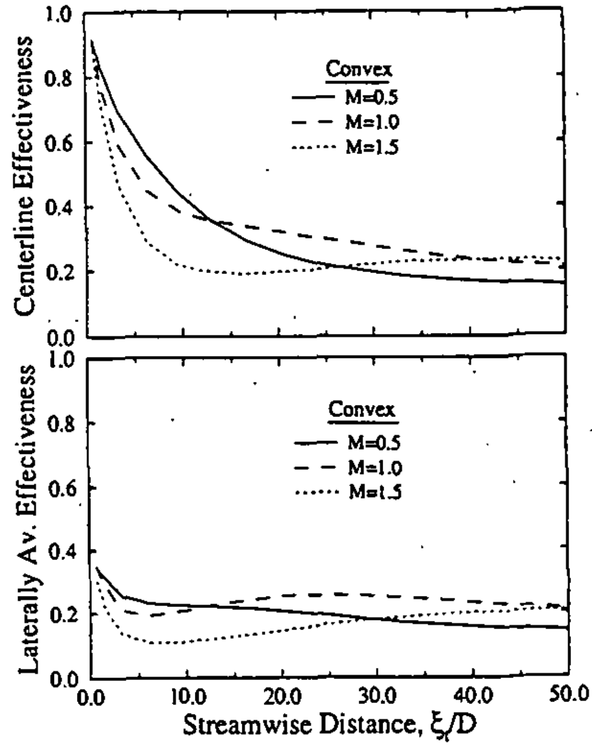

Fig. 3 The effect of blowing ratio on cooling effectiveness of a convex surface (α=35°, L/D=5)

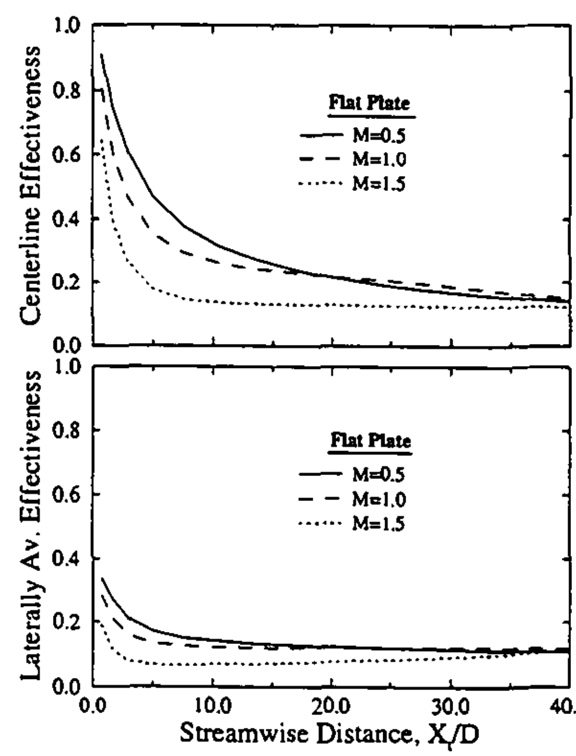

Fig. 4 The effect of blowing ratio on cooling effectiveness of flat surface (α=35°, L/D=4)

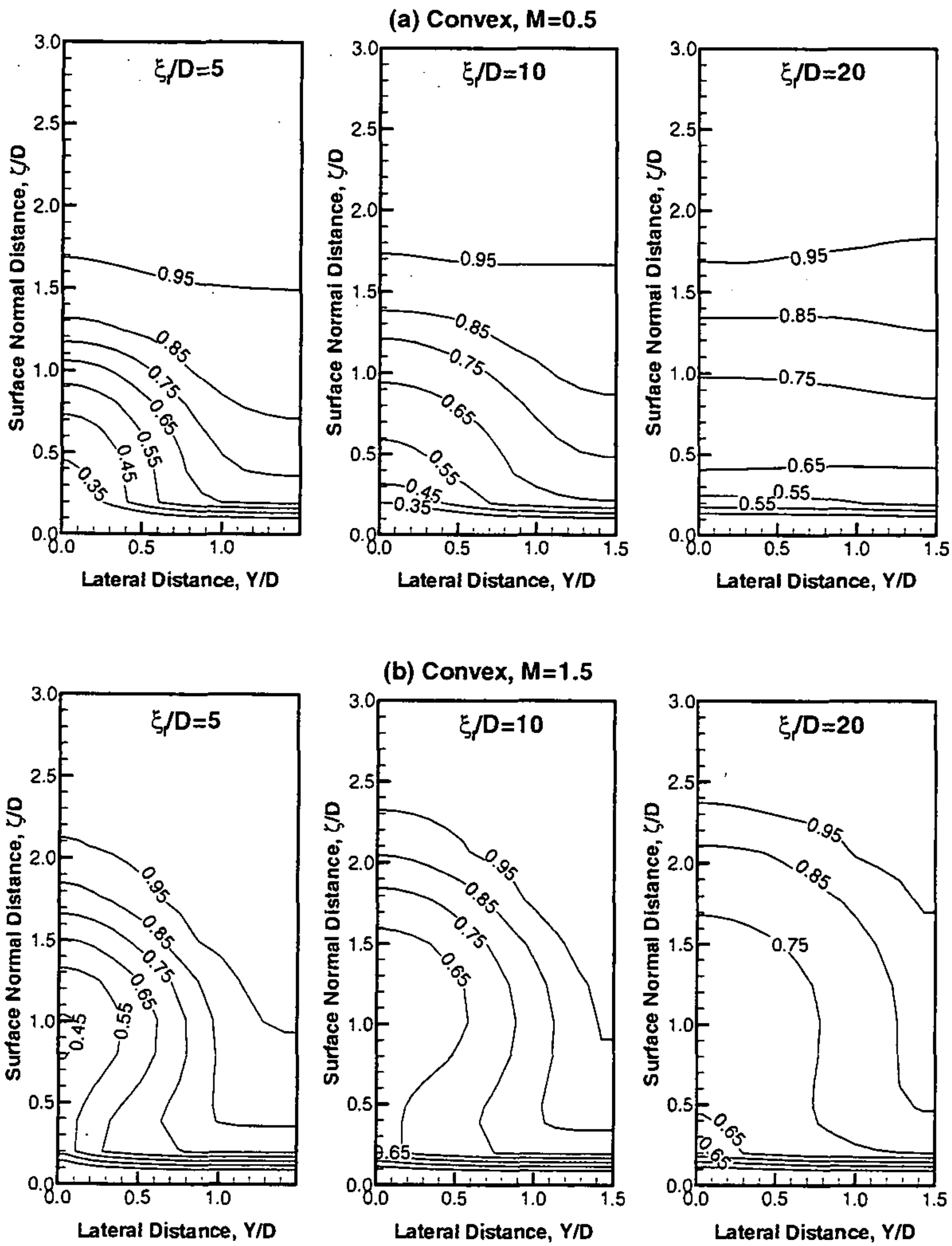

Fig. 5 The effect of blowing ratio on U_ξ/U_∞ contours in cross-stream planes on a convex surface

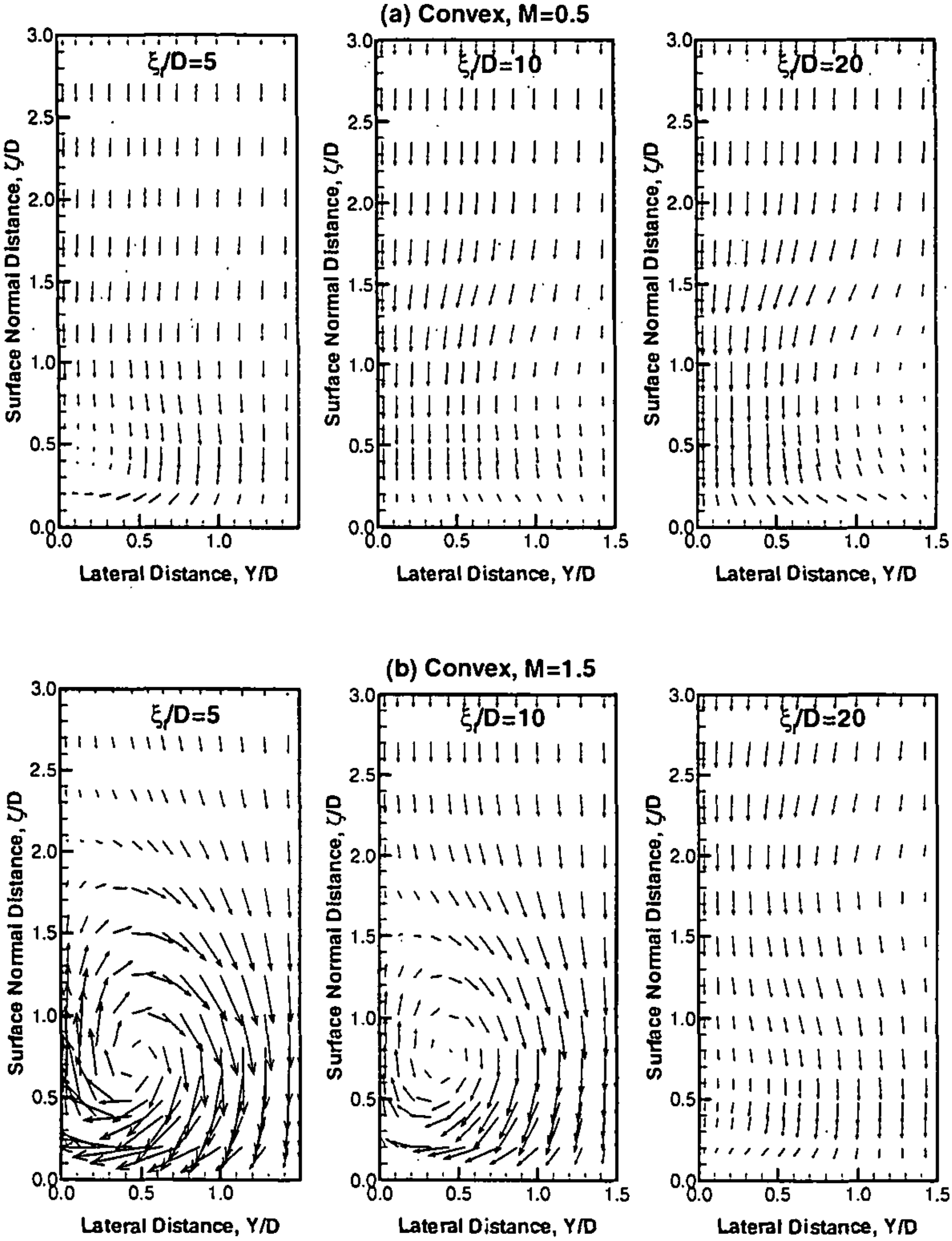

Fig. 6 The effect of blowing ratio on counter-rotating vortices on a convex surface

The effect of blowing ratio on cooling effectiveness is shown in Fig. 3. This figure shows the variations of the centerline and laterally averaged effectiveness for blowing ratios of 0.5, 1.0, and 1.5. The general trend in this figure is that, in the near-field, the cooling effectiveness decreases with the increase in blowing ratio, and in the far-field, it increases with the increase in blowing ratio. The optimum blowing ratio in this figure appears to be around M=1.0. This is in contrast to the optimum blowing ratio of about 0.5 established by many flat-plate studies. For comparison purposes, the variation of cooling effectiveness with blowing ratio obtained from a flat-plate model of Berhe (1997) is given in Fig. 4. In this figure, the optimum blowing ratio is around 0.5. It must be noted that the only difference between these two configurations is surface curvature.

The implication of these results is that the optimum blowing ratios on suction surfaces of turbine blades are higher than the values established by flat-plate models. Further, for strongly curved surfaces, such as the leading edges of turbine blades, the optimum blowing ratios may be even higher. In fact, in a recent study, Cruse et al. (1997) have shown that, at the leading edge, the optimum blowing ratio may be greater than 1.5. The reasons for the higher optimum blowing ratios on convex surfaces are: (1) the jet penetration is smaller, and (2) the counter-rotating vortices are weaker. As discussed in the companion paper by Berhe and Patankar (1998), on convex surfaces, pressure gradients exist that force the coolant jets towards the walls. As a result, the critical blowing ratio at which jet lift-off occurs is higher and, consequently, the optimum blowing ratio is larger. In addition, as discussed in the introduction, convex surfaces are known to reduce the near-wall shear stresses and suppress the negative effects of the counter-rotating vortices.

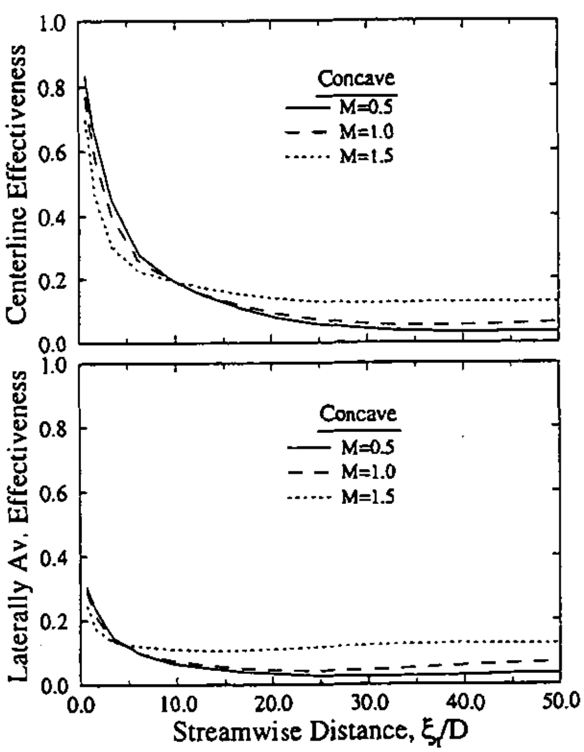

Fig. 7 The effect of blowing ratio on cooling effectiveness of a concave surface (α=35°, L/D=5).

Figures 5 and 6 show the effects of blowing ratio on jet penetration and counter-rotating vortices on the convex surface. These figures show contours plots of U_r/U_∞ and velocity vector plots in cross-stream planes. Three plots are shown for each blowing ratio (M=0.5 and M=1.5) corresponding to streamwise locations of 5D, 10D, and 20D. From Fig. 5, it is evident that, at M=0.5, the jet is fully attached to the surface. However, at M=1.5, the jet appears to be is first detached and then reattached further downstream. This detachment of the coolant jet from the test surface is responsible for much of the decrease in the near-filed cooling effectiveness shown in Fig. 3. Fig. 6 shows the amplification of the strength of the counter-rotating vortices with the increase in blowing ratio. For M=0.5, the counter-rotating vortices are almost fully suppressed at ξ_r/D=5. However, for M=1.5, the vortices are still strong even at ξ_r/D=10. As we have already discussed, stronger vortices generally degrade the film cooling performance by replacing the near-wall cold air with hot, mainstream gases.

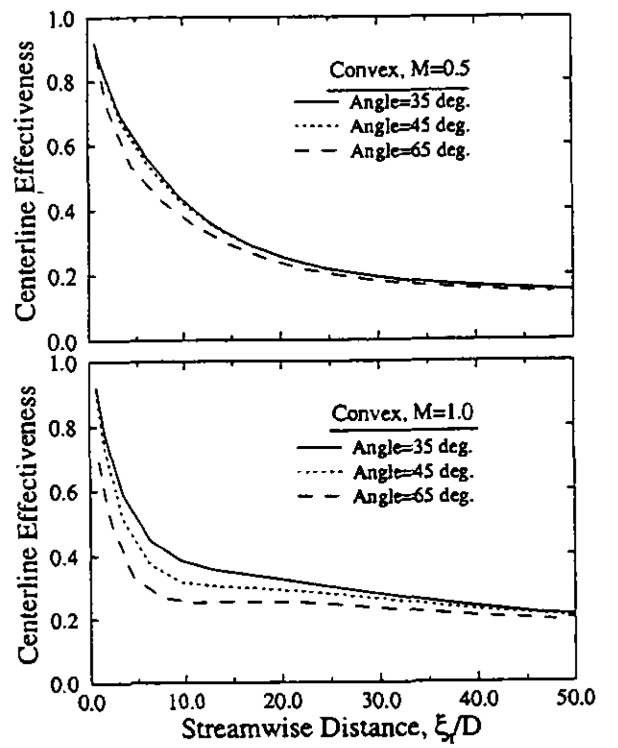

Fig. 8 The effect of injection angle on cooling effectiveness of a convex surface (L/D=5).

The effect of blowing ratio on cooling effectiveness of the concave surface is shown in Fig. 7. Examination of this figure reveals two main points. First, the effect of blowing ratio on cooling effectiveness of concave surfaces is not as strong as its effect on cooling effectiveness of convex surfaces. This is because, on concave surfaces, the flow is dominated by strong vortices. This results in a greater mixing of the coolant jets with mainstream gases and produces a slow increase of effectiveness with blowing ratio. The second point to be noted is that, as Schwarz (1986) observed, for much of the downstream region, the cooling effectiveness increases with the increase in blowing ratio.

This result is also consistent with the findings of Ames (1997) who showed that higher blowing ratios generally produce higher cooling effectiveness on pressure surfaces of turbine blades.

The Effect of Injection Angle

The main effect of injection angle is that it changes the jet trajectory or jet penetration into the mainstream. As the injection angle increases, the vertical momentum increases. This, in turn, increases the jet penetration and lowers the cooling effectiveness. Examination of velocity vector plots in cross-stream planes reveals that, unlike the blowing ratio, the injection angle doe not appear to affect the counter-rotating vortices.

Figure 8 shows the distribution of cooling effectiveness for injection angles of 35, 45, and 65 degrees. It is clear that, for both M=0.5 and M=1.0, the smallest injection angle produced the best cooling performance. As just mentioned, this is because the larger injection angles deploy more of the coolant fluid away from the test surface. However, it must be noted that, the above-noted decrease in cooling effectiveness with increased injection angle is not as large as those reported in earlier studies using flat-plate models, such as those of Kohli and Bogard (1995), and Berhe (1997). This is because, on convex surfaces, the effect of increased jet penetration (due to larger angles) is partly compensated by cross-stream pressure gradients which force the coolant jets back to the walls.

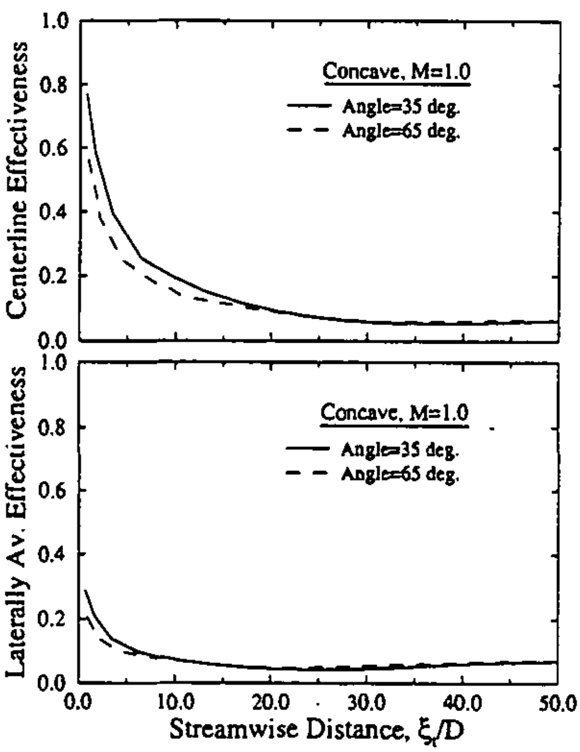

Fig. 9 The effect of injection angle on cooling effectiveness of a concave surface (M=1.0, P/D=3)

The effect of injection angle was also investigated on film cooling performance of concave surfaces. Computations were performed for injection angle of 35 and 65 degrees for M=0.5 and M=1.0. For both blowing ratios, the effect of injection angle on cooling effectiveness was found essentially insignificant. The result for M=1.0 is shown in Fig. 9. The conclusion is that the effect of injection angle on cooling effectiveness of concave surfaces is much weaker than its effect on cooling effectiveness of flat surfaces. The insensitivity of the cooling effectiveness to variations in injection angle may be attributed to the stronger mixing that exists on these surfaces. As we have discussed earlier, on concave surfaces, the injected coolant mass is thoroughly mixed with the mainstream gases that the effect of increased jet penetration due to larger injection angles is minimized. However, we have also found that, when the hole spacing is reduced, the effect of injection angle becomes more significant. We will further discuss this issue later in this paper.

In conclusion, the present computations show that the injection angle still has a significant effect on cooling performance of convex surfaces. However, on concave surfaces, its effect is greatly reduced by the stronger vortices that exist on these surfaces.

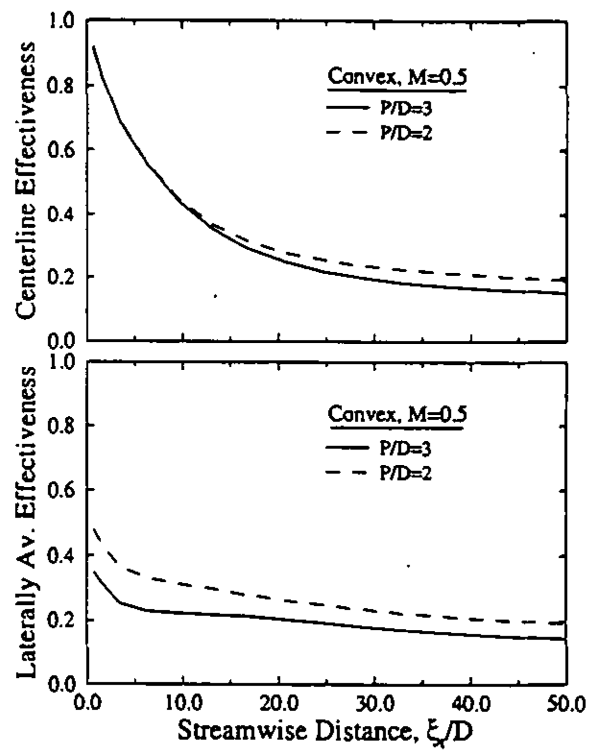

Fig. 10 The effect of hole spacing on cooling effectiveness of a convex surface (M=0.5).

The Effect of Hole Spacing

To study the effect of hole spacing on film cooling performance, we considered two values of the P/D ratio, P/D=3 and P/D=2. Computations were performed on both the convex and concave film cooling geometries. Figs. 10 and 11 show the distribution of the centerline and laterally averaged effectiveness for the convex surface for M=0.5 and M=1.0, respectively. It is obvious that the smaller hole spacing has produced a significant increase in cooling effectiveness, especially in the laterally averaged effectiveness. Furthermore, the increase in cooling effectiveness is greater at M=1.0 than at M=0.5.

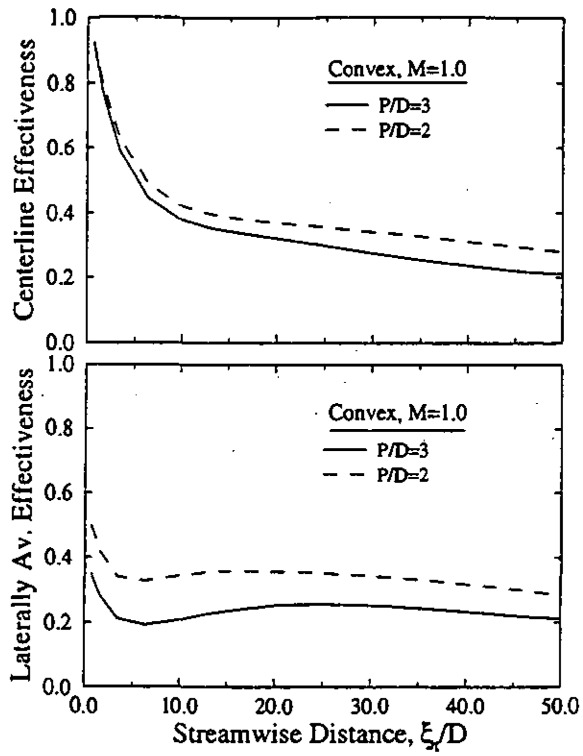

Fig. 11 The effect of hole spacing on cooling effectiveness of a convex surface (M=1.0)

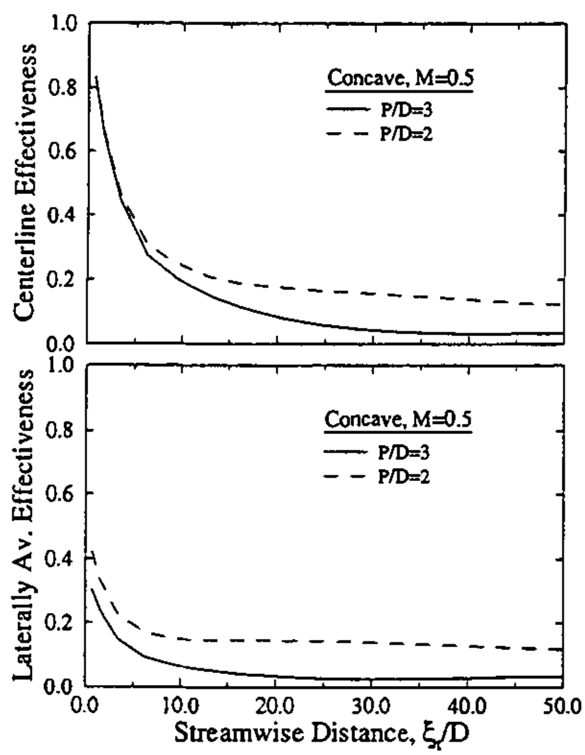

Fig. 12 The effect of hole spacing on cooling effectiveness of a concave surface (M=0.5)

Figures 12 and 13 show the corresponding distribution of cooling effectiveness for the concave surface for M=0.5 and M=1.0, respectively. It is evident that, in this case, the small change in P/D ratio has produced a dramatic increase in the cooling effectiveness, especially for M=1.0. The concave surface, which at P/D=3 is almost unprotected from the effects of the hot gases, now has a much higher cooling effectiveness. In addition, note that: (1) both the centerline and laterally averaged effectiveness appear to be comparable, and (2) for much of the region downstream of the injection hole, the cooling effectiveness is rather uniform. These are the qualities one would want in a good discrete-hole film cooling. Hence, hole spacings smaller than the ones normally used in practical film cooling applications (P/D~3), appear to be highly desirable and essential to protect curved surfaces adequately.

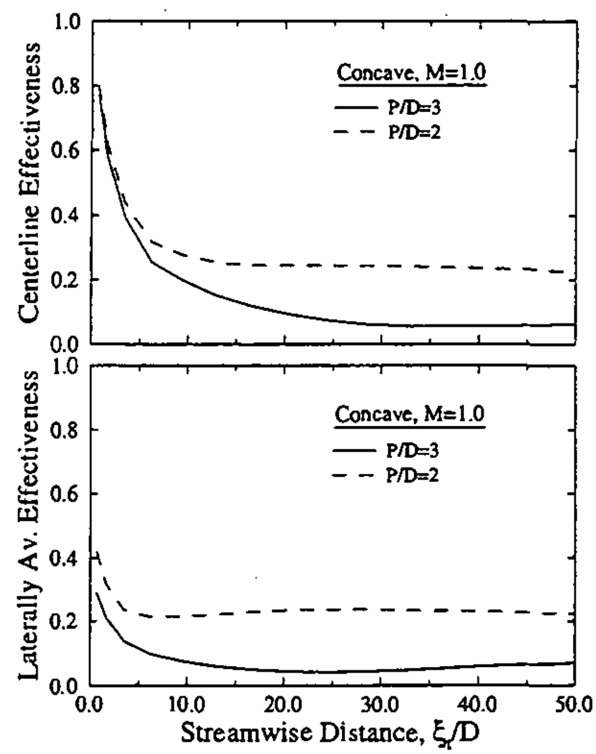

Fig. 13 The effect of hole spacing on cooling effectiveness of a concave surface (M=1.0)

To study the underlying reasons for the higher film cooling performance at P/D=2, we examined plots of the streamwise mean velocity contours and velocity vectors in cross-stream planes. We found that the higher cooling performance at P/D=2 is not only due to the increased coolant mass per unit area, but also the smaller jet penetration and weaker counter-rotating vortices. Figs. 14 and 15 show, respectively, plots of the streamwise mean velocity contours and velocity vectors in cross-stream planes at ξ_r=5D, 10D, and 20D. From Fig. 14, it is clear that, for P/D=2, the jet penetration is smaller and the rate of flow relaxation higher than for P/D=3. In addition, from the velocity vector plots displayed in Fig. 15, we can see that the counter-rotating vortices for P/D=2 are significantly weaker than those for P/D=3. These results are consistent with the findings of Kruse (1985), who noted that when the hole spacing is small, the counter-rotating system

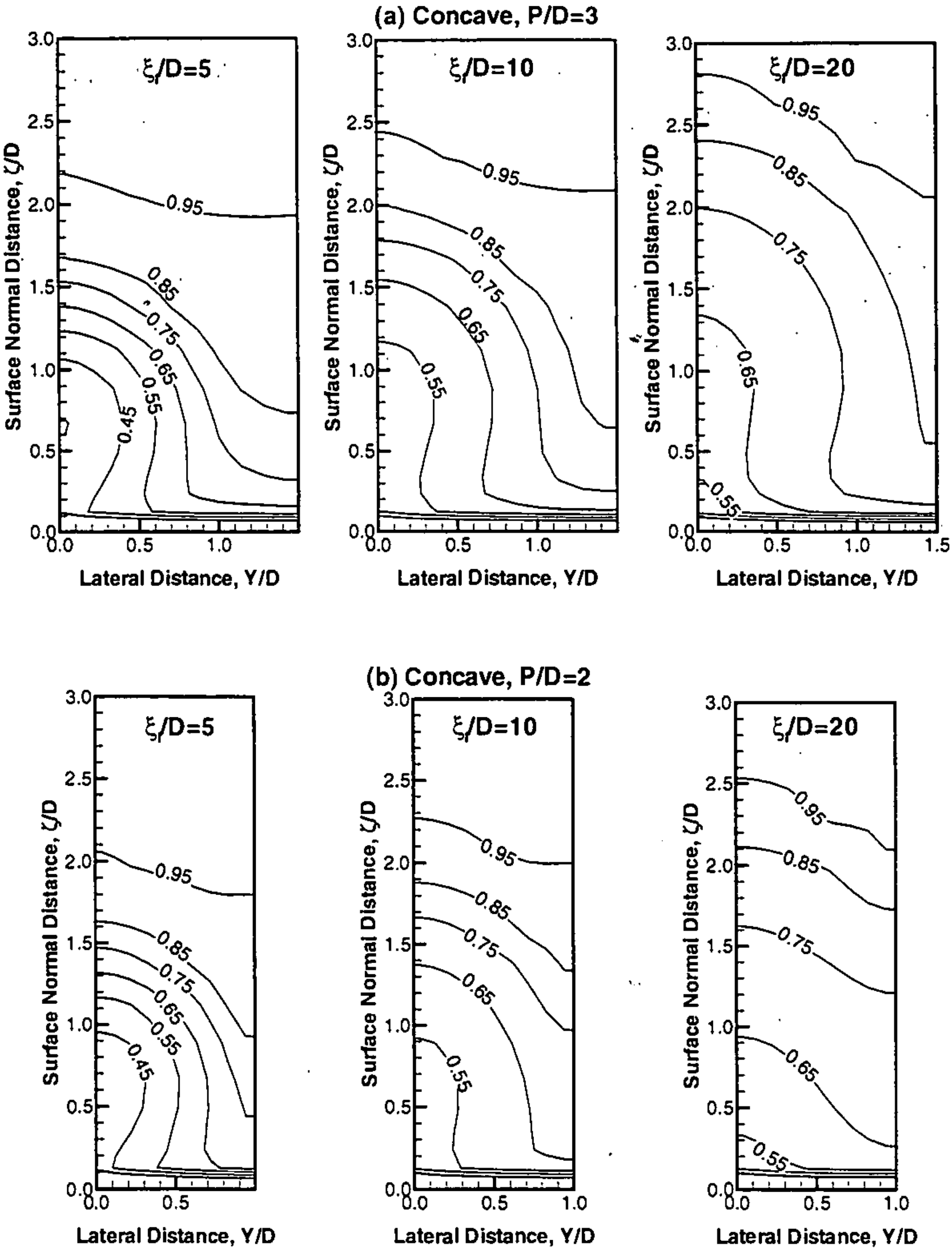

Fig. 14 The effect of hole spacing on U_ξ/U_∞ contours of a concave surface (M=1.0)

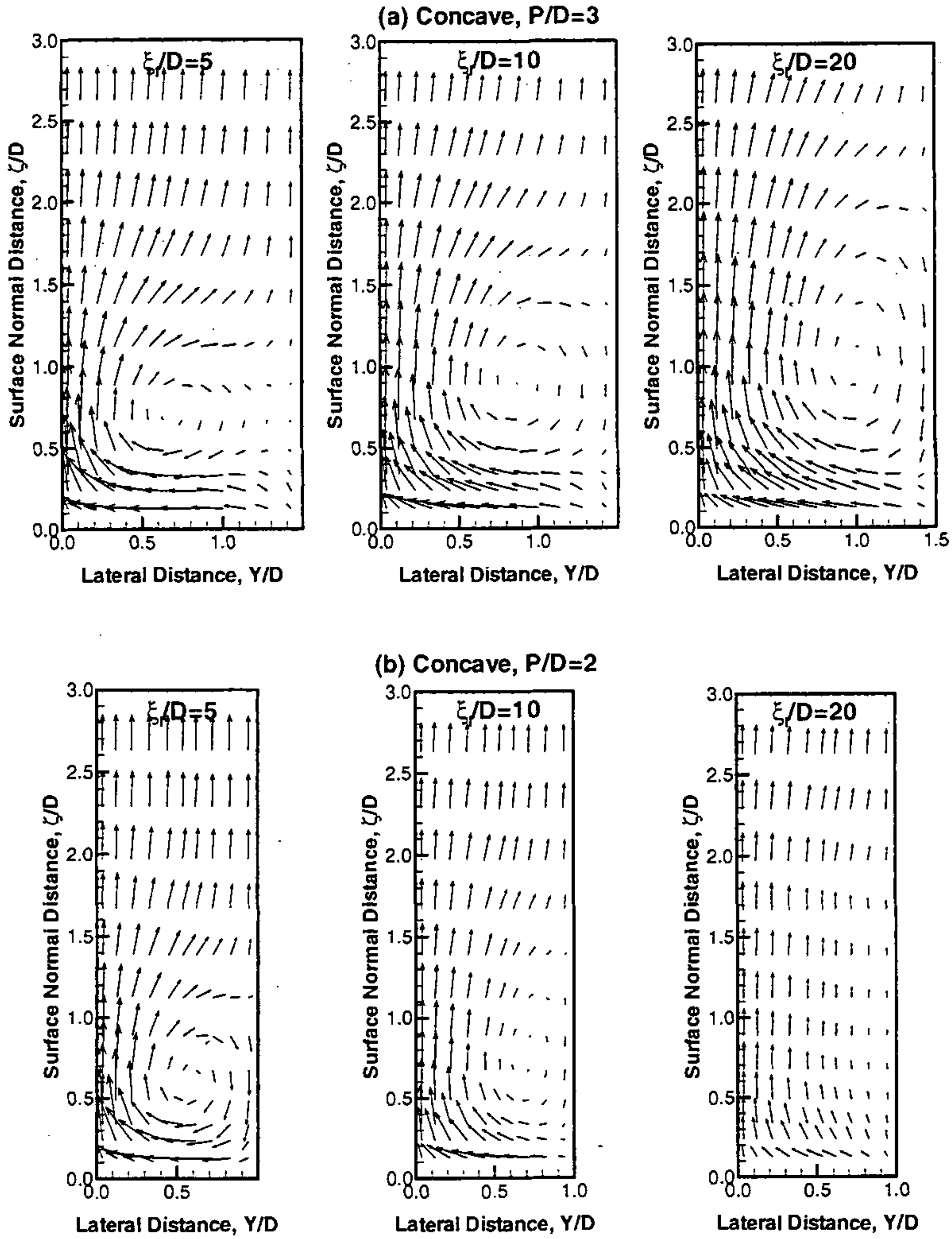

Fig. 15 The effect of hole spacing on counter-rotating vortices of a concave surface (M=1.0)

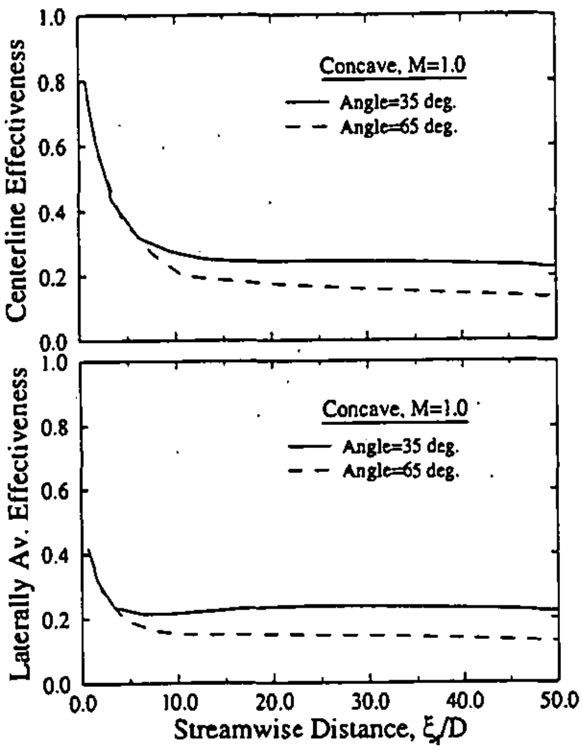

Fig. 16 The effect of injection angle on cooling effectiveness of a concave surface (M=1.0, P/D=2)

of vortices of adjacent jets interact in such a way that the tendency to re-attach to the wall is intensified and the jet penetration into the mainstream is reduced.

In the subsection that discusses the effect of injection angle on cooling effectiveness, we concluded that, on concave surfaces, the effect of injection angle on cooling effectiveness is very weak. The main reason given for the insensitivity of cooling effectiveness to variations in injection angle was the existence of stronger vortices on these surfaces. Tests were, therefore, conducted to re-examine the effect of injection angle on cooling effectiveness for P/D=2, since in this case the vortices are weaker. We considered two injection angles for this purpose, 35° and 65°. The resulting distribution of cooling effectiveness are shown in Fig. 16. As may be expected, for P/D=2, the effect of injection angle on cooling effectiveness is more significant than was the case for P/D=3.

The Effect of Hole Staggering

The advantages of a smaller hole spacing can also be realized by using a staggered-hole arrangement. For example, instead of having one row of holes where the hole spacing is 2D, we can have two rows of staggered holes where the hole spacing in each row is 4D. To demonstrate this, we considered the film cooling layout shown in Fig. 2. This figure shows two rows of staggered holes, where the streamwise distance between rows is 5D. Since injection is streamwise, by symmetry, only half of each hole was considered. Both convex and concave surfaces were studied with this configuration for blowing rates of 0.5 and 1.0. The other geometric parameters used in this case were the same as those used earlier, i.e., $\alpha=35°$, L/D=5, etc.

Figures 17 and 18 show the distribution of adiabatic effectiveness on the convex surface for M=0.5 and M=1.0, respectively. In these figures, the results for the staggered-hole arrangement (P/D=4) are compared against the results for the one-hole arrangement with P/D=2. From these figures, we may note the following two main points. First, except in the region between the two rows, the laterally averaged effectiveness for the two film cooling arrangements are nearly the same for both M=0.5 and M=1.0. In the region between the two rows, the cooling effectiveness for the staggered-hole arrangement is lower because there is only one hole to cover a larger area (P/D=4). Second, the centerline effectiveness following the second hole (plane 2) is much larger than the centerline effectiveness following the first hole (plane 1). This is because, the development of the counter-rotating system of vortices following the second hole is inhibited by the vortices of the first hole. Although to a lesser degree, the vortices of the first hole are also affected by vortices of the second hole.

Figures 19 and 20 show the effects of hole staggering on film cooling effectiveness of the concave surface for M=0.5 and M=1.0, respectively. Again, the results for the one-hole arrangement are compared with the results for the staggered-hole arrangement. The results shown are very similar to those shown in Figs. 17 and 18. First, the laterally averaged effectiveness for the two film cooling arrangements are nearly the same. Second, the distribution of the centerline effectiveness following the second hole (plane 2) is much larger than that following the first row (plane 1). This is again due to the suppression of the vortices of the second hole by the vortices of the first hole.

The effects of hole staggering on jet penetration and counter-rotating vortices were studied using plots of U_t/U_∞ contours and velocity vectors in cross-stream planes. Fig. 21 shows these plots for the concave surface for M=1.0. By comparing these plots with the plots shown in Figs. 14 and 15 (at ξ_1=5D), we can see that, for the staggered-hole arrangement, the jet penetration is also smaller and the counter-rotating vortices weaker. Note that, the plots shown in Fig. 21 are for streamwise distances of 10D, 20D, and 40D, following the leading edge of the first row. Hence, as far as the second row is concerned, these streamwise distances are equivalent to 5D, 15D, and 35D, respectively, from the leading edge of the second hole. In conclusion, hole staggering also reduces jet penetration, weakens counter-rotating vortices, and increases the film cooling effectiveness.

The Effect of Hole Length

The effect of hole length on cooling performances of convex and concave surfaces was investigated by considering L/D ratios of 1.75, 5.0, and 6.0. For the blowing ratios of 0.5, 1.0, and 1.5 examined, the computed cooling effectiveness results for the three L/D ratios were found to be essentially the same, i.e., no significant differences were observed. As discussed in Berhe (1997), on both the flat and curved surfaces, the main effect of hole length is to change the velocity and turbulence intensity profiles at hole exit. However, the effect of these changes on cooling effectiveness is small, especially on curved surfaces. This is because of the existence of pressure gradients on convex surfaces and strong vortices on concave surfaces. On convex surfaces, the pressure gradient forces the coolant jets towards the walls so that the effect of some variations in the velocity profile at hole exit is minimized. Similarly, on concave surfaces, the coolant jets are more thoroughly mixed with the mainstream gases

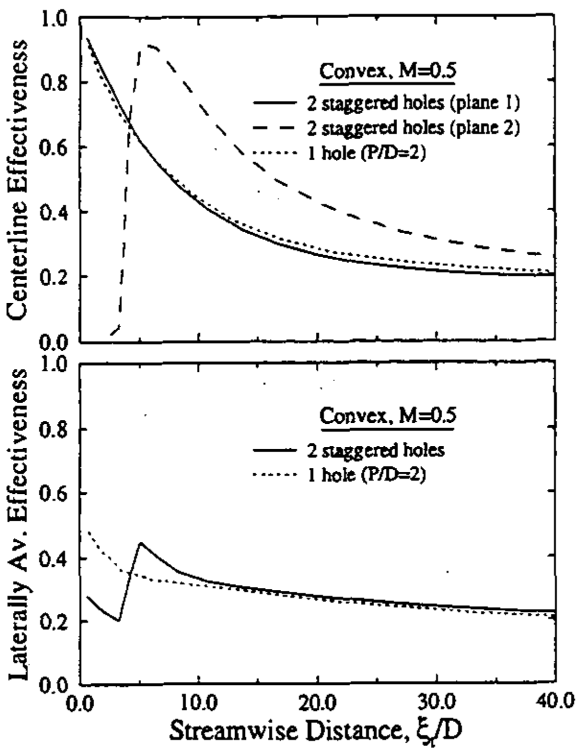

Fig. 17 The effect of hole staggering on cooling effectiveness of a convex surface (M=0.5)

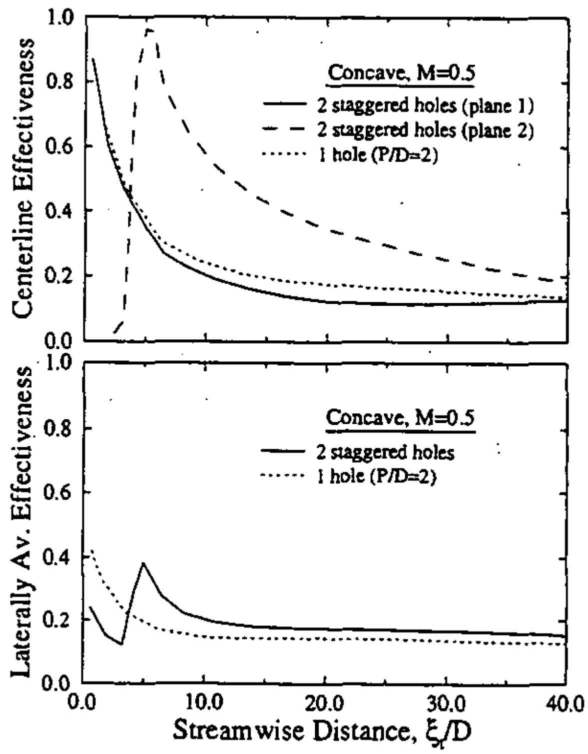

Fig. 19 The effect of hole staggering on cooling effectiveness of a concave surface (M=0.5)

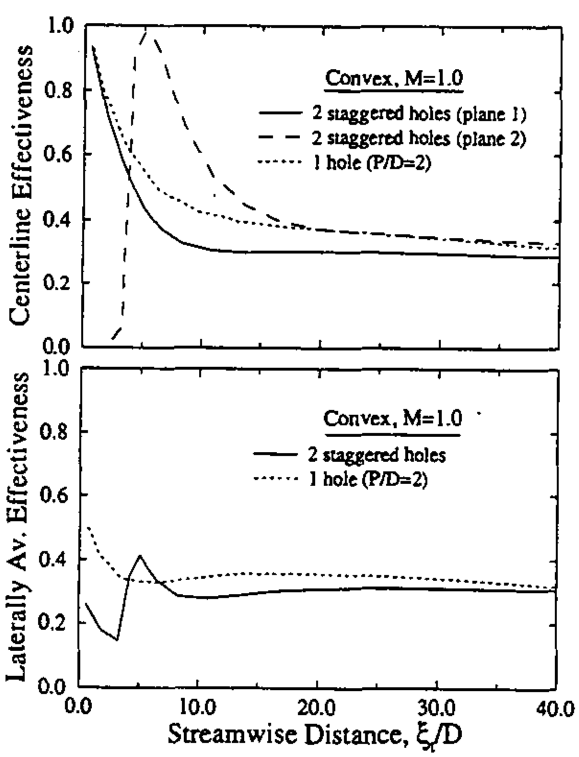

Fig. 18 The effect of hole staggering on cooling effectiveness of a convex surface (M=1.0)

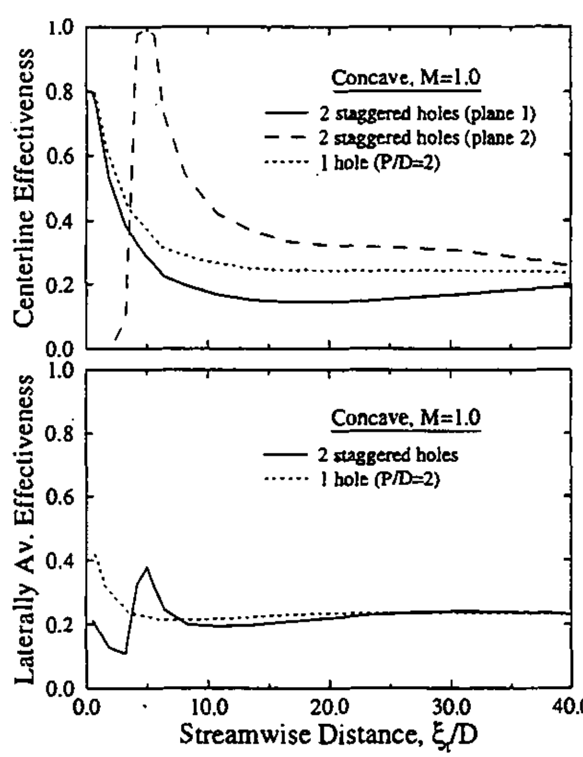

Fig. 20 The effect of hole staggering on cooling effectiveness of a concave surface (M=1.0)

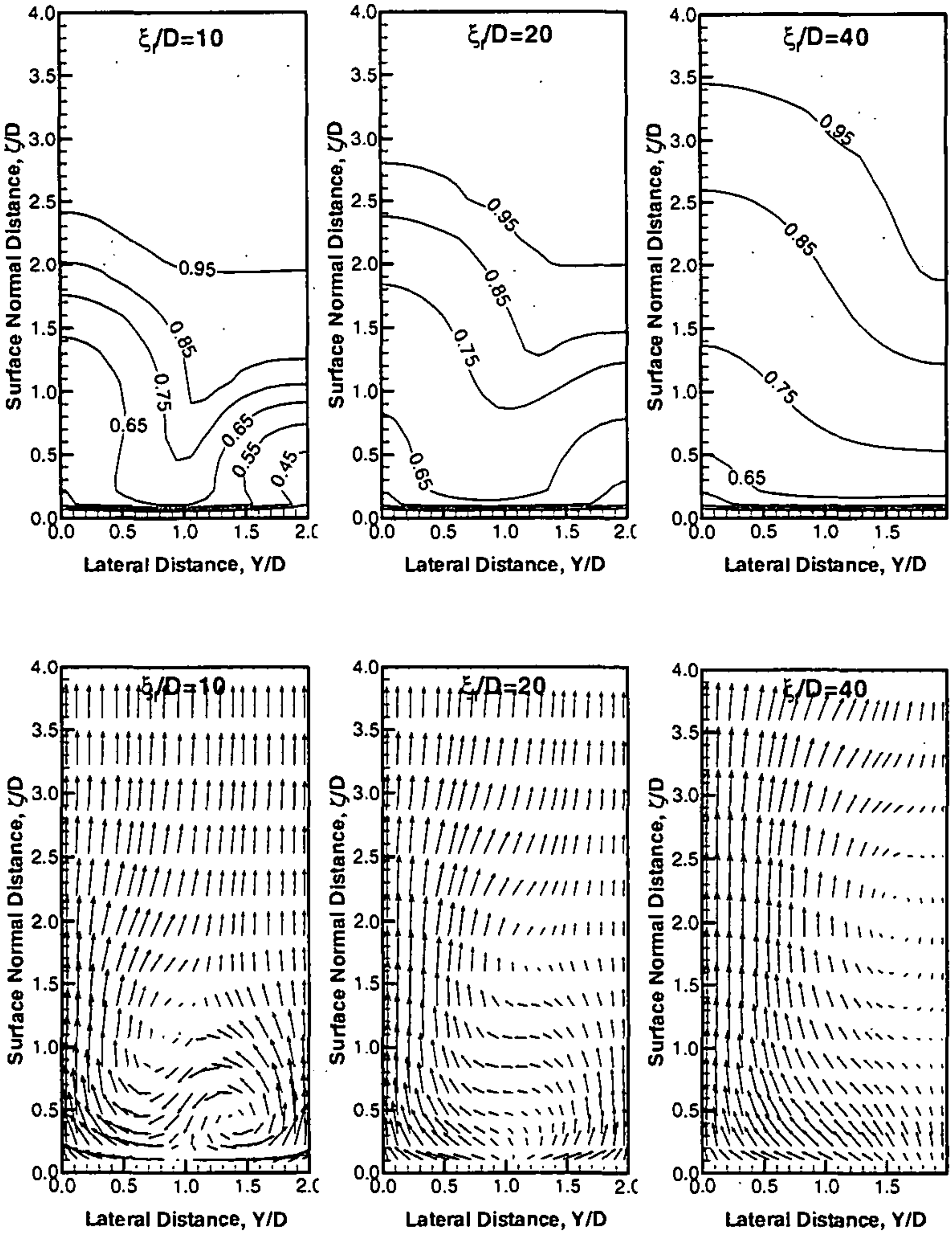

Fig. 21 The effect of hole staggering on U_ξ/U_∞ contours and counter-rotating vortices on a concave surface (M=1.0)

that the effect of some variations in velocity profile at hole exit is insignificant. In conclusion, as far as surface cooling effectiveness is concerned, the hole length is not a significant film cooling parameter.

CONCLUSIONS

Three-dimensional film cooling computations have been conducted on convex and concave film cooling geometries which included the mainflow, injection hole, and supply plenum regions. The effects of several parameters on film cooling performance have been investigated, including the effects of blowing ratio, injection angle, hole length, hole spacing, and hole staggering. The results presented and discussed include plots of adiabatic effectiveness as well as plots of velocity contours and velocity vectors at several cross-sectional planes.

The blowing ratio is one of the most significant parameters investigated. Higher blowing ratios produce larger jet penetration and stronger counter-rotating vortices. These two factors degrade the film cooling performance when the blowing ratio exceeds its optimum value. On the convex geometry studied, the optimum blowing ratio was found to be around 1.0, as contrasted to the optimum blowing ratio of about 0.5 obtained for flat-plate geometries. The optimum blowing ratio on convex surfaces is higher because the pressure gradients that exist on these surfaces force the coolant jets towards the walls. On the other hand, on the concave surface studied, larger blowing ratios generally produced higher cooling effectiveness.

The injection angle affects the cooling effectiveness mainly by affecting the jet penetration into the mainstream. On the convex surface studied, smaller injection angles produced higher cooling effectiveness than larger angles. However, on the concave surface studied, the effect of injection angle on cooling effectiveness was found to be much less significant.

Hole spacing was found to have a very significant effect on cooling effectiveness, especially on concave surfaces. By reducing the hole spacing from 3D to 2D, a dramatic increase in both the centerline and laterally averaged cooling effectiveness was obtained. This increase in cooling effectiveness was found due to not only the increase in coolant mass per unit area, but also the decrease in jet penetration and the weakening of the counter-rotating vortices.

The advantages of a smaller hole spacing can also be realized by using a staggered-hole arrangement. The staggered-hole arrangement studied produced smaller jet penetration, weaker vortices, and higher cooling effectiveness.

Except in situations where the hole length is very small, the hole length was found to have an insignificant effect on cooling effectiveness of curved surfaces. This is because, on both convex and concave surfaces, surface effects (vortices on concave surfaces and pressure gradients on convex surfaces) minimize the effects of changes in velocity and turbulence profiles at hole exit.

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