Surface Injection Effect on Mass Transfer from a Cylinder in Crossflow: A Simulation of Film Cooling in the Leading Edge Region of a Turbine Blade

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ABSTRACT

A naphthalene sublimation technique is used to study the effect of surface injection on the mass (heat) transfer from a circular cylinder in crossflow. Using a heat/mass transfer analogy the results can be used to predict film cooling effects in the leading edge region of a turbine blade. Air injection through one row of circular holes is employed in the stagnation region of the cylinder. Streamwise and spanwise injection inclinations are studied separately, and the effects of blowing rate and injection location relative to the cylinder front stagnation line are investigated. Streamwise injection produces significant mass transfer increases downstream of the injection holes, but a relatively small increase is observed between holes, normal to the injection direction. The mass transfer distribution, measured with spanwise injection through holes located near the cylinder front stagnation line, is extremely sensitive to small changes in the injection hole location relative to stagnation. When the centers of the spanwise injection holes are located 5* or more from the stagnation line, the holes lay entirely on one side of the stagnation line and the injection affects the mass transfer only on that side of the cylinder, approaching the pattern observed with streamwise injection.

NOMENCLATURE

\( d \) diameter of the test cylinder, 63.5 mm in present study
\( D \) injection tube inner diameter, 5.95 mm
\( D_f \) mass diffusion coefficient for naphthalene vapor in air; taking \( S_c = 2.5 \) (Sogin, 1958), \( D_f = 0.0025 \). [Note a more recent study by Chen (1987) indicates a smaller value of \( S_c \) and \( D_f \). This would not affect the relative values of the mass transfer coefficient and Sherwood number with and without blowing.]

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89-GT-276

Printed in USA.
s  spanwise distance between centers of injection holes

\( t \)  thickness of naphthalene layer

\( T \)  temperature

\( T_0 \)  reference temperature

\( T_{aw} \)  adiabatic wall temperature

\( T_r \)  freestream recovery temperature

\( T_w \)  wall temperature

\( T_2 \)  film coolant temperature at the point of injection

\( T_m \)  mainstream temperature

\( T_l \)  local temperature of naphthalene surface averaged over exposure time in the wind tunnel

\( T_u \)  turbulence intensity

\( U_2 \)  mean velocity in injection tube

\( U_m \)  mean velocity of mainstream

\( W \)  width of test section

\( x \)  direction along the tunnel test section

\( x' \)  downstream distance from downstream edge of injection holes

\( y \)  direction along the cylinder center line; \( y = 0 \), on the tunnel bottom wall

\( y' \)  upward distance along the span of the cylinder measured from center of injection holes

\( z \)  direction across the tunnel test section; \( z = 0 \), on the cylinder centerline

reek Symbol

\( \alpha_i \)  streamwise angle between the injection hole centerline and local cylinder surface, either 37° or 90° in this study

\( \beta_i \)  spanwise angle between the injection hole centerline surface, either 20° or 90° in this study

\( \delta^* \)  displacement thickness of endwall boundary layer just upstream of the cylinder

\( \Delta t \)  change in local naphthalene thickness due to exposure in the wind tunnel

\( \Delta t_c \)  time of cylinder exposure in wind tunnel

\( \eta \)  film cooling effectiveness for an adiabatic wall, \( \eta = (T_{aw} - T_w)/(T_2 - T_w) \)

\( \Theta \)  angle around the cylinder measured from the front stagnation point, degrees

\( \Theta_{inj} \)  angular location of injection hole center relative to cylinder front stagnation point, degrees

\( \theta^* \)  dimensionless temperature, \( \theta^* = (T_2 - T_w)/(T_w - T_0) \)

\( \mu \)  dynamic viscosity of air

\( v \)  kinematic viscosity of air, \( \mu/p \)

\( \rho \)  density of air

\( \rho_s \)  density of solid naphthalene, 1.145 gm/cm³ (Karni, 1985)

\( \rho_{v_i} \)  density of naphthalene vapor at an inactive (non-subliming) surface, zero in this study

\( \rho_{v,w} \)  local naphthalene vapor density on the cylinder surface averaged over exposure time in the wind tunnel

\( \rho_{v,m} \)  density of naphthalene vapor in the mainstream, zero in this study

Dimensionless Parameters

\( Nu \)  local Nusselt number, \( h(T_w - T_{aw})/(T_0 - T_m) \)

\( Re \)  Reynolds number based on cylinder diameter, \( U_0d/\nu \)

\( Sc \)  Schmidt number, \( \nu/D_f \)

\( Sh \)  local Sherwood number, \( h_{md}/D_f \)

\( Sh_{sp} \)  spanwise average Sherwood number at a given angle

INTRODUCTION

Application of film cooling through a single row or multiple rows of circular holes is common in gas turbine systems. The need to improve performance by increasing turbine inlet temperature, without shortening the components' lifespan, has prompted a large number of studies aimed at a better understanding of the complex flow and heat transfer mechanisms involved in film cooling (cf. Metzger, 1983). Advanced materials such as nickel super alloys and various ceramics which are used in modern turbines (Kear, 1986) have, in general, relatively low thermal conductivity and diffusivity. Thus, large local variations of the heat transfer coefficient can produce significant temperature gradients in the wall of a turbine blade. These gradients may cause high thermal stresses and ultimately could lead to blade failure. An effective film cooling design must reduce the temperature gradients over the surface, as well as the mean wall temperature. Therefore, knowledge of the heat transfer distribution over the blade surface, with various coolant injection configurations, is necessary for a successful turbine design.

Two methods have been developed to predict film cooling effects on heat transfer. The first method (Eckert, 1983 and Goldstein, 1971) defines the heat transfer coefficient with an adiabatic wall temperature

\[ q_w = h_T(T_w - T_{aw}) \]  \( (1) \)

For a constant property flow, the heat transfer coefficient \( h_T \) is independent of the temperature difference \( T_w - T_{aw} \). A dimensionless adiabatic wall temperature, known as the film cooling effectiveness, \( \eta \), is given by:
In this method, the heat transfer coefficient and the effectiveness are determined separately. Then, for any given mainstream and coolant temperatures and a prescribed wall heat flux, the wall temperature distribution can be obtained using Eq. (1).

In the second method (Metzger et al., 1968 and Choe et al., 1974) the heat transfer coefficient is defined by the equation

$$h = \frac{T_m - T_w}{T_w - T_r}$$

For low-speed constant property flows, $T_r = T_m$

$$h = \frac{T_w - T_m}{T_w - T_r}$$

In this approach provides a direct means of determining heat transfer coefficients for film cooling on an isothermal surface. Here, the heat transfer coefficient $h'$ is not independent of the temperature difference $T_w - T_m$; but as shown in Metzger et al., 1968, Metzger and Fletcher, 1971, and Eckert et al., 1971, for a constant property flow, $h'$ varies linearly with the dimensionless temperature

$$\theta^* = \frac{T_m - T_r}{T_w - T_r}$$

Note that unlike $h_H$, the coefficient $h'$- defined by Eq. 3- can take on unusual (e.g. negative) values, especially close to an injection location. The coefficients $h$ and $h'$ obtained on an isothermal surface for $\theta^* = 0$ and 1, respectively, can be used to approximate heat transfer coefficients on a surface where gradual temperature variations take place (Eckert, 1983). In that case,

$$h_0 = h_H$$

and the relation between $h'$ and $\theta^*$ is given by

$$h_H = 1 - \theta^*$$

In various studies (Metzger and Fletcher, 1971, Miller and Crawford, 1984, and Ligrani and Canic, 1986) values of $h_H$ and $\theta^*$ were approximated from $h'$ and $\theta^*$ data using a linear extrapolation based on Eq. (6).

Values of the heat transfer coefficient $h_H$ for two-dimensional slot injection across the span of a flat plate are presented by Hartnett, Birkebak and Eckert, 1961a and 1961b. Their data show relatively large variations near the injection slot; as the downstream distance from the slot increases, $h_H$ quickly declines approaching the coefficient obtained without injection. Measurements of heat transfer coefficients averaged across the test surface are reported in some studies of three-dimensional film cooling from a single row and multiple rows of circular holes (Metzger and Fletcher, 1971; Mayle and Camarata, 1975; Liess, 1975; Metzger, Kuenstler and Takeuchi, 1976; Lander, Fish and Soo, 1972; Ligrani and Breugelmans, 1981). Effects of parameters such as injection geometry, blowing rate, pressure gradient, and boundary layer transition on variation of spanwise-averaged coefficients in the mainflow direction were investigated in these studies.

Local heat transfer coefficients ($h_H$) over a film-cooled plate with one and two rows of injection holes were measured by Eriksen and Goldstein, 1974 and Jabbari and Goldstein, 1978. Mick and Mayle (1988) measured local $h_H$ values using two rows of spanwise injection holes located 15° and 44° from the stagnation line of a blunt body with a circular leading edge, followed by a flat section. Local measurements near the leading edge of a turbine vane and on the front portion of a cylinder were conducted at Purdue University by Hanus and L'Ecuyer, 1977; Luckey, Winstanley, Hanus and L'Ecuyer, 1977; Luckey and L'Ecuyer, 1981; and Bonnice and L'Ecuyer, 1983. In these studies $h'$ values were obtained near the center of the wind tunnel (cylinder mid-span). Spanwise injection through one to five rows of holes was employed.

In an experimental set-up where significant temperature differences exist (Eriksen et al., 1974; Jabbari et al., 1978; Mick et al., 1988; Hanus et al., 1977; Luckey et al., 1977; Luckey et al., 1981; and Bonnice et al., 1982) wall condensation makes it difficult to sustain the imposed boundary condition ($T_m = constant or q_w = constant$) near the injection holes and close to the edges of the test surface. Consequently, in several studies the analysis between heat and mass transfer was utilized to obtain transfer coefficients on flat surfaces (Hay, Lampard and Saluja, 1980a; Hay Lampard and Saluja, 1980b; Goldstein and Tridgell, 1982; and Kusuma, Hirata and Kasagi, 1981). The last two studies demonstrated how mass transfer using naphthalene sublimation can provide contours of local transfer coefficients on a flat plate near the holes of single-row and multiple-row injection geometries.

When naphthalene sublimation is used, a direct analogy to the adiabatic wall heat transfer coefficient ($h_H$) defined by Eq. (1) leads to the following definition of a mass transfer coefficient:

$$h_m = \frac{\dot{M}}{\bar{V}_{w, v} - \bar{V}_{v, i}}$$

Alternatively, an equivalent relation to Eq. (3) gives

$$h_m = \frac{\dot{M}}{\bar{V}_{w, v} - \bar{V}_{v, w}}$$

In the naphthalene sublimation technique used in the present study a nearly-uniform vapor density is maintained over the entire cylinder surface, and the naphthalene vapor concentration in the mainstream and in the injected gas is zero. This is equivalent to isothermal boundary conditions with $T_w = T_m$ (or $\theta^* = 0$). Thus, Eqs. (7) and (8) both reduce to

$$h_m = \frac{\dot{M}}{\bar{V}_{v, w}}$$

In the present study local mass transfer coefficients are obtained around the entire circumference of a circular cylinder and along a span containing five injection holes (in a single row). Spanwise and streamwise inclined injections are employed at blowing rates of 0.5, 1.0 and 2.0. The injection location is varied relative to the cylinder's front stagnation line. In each test run, measurements are taken at about 3800 local points over the cylinder surface. Thus, exact details of the mass transfer distribution pattern are revealed. Injection geometry and blowing rate effects in the region away from the
base of the cylinder — where endwall effects on the flow are relatively small — are reported here. The injection effects near the endwall will be reported later.

EXPERIMENTAL APPARATUS AND MEASUREMENT TECHNIQUES

The primary objective of the experimental apparatus is to provide a means of determining the local rate of naphthalene sublimation from the cylinder surface during exposure to an air flow. This local mass transfer rate is then expressed in terms of the coefficient $h_e$ and the Sherwood number. Detailed descriptions of the experimental apparatus and the measurement procedure are given by Karni, 1985. The maximum measurement error in obtaining $h_e$ is 6%.

The test cylinder $(d = 63.5$ mm) is shown in Fig. 1; a portion extending over about 60° of the cylinder circumference and along its entire naphthalene-covered span is removed [see Fig. 1(a)] and two sections with different injection inclinations are made to fit in that region [Figs. 1(b) and 1(c)]. During tests the cast naphthalene layer covers the outer surface of the section used as if it were an integral part of the cylinder. Teflon (Polytetra-Fluoro-Ethylene) injection tubes are installed in these sections; in one section, the tubes are inclined such that the injected air enters the mainstream at a spanwise angle of 20° to the cylinder surface [Fig. 1(b)]; in the other section, the tubes are angled 37° to the surface in the streamwise direction [Fig. 1(c)]. All injection tubes have an inside diameter of 5.95 mm and a wall thickness of 0.35 mm. They extend 1.0 mm out of the section surface and thus are flush with the naphthalene layer.

The time of exposure in the wind tunnel $(A_t)$ is between 35 and 70 minutes (depending on operating conditions). During tests 0.020-0.13 mm of naphthalene sublimed from the cylinder surface. Since the mainstream and secondary air contain no naphthalene, the local mass transfer coefficient is...
RESULTS

1. Streamwise Injection

The Sherwood number distributions for a streamwise injection angle, $\alpha_i$ of 37°, an injection locations $\theta_{inj}$ of 10° and blowing rate $M$ of 0.50, 1.0 and 2.0, are shown in Figs. 2(a), (b) and (c), respectively. These and all other computer-drawn contour plots are obtained from the actual measurements around the entire cylinder circumference and over part of its span. The difference between adjacent contour lines corresponds to a Sh change of 200. The injection holes are shown by the shaded regions in the left-hand side of each figure. Since the measurement points located nearest each hole are not evenly distributed around its periphery, the contour lines very near the holes are somewhat distorted during the computer drawing process and do not follow the exact shape of the hole where Sh = 0.

Figure 2 demonstrates that the injected air jets produce large Sh values and steep local gradients downstream of the injection holes while a relatively small increase in Sh is seen between the holes. The contours clearly indicate the flow pattern near the injection holes. Somewhat similar mass transfer trends were reported in studies of streamwise injection over flat plates by Hay et al., 1985a; Kumada et al., 1981; and Goldstein et al., 1982. In Goldstein et al., 1982 larger increases of Sh were observed between injection holes on a flat plate. The present data show that the region downstream of each hole, where the injected flow has a relatively large effect increases with increasing blowing rate, but is generally limited to the front.

TABLE 1

<table>
<thead>
<tr>
<th>Streamwise Injection</th>
<th>Spanwise Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_i=37^\circ$</td>
<td>$\theta_{inj}=90^\circ$</td>
</tr>
<tr>
<td>$\alpha_i=90^\circ$</td>
<td>$\theta_{inj}=20^\circ$</td>
</tr>
<tr>
<td>$M$</td>
<td>$\theta_{inj}$(degrees)</td>
</tr>
<tr>
<td>0.50</td>
<td>10</td>
</tr>
<tr>
<td>0.50</td>
<td>20</td>
</tr>
<tr>
<td>0.50</td>
<td>30</td>
</tr>
<tr>
<td>1.01</td>
<td>10</td>
</tr>
<tr>
<td>1.02</td>
<td>10</td>
</tr>
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<td>1.01</td>
<td>20</td>
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<tr>
<td>1.00</td>
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<td>10</td>
</tr>
<tr>
<td>2.01</td>
<td>20</td>
</tr>
<tr>
<td>1.99</td>
<td>30</td>
</tr>
</tbody>
</table>

1Test runs where the lower edge of the first injection hole is located 1.0 hole-diameter above the endwall. In all the other tests, the lower side of the first injection hole is adjacent to the tunnel bottom wall.

In all the tests, measurements are conducted over a span containing 5 injection holes (including the region immediately above the endwall) and around the entire cylinder circumference. Spanwise injection is directed toward the endwall.

OPPERATING CONDITIONS

The various operating conditions are specified in Table 1. In all the test runs, the freestream velocity and the Reynolds number are within 2% of the values given in the table. The mainstream turbulence intensity is measured while the cylinder is out of the wind tunnel. In all the tests, measurements are conducted over a span containing 5 injection holes (including the region immediately above the endwall) and around the entire cylinder circumference.

<table>
<thead>
<tr>
<th>Freestream</th>
<th>Endwall Boundary Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re = 76,000$</td>
<td>$\delta = 2.23 \text{ mm}$</td>
</tr>
<tr>
<td>$U_m = 19.16 \text{ m/s}$</td>
<td>$\delta_2 = 1.56 \text{ mm}$</td>
</tr>
<tr>
<td>$Tu = 0.45%$</td>
<td>$H = 1.43$</td>
</tr>
<tr>
<td>cylinder diameter, $d = 63.5 \text{ mm}$</td>
<td>$H = 1.43$</td>
</tr>
<tr>
<td>injection hole diameter, $D = 5.95 \text{ mm}$</td>
<td>blockage ratio, $d/W = 0.104$</td>
</tr>
<tr>
<td>aspect ratio, $L/d = 4.8$</td>
<td>aspect ratio, $L/d = 4.8$</td>
</tr>
</tbody>
</table>

Fig. 2 Sh distribution for streamwise injection. Contours of Sh x 10$^{-2}$, $\alpha_i = 37^\circ$; $\theta_{inj} = 90^\circ$; $\theta_{inj} = 10^\circ$; s/D = 3.
A symmetric Sh distribution is observed downstream of holes located at y/d > 0.5, but the spanwise pressure gradients, created by the endwall boundary layer in the cylinder's front stagnation region, divert the jets of the lower injection hole toward the tunnel wall.

Figure 3 shows angular variations of Sh at selected spanwise distances from the center of an injection hole located far from the endwall for αi = 37°, M = 0.50, and Bi = 10°. The circumferential Sh distribution measured over a cylinder with no injection holes is also shown in this figure. The spanwise distance from the hole's center is denoted by y'. The location of a given y' with respect to the injection hole is shown in the insert at the top right corner of Fig. 3. Immediately downstream of the hole's centerline (y'/D = 0), Sh is more than 3 times its value without injection. As y'/D and/or 8 increase, Sh decreases sharply. Figures 2 and 3, show that Sherwood number values measured upstream of an injection hole's centerline and on the opposite side of the cylinder's symmetry line are nearly unaffected by the injected jets; the mass transfer pattern in these regions is similar to that measured by Karni, 1985 over a cylinder with no injection holes.

Variations of spanwise average Sherwood number, Sh, around the cylinder for αi = 37° are presented in Fig. 4. The Sh distribution obtained far from the endwall on a cylinder with no injection holes is also shown in this figure. The spanwise-averaged coefficients confirm the trends seen in Figs. 2 and 3 (local Sh distributions). Maximum value showing an increase of 2 - 3 times over the mass transfer without injection are observed immediately downstream of the injection holes. In the region most influenced by injection (8inj < 8 < 120°), Sh values located immediately downstream of injection fall sharply as 8 increases, reaching a minimum near the laminar boundary layer separation angle (8 = 80°-90°); a second peak is observed at 8 = 110° - 120°. At 80° < 8 < 180°, Sh has a pattern similar to a Nu(Sh) distribution over an impermeable circular cylinder at critical and supercritical Re (Schmidt and Wenner, 1941; Giedt, 1949; Achenbach, 1975; and Sogin and Subramanian, 1961) At high Reynolds numbers (Re > 2x10^5), the down-
stream portion of the cylinder boundary layer becomes turbulent producing a sharp increase of heat (mass) transfer, and the separation angle is between 110° and 150°. It is possible that the additional momentum supplied by the jets causes a delay in the boundary layer separation, and over some portions of the cylinder span a transitional or turbulent boundary layer exists at θ = 90° - 130°.

Figure 4 shows that on the side of the cylinder where no injection is employed (θ < 0°) Šf isp is similar to the impermeable wall coefficient over the front of the cylinder; but, for M = 1.0 and 2.0, Šf isp is somewhat lower than this coefficient in the wake region. At θinj = 30°, relatively low Šf isp values are obtained in the wake for M = 0.5 as well. This may be caused by the jets' interference with the characteristic wake pattern of alternating vortex shedding. Note that similar reductions of heat (and mass) transfer were measured in the wake of a smooth impermeable cylinder exposed to a mainstream with high turbulent intensity, (Kestin and Wood, 1971, and Lowery and Vachon, 1975), and when a splitter plate was installed at θ = 180° (Hiwada, Niwa, Kumada and Mabuchi, 1979).

II. Spanwise Injection

The investigation of spanwise injection focuses on the influence of small variations in θinj near the cylinder front stagnation line at different blowing rates. As in Fig. 2 all computer-drawn contour plots (Figs. 5 and 6) are prepared via interpolations of the actual measurements. The injection holes (which, in these figures, are divided into two parts) are indicated by the shaded regions near the left and right boundaries of the figures. Note that the injected jets are directed toward the endwall.

Sherwood number distributions for an injection angle, θi, of 20°, a blowing rate, M, of about 0.5, and injection locations, θinj of 1°, 3° and 5° are presented in Figs. 5(a), (b) and (c), respectively. Note that based on their inner diameter, the maximum angular range of the holes is about 10° (θinj ± 5°); thus, at θinj = 5°, the injection holes are entirely on one side of the cylinder stagnation line. A nearly symmetric (around θ = 0) Šh distribution is seen in Fig. 5(a) (θinj = 1) as θinj increases to 3° [Fig. 5(b)] and to 5° [Fig. 5(c)], the injection effects become skewed. Although the jets are injected with a relatively large spanwise velocity component (θi = 20°) and a zero streamwise component (αi = 90°), they appear to be turned downstream by the main flow immediately upon their entry when θinj = 3° or 5° [Fig. 5(b) and (c)]. Consequently the mass transfer pattern approaches that observed with streamwise injection (Fig. 2). Mick and Mayle (1988) observed a similar pattern while employing two rows of injection holes at θi = 30° and θinj = 15° and 44°. In Figs. 5(a,b,c) low transfer coefficients are seen along the cylinder span at θ = 80°, and local Šh peaks are detected at θ = 100° to 110°.

Sherwood number distributions for θi = 20°, M = 2.0, and θinj = 0° and 5° are presented in Figs. 6(a) and (b), respectively. A symmetric Šh distribution is seen over both sides of the cylinder stagnation line for θinj = 0° [Fig. 6(a)], but the Šh distribution is quite skewed at θinj = 5° [Fig. 6(b)]. However, at M = 2.0 and θinj = 5° [Fig. 6(b)] the jet trajectories retain larger downward spanwise components after entering the main flow than do their counterparts at m = 0.5 [Fig. 5(c)]. The skewed distribution obtained at all blowing rates for θinj ≤ 5° probably result from the entire hole cross-section being located on one side of the cylinder front stagnation line. Thus, the other
side of this line is unaffected by injection at $M = 0.5$ and 1.0, and only modest increases over a small region are seen at $M = 2.0$. For $M = 2.0$ (Fig. 6), relatively low $Sh$ values are detected at $8 = 90^\circ - 100^\circ$, and local highs are seen at $8 = 110^\circ - 115^\circ$. Especially large $Sh$ variations occur at $80^\circ < 8 < 120^\circ$ when $8_{inj} = 5^\circ$ is employed [Fig. 6(b)].

Figure 7 shows angular variations of $Sh$ at selected spanwise distances from the center of an injection hole located far from the endwall for $M = 1.0$, $8_1 = 20^\circ$, and $8_{inj} = 3^\circ$. The relation between the distance from the hole's center ($y'$) and the injection hole is shown in the insert at the top of the figure. These data show that as the downward distance from the hole's center increases, the injection effect increases on both sides of the hole. Maximum $Sh$ values of about 2.5 times that without injection are observed adjacent to the holes and just below them.

Spanwise average Sherwood number ($Sh_{sp}$) values are presented in Fig. 8. The circumferential $Sh$ distribution obtained far from the endwall on a cylinder with no injection holes is also shown in these figures. The spanwise-averaged coefficients show some of the trends seen in Figs. 5-7 (local $Sh$ distributions). The $Sh$ peaks near the injection holes increase with the blowing rate and are 2 - 3 times the $Sh$ value without injection. For a given blowing rate, $Sh_{sp}$ on the side of the cylinder's stagnation line opposite to injection (in the angular range $-130^\circ < 8 < 0^\circ$) drops sharply as $8_{inj}$ increases (approaching an impermeable wall distribution), whereas $Sh_{sp}$ values on the injection side (at $8_{inj} < 8 < 130^\circ$) are nearly unaffected by changes in the injection location. The last observation is surprising, considering the great influence of small $8_{inj}$ variations on local $Sh$ distribution (Figs. 5-6) and the fact that the bulk mass flow over the injection side increases as $8_{inj}$ increases while the bulk flow...
over the other side decreases. For \( \theta_{inj} = 5^\circ - 7^\circ \), the \( \overline{Sh}_{sp} \) values on the side opposite to injection closely follow the impermeable wall distribution in the angular range \( -90^\circ < \theta < 0^\circ \) (Fig. 8). The average coefficients on the injection side (or both sides for \( 0^\circ \leq \theta_{inj} \leq 3^\circ \)) peak immediately downstream of injection and fall sharply as \( \theta \) increases. A minimum \( \overline{Sh}_{sp} \) is reached between \( \theta = 80^\circ \) and \( \theta = 100^\circ \), depending on blowing rate. A second peak is observed at \( \theta = 100^\circ - 120^\circ \), and further downstream, \( \overline{Sh}_{sp} \) decreases, approaching values comparable to those obtained without injection. Similar to average coefficients for streamwise injection (Fig. 4), the \( \overline{Sh}_{sp} \) distribution at \( 90^\circ < \theta < 180^\circ \) between \( \theta = 80^\circ \) and \( \theta = 100^\circ \), depending on blowing rate. A second peak is observed at \( \theta = 100^\circ - 120^\circ \), and further downstream, \( \overline{Sh}_{sp} \) decreases, approaching values comparable to those obtained without injection. Similar to average coefficients for streamwise injection (Fig. 4), the \( \overline{Sh}_{sp} \) distribution at \( 90^\circ < \theta < 180^\circ \) between \( \theta = 80^\circ \) and \( \theta = 100^\circ \), depending on blowing rate. A second peak is observed at \( \theta = 100^\circ - 120^\circ \), and further downstream, \( \overline{Sh}_{sp} \) decreases, approaching values comparable to those obtained without injection.

As shown in Table 2, the main difference between the present injection geometry and that of Bonnice and L’Ecuyer, 1983 is the ratio of cylinder to injection hole diameter, \( d/D \). Thus, for a given \( x'/D \), their data points are, in fact, at a much smaller angular distance \( \theta_{inj} \) than present data. This may account for the somewhat different \( h/h_0 \) patterns obtained in the two studies at \( y'/D = 0.0 \) [Fig. 10(a)]. The fact that larger injection holes are used in the present study implies that, at a given blowing rate, the total injected mass flow in present tests is higher than that of Bonnice and L’Ecuyer, 1983. Thus, their average values \( h/h_0 \) at \( M = 2.0 \) agree better with present data at \( M = 1.0 \) than at \( M = 2.0 \) [Fig. 10(b)].
CONCLUSIONS

Several surface injection parameters affecting mass transfer from a circular cylinder (or a turbine vane leading edge) have been investigated. The following conclusions may be drawn from the results obtained with spanwise and streamwise injection holes at angular locations of 0° to 7° and 10° to 30° from stagnation, respectively, and at blowing rates of 0.5 to 2.0.

a) The injected jets produce large Sh values and steep local gradients downstream of the streamwise injection holes while a relatively small increase in Sh is detected between the holes. A somewhat similar periodic pattern, corresponding to individual jet trajectories, is also observed for spanwise injection when the holes are located entirely on one side of the cylinder stagnation line (i.e., θ inj ≥ 5°). For such geometries, the injection effects on the opposite side of the stagnation line are relatively very small.

b) For streamwise injection, the size of the region directly downstream of each hole, where high Sh values are found, increases with M and decreases as the injection is shifted downstream (i.e., as θ inj increases).

c) The local mass transfer distribution for spanwise injection near the stagnation line is extremely sensitive to small variations in θ inj. Nearly symmetric Sh distributions are obtained for θ inj = 0° to 1°, but, for θ inj of 3° or higher, the injection effects become very skewed. Despite that, the spanwise-averaged coefficients over the side of the stagnation line where injection is employed vary little with θ inj. Shsp does, however, approach the values for a cylinder without injection on the other side of the symmetry line as θ inj increases.

d) For both streamwise and spanwise injections, Sh values generally decrease with downstream distance from injection, reaching a minimum at θ = 80° - 100°. Further downstream, local peaks are observed at θ = 100° - 120°. This trend could result from a boundary layer transition to turbulence, which may occur over portions of the cylinder span at θ = 80° - 90°.

e) Mass transfer values lower than those obtained with a uniform cylinder are observed in the downstream portion of the wake (θ = 180° ± 50°) for streamwise injection at M = 1.0 and 2.0. A similar pattern is seen with spanwise injection at M = 2.0 and, if θ inj is between 3° and 7°, at M = 1.0, also. This trend is probably due to the injected jets interfering with the characteristic wake pattern of alternate vortex shedding.

f) Downstream of injection, the spanwise-averaged Sherwood number generally increases with blowing rate.

REFERENCES


