PERGAMON

International Journal of Heat and Mass Transfer 41 (1998) 3441–3450

International Journal of HEAT and MASS TRANSFER

# Mass transfer from rotating circular cylinders in a submerged slot jet of air

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Received 27 August 1997; in final form 28 January 1998

**Abstract**

Isothermal convective mass transfer behaviour of a horizontal rotating circular cylinder exposed to a two dimensional slot jet of air was determined as a function of the flow and the geometrical parameters using a photo-evaporative mass transfer measurement technique. The rotational Reynolds number ($Re_w$) varied from 0–8.0 × $10^4$, the jet exit Reynolds number ($Re_j$) from 4.6 × $10^4$–2.70 × $10^5$, the ratio of the cylinder diameter to the jet slot height ($d/D$) from 3.333–15, the ratio of the distance between the jet exit and the front of the cylinder to the slot height ($L/D$) from 1–16, the ratio of the off-set between the axis of the cylinder and the symmetry plane of the jet to the slot height ($E/D$) from −0.555–2.133 and the jet impingement angle ($\phi$) from 20°–90°. Some correlations of the mean Sherwood number ($Sh$) have been produced by using the experimental data. Comparison of the mass transfer performance of the present configuration with those of a stationary cylinder in the same jet flow and in a uniform crossflow of the similar velocities indicated that the rotation had a deleterious effect on the mean mass transfer. 

*Key words:* Heat transfer; Mass transfer; Jet flow; Rotating cylinders; Slot jets; Impinging jets.

**Nomenclature**

$c$ calibration constant [kg m$^{-2}$]
$D$ jet nozzle height [m]
$D_{AB}$ mass diffusion coefficient of the solvent in air [m$^2$ s$^{-1}$]
$d$ diameter of the cylinder [m]
$I$ intensity of reflected infra-red light [V]
$I_0$ overall intensity change between completely wet and dry paper [V]
$L$ the distance between the jet exit and the cylinder surface [m]
$N$ mass flux [kg m$^{-2}$ s$^{-1}$]
$Re$ Reynolds number
$Sh$ Sherwood number
$t$ time [s]
$u$ velocity [m s$^{-1}$].

*Greek symbols*
$\phi$ jet impact angle [deg]
$\mu$ viscosity [kg m$^1$ s$^{-1}$]
$\rho$ density [kg m$^{-3}$].

*Subscripts*
c crossflow conditions
f free stream conditions
j jet nozzle exit conditions
s surface conditions
w cylinder walk conditions.

## 1. Introduction

Jet impingement is often used when a high transport coefficient is required. It also provides a means of localising high transfer coefficients at specific locations on the impingement surface. There are numerous examples of industrial processes in which jet flows play important roles as convecting media; drying of textiles, veneer, film materials and paper, cooling of glass, plastic, metal

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0017–9310/98 $19.00 
PII: S0017-9310(98)00056-8

objects of various sizes and shapes and parts of machinery, and maintaining the temperatures of turbine blades below metallurgically allowed limits. Jet impingement is also of interest in aeronautical applications such as in vertical take-off and landing systems.

When a jet flow strikes a stationary cylinder normal to the cylinder axis high, local convection rates occur in the region of the forward stagnation point. Rotation of the cylinder exposes the entire circumference to the impingement flow, but interactions between the rotating surface and the impinging flow may have a deleterious effect on average convection rates. The interaction of a cylinder with a jet flow is complex and very dependent on the position of the cylinder within the jet [1, 2], particularly in close proximity to the nozzle where the jet flow structure is changing rapidly. Thus important parameters in the design of cylinders in jet flow systems are the ratio of the rotational Reynolds number to the jet exit Reynolds number ($Re_w/Re_j$), the ratio of the cylinder diameter to the jet slot height ($d/D$), the ratio of the distance between the jet exit and the front of the cylinder to the slot height ($L/D$), the ratio of the off-set between the axis of the cylinder and the symmetry plane of the jet to the slot height ($E/D$) and the jet impingement angle ($\phi$). When designing such a system, it would clearly be of value to have available a correlation relating the average Nusselt or Sherwood number to these principle independent variables of the configuration.

There is much detailed information on the convective characteristics of single jet flows impinging on flat stationary surfaces [3–5] which may be adequate for the purposes of estimating the effect of similar jet flows impinging on a curved stationary surface (concave or convex [2, 6]). The limited number of experimental investigations of stationary cylinders in jet flows have reported significant effects of design parameters [2, 6–11]. Zhang et al. [12] experimentally investigated the heat transfer behaviour of a slot jet (i.e. a two-dimensional slot jet similar to that employed in the present study) impinging on a slowly rotating cylinder. As the rotation speed they employed was less than the critical speed below which the heat transfer is independent of the rotational speed, their study is not adequate for determining the real effect of the rotation. Theoretical studies of rotating cylinders in jet flows have been limited to laminar slot jet flow around a slowly rotating cylinder [13]. It appears that there is no comprehensive study of heat transfer behaviour of rotating cylinders in jet flows. Studies using moving belts [14, 15] report both increases and decreases in the heat transfer with belt motion. Moreover, they have investigated the effects of design parameters in isolation of each other and often for a narrow range of the parameters, some of them report contradicting results and none of them have investigated effects of all the design parameters in a single comprehensive study. Thus, they are of no direct help in the design of systems which may span a wide range of geometries, rotational speeds and jet speeds. Therefore, it is intended by the present study to provide detailed experimental data for improving the understanding of the impingement jet flows over curved moving surfaces. The particular interest in the present study was in the process of drying a wet rotating cylinder using an air jet of the room temperature.

## 2. Experimental details

A photo-evaporative mass transfer measurement technique based on the infra-red reflective properties of drying surfaces proposed by Utton and Sheppard [16] has been developed by Pekdemir [1]. The essence of this technique is the direct relationship between the degree of wetness of certain absorbent surfaces and the reflectivity of visible or infra-red light (IR). The convection surface of interest (the cylinder) is covered with chromatographic paper (surface roughness relative to cylinder diameter = 0.0014) and wetted with a volatile liquid (1-butanol). A small low-power beam of IR is focused at a point on the surface (e.g. 1 mm diameter) and a detector monitors the decrease in reflected intensity as the paper is convectively dried. There is a simultaneous linear variation in both the reflected light intensity and moisture content with time in the constant drying rate period. Those who are interested in the detailed description and validation of the technique and the apparatus are referred to [1, 2]. In addition to the apparatus described in [1, 2] was a direct current motor connected directly to the cylinder axle to rotate the cylinder with varying speeds. The maximum rotational speed of the cylinder was 1000 rpm (surface speed = 5 m $s^{-1}$).

To simplify the experimental work, the system was isothermal (i.e. the nozzle air, the surrounding air and the cylinder were all at the same [room] temperature). The experimental mass transfer system had a Schmidt number of 2 and a constant wall concentration boundary condition, so that a good analogy exists for gas phase heat transfer at a constant temperature wall.

## 3. Results and discussion

A study was made of the isothermal convective mass transfer from a rotating cylinder in a jet flow. The rotational Reynolds number ($Re_w$) varied from 0–$8.0 \times 10^4$, the jet exit Reynolds number ($Re_j$) from $4.6 \times 10^4$–$2.7 \times 10^5$, the ratio of the cylinder diameter to the jet slot height ($d/D$) from 3.333–15, the ratio of the distance between the jet exit and the front of the cylinder to the slot height ($L/D$) from 1–16, the ratio of the off-set between the axis of the cylinder and the symmetry plane of the jet to the slot height ($E/D$) from $-0.555$–2.133 and the jet impingement angle ($\phi$) from 20°–90°

(normal impingement). The flow and mass transfer characteristics of the rotating cylinder in the jet flow are represented by $Re_w$, $Re_j$, and the mean Sherwood number ($\overline{Sh}$) which are defined as follows:

$$Re_w = \frac{u_w\, d\rho}{\mu},\ Re_j = \frac{u_j\, d\rho}{\mu} \quad \text{and}$$

$$\overline{Sh} = \frac{\bar{N}d}{\rho_s D_{AB}} = c\overline{\left(\frac{dI/dt}{I_0}\right)}\frac{d}{\rho_s D_{AB}} \qquad (1)$$

where $u_w$ is the cylinder surface velocity, $u_j$ the jet exit velocity, $d$ diameter of the cylinder, $\rho$ density of the free stream fluid, $\mu$ dynamic viscosity of the free stream fluid, $\bar{N}$ mean mass flux, $\rho_s$ density (concentration) of the vapour of the volatile liquid at the surface conditions, $D_{AB}$ diffusion coefficient of the volatile liquid in air, $c$ the paper calibration constant, $dI/dt$ slope of the constant drying section of the drying curve and $I_0$ overall light intensity change. (See [1] for more detailed descriptions and explanations.)

An uncertainty (error) analysis, which signifies the error contributions from the uncertainties in the equipments used in the measurement of the independent variables effecting final measurement, was carried out for estimating the accuracy of the mass transfer measurements [1]. The result showed that the mass transfer data could be in error up to 12% (equivalent to about 6% uncertainty). The larger sources of the error were the surface temperature ($T_s$) and $dI/dt$. The repeatability of the results was also investigated and it was shown that mass transfer coefficient values could be repeatedly determined within 11% of the mean value. The results obtained from a stationary cylinder [2] indicated that the flow was two dimensional over the part of the cylinder which was within the jet nozzle cross-sectional area when projected on the cylinder. Although the mass transfer data were collected at 9 different equally spaced points along the axis of the cylinder [1], the results reported below are those obtained with an axially central sensor and so exemplify the behaviour in the central two-dimensional region of the flow.

### 3.1. The effect of the rotational and the jet exit Reynolds numbers

The results indicated that the mean mass transfer increased with increasing $Re_j$. In the absence of the jet flow, $\overline{Sh}$ increased slightly with increasing $Re_w$ for smaller rotational speeds. The effect of rotation was negligible at higher $Re_j$ for $Re_w \leqslant 2.5\times10^4$ (200 rpm), indicating that the rotational speed was still below the critical velocity for this $Re_w$ range. A typical result is shown in Fig. 1. This figure indicates that the mass transfer variation with $Re_w$ for a sufficiently small $Re_j$ ($4.6\times10^4$) exhibits three different regimes: at very low $Re_w$, up to $(Re_w/Re_j) = 0.15$, $\overline{Sh}$ decreases with increasing $Re_w$ indicating that the

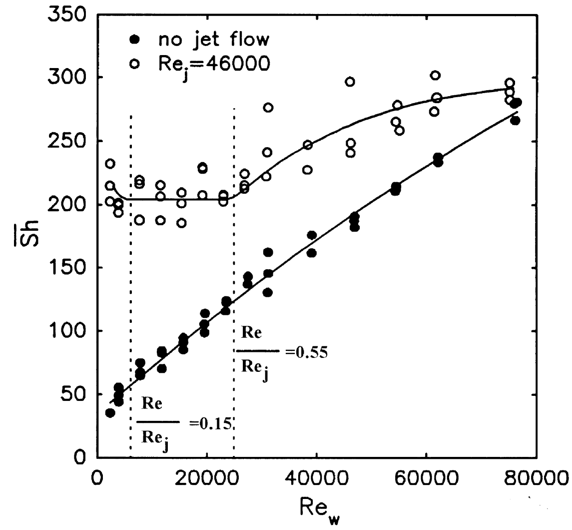


Fig. 1. A comparison of the variation of $\overline{Sh}$ from a rotating cylinder with $Re_w$ in a two-dimensional slot jet flow of air with that in stagnant air.

negative effect of rotation is more dominant than that of the positive effect. Beyond this region, up to $(Re_w/Re_j) = 0.55$, $\overline{Sh}$ is independent of $Re_w$ as the positive and the negative effect of the rotation cancels each other out. For $(Re_w/Re_j) \geqslant 0.55$, $\overline{Sh}$ increases with increasing $Re_w$ because the positive effect of the rotation becomes more and more dominant.

Figure 2 shows the variation of $\overline{Sh}$ with $Re_w$ for various

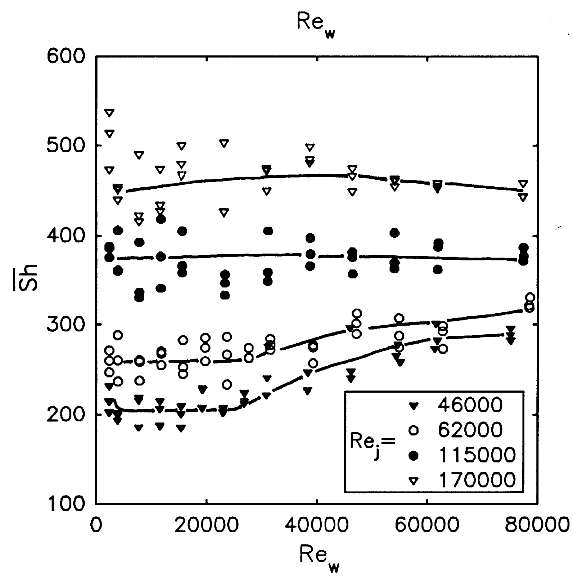


Fig. 2. Variation of $\overline{Sh}$ from a rotating cylinder in a two-dimensional jet flow with $Re_w$ for various $Re_j$, $L/D = 6$, $d/D = 3.333$, $E/D = 0.0$, and $\phi = 90°$.

$Re_j$ for a larger range of $Re_w$ than that of Fig. 1. It is seen that for $Re_j > 6.2 \times 10^4$ the three regimes identified above can no longer be observed. This is because at higher $Re_j$ the effect of the rotation on the mass transfer is negligible in comparison with that of the jet flow.

Figure 3 shows the variation and correlation of $\overline{Sh}$ with $Re_j$ for a range of $Re_w$. It is seen that at about $Re_j = 1.7 \times 10^5$ the flow around the cylinder changes from laminar to turbulent regime. This change is marked by the sudden jump in the slope of the curve.

### 3.2. *The effect of the ratio of* L/D

The effect of the jet exit to cylinder front edge spacing (i.e. $L/D$) was investigated for various values of $Re_j$, $E/D$, and $d/D$. Figure 4 shows the effect of the ratio of $L/D$ on $\overline{Sh}$ for $Re_w = 1.6 \times 10^4$ as function of $Re_j$. At $Re_j = 4.7 \times 10^4$ $\overline{Sh}$ remains constant up to $L/D = 4$ indicating that the potential core region extends only up to $L/D = 4$. For $L/D > 4$, $\overline{Sh}$ gradually decreases with increasing $L/D$ because of the velocity decay.

At $Re_j = 7.8 \times 10^4$, the mass transfer curve indicates that the increase in the turbulence level in the core region starts to show its effect, resulting in a slight increase in $\overline{Sh}$ up to $L/D = 4$ where is reaches its maximum value. Thereafter again the velocity decay cancels the effect of the increasing turbulence and leads to a gradual decrease in $\overline{Sh}$ with increasing $L/D$.

The variation of $\overline{Sh}$ with $L/D$ for $Re_j = 1.2 \times 10^5$ shows similar behaviour to that at $Re_j = 7.8 \times 10^4$. $\overline{Sh}$ increases with $L/D$ up to $L/D = 8$ as a result of increasing turbulence. Beyond $L/D = 8$, $\overline{Sh}$ decreases gradually with increasing $L/D$, indicating that beyond this point the effect of the velocity decay cannot be compensated by the increase in the turbulence level.

The variation of $\overline{Sh}$ with $L/D$ for $Re_j > 1.2 \times 10^5$ shows similar behaviour. $\overline{Sh}$ is independent of the slot to cylinder distance up to $L/D = 8$ and thereafter it decreases gradually with increasing $L/D$. This behaviour indicates that for $Re_j > 1.2 \times 10^5$ either the initial turbulence level at the jet exit is so high that a further increase due to the mixing is not influential, or the effect of the increase in the turbulence intensity is cancelled out by the jet velocity decay with increasing $L/D$.

Figure 5 shows the effect of $L/D$ on $\overline{Sh}$ for various values of the off-set ($E/D$). The definition of the off-set is schematically illustrated in Fig. 6(a). Figure 5 shows that the off-set from the jet centre line on either side of the jet has a similar effect on $\overline{Sh}$ for smaller off-sets. Unfortunately, it was not possible to extend the off-set in the negative direction beyond $-0.555$. The off-set impingement may cause a significant deviation in the variation

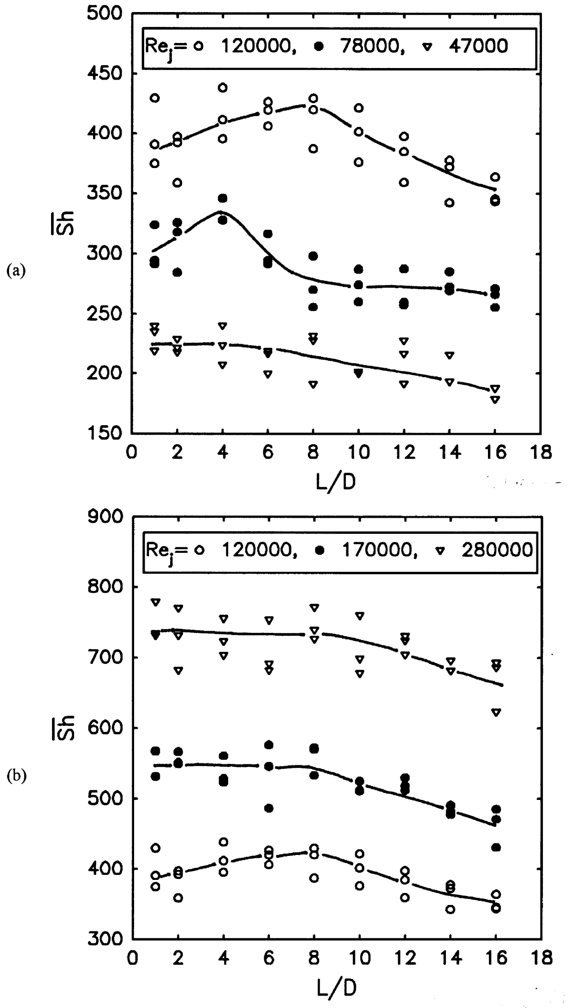


Fig. 4. The effect of $L/D$ on $\overline{Sh}$ as function of $Re_j$ for $Re_w = 1.6 \times 10^4$, $d/D = 1.6 \times 10^4$, $d/D = 3.333$, $E/D = 0.0$, and $\phi = 90°$.

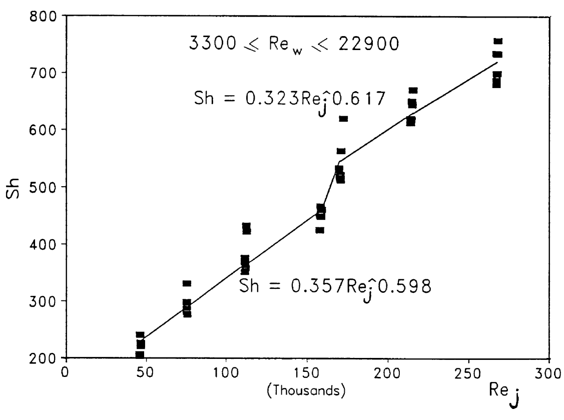


Fig. 3. Variation of $\overline{Sh}$ with $Re_j$ for a range of $Re_w$, $L/D = 6$, $d/D = 3.333$, $E/D = 0.0$, and $\phi = 90°$.

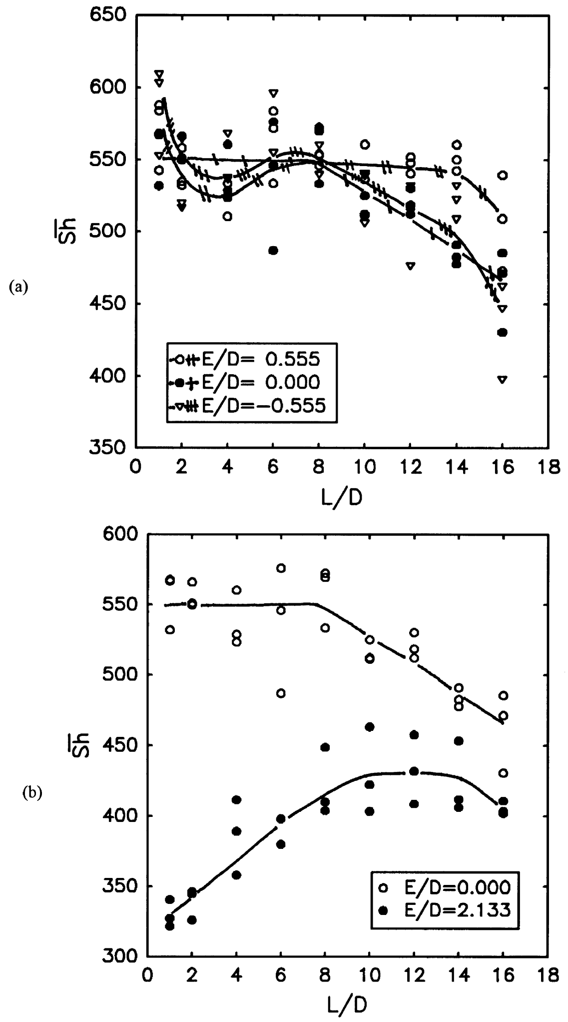


Fig. 5. The effect of $L/D$ on $\overline{Sh}$ as function of $E/D$ for $Re_w = 1.6\times10^4$, $Re_j = 1.7\times10^5$, $d/D = 3.333$, and $\phi = 90°$.

of $\overline{Sh}$ with $L/D$ from that with symmetrical impingement. At smaller off-sets, although the deviation is not very significant and sometime lesser than the deviation among the experimental data for the same $E/D$, it is still detectable when considering the general trend of the data. For $L/D \leqslant 8$, at $E/D = 0.555$ and $-0.555$, first a decrease and then an increase in $\overline{Sh}$ occurs with increasing $L/D$. The reason for this decrease in $\overline{Sh}$, in the range of $L/D \leqslant 4$, may be that at this jet exit velocity the expansion of the jet flow and the increase in the mixing induced turbulence is not very significant in spite of the decreasing velocities in the region of the jet flow surrounding the potential core. Thus with increasing distance from the jet exit a larger portion of the cylinder will remain within this low velocity region of the jet. Hence the mass transfer from the cylinder will decrease with increasing distance from the jet exit. But for $L/D > 4$ the expansion of the jet and the turbulence increase in the mixing region of the jet is large enough to compensate for the effect of the decreasing velocities in the central area of the jet. Thus a slight increase in the mean mass transfer rate occurs in the range of $4 < L/D \leqslant 6$. For $L/D \geqslant 8$, at $E/D = -0.555$ mass transfer rate is approximately the same as that for symmetrical impingement. This may be because at larger distances the jet flow expands enough so that for an off-set of $+0.555$ the cylinder still remains in the main part of the jet flow. On the other hand the higher mass transfer rate for an off-set of $-0.555$ may be because of jet deflection caused by the asymmetrical pressure field around the rotating cylinder.

At higher off-set, $E/D = 2.133$, the mass transfer is significantly less than that of symmetrical impingement, especially at smaller jet exit to cylinder distances. $\overline{Sh}$ increases with increasing distance from the jet exit up to $L/D = 10$, then it remains constant up to $L/D = 14$, and thereafter it decreases. This behaviour can be attributed to the expansion of the jet flow as it moves downstream. The larger the distance from the jet exit, the greater the expansion of the jet and also the flatter the radial velocity profile in the jet flow. The constant section of this curve indicates that the jet flow field in this region does not change much. Further downstream a decrease in $\overline{Sh}$ occurs with increasing jet to cylinder distance ($L/D$).

The ratio of $d/D$ may be considered to be a measure of the surface curvature as well as the relative height of the jet nozzle. It was shown by Gau and Chung [6] that for $d/D \geqslant 50$, the cylindrical surface could be considered as a flat plate with respect to the jet nozzle height as the results obtained with $d/D \geqslant 50$ were the same as those with a flat plate. The $d/D$ ratios used in the present work were 3.333 (with maximum height of the nozzle $D = 4.5$ cm), 7.5 ($D = 2$ cm) and 15.0 ($D = 1$ cm). The different values of $D$ were obtained by adjusting the opening of the nozzle unit fixed to the exit of the wind tunnel.

The effect of the ratio of $d/D$ is shown in Fig. 7. Although there is a large variation in $\overline{Sh}$ with $L/D$, variation with $d/D$, especially at smaller distances from the jet exit, is not systematic as both decreases and increases occur with decreasing jet nozzle height (increasing $d/D$). The curve for $d/D = 3.333$ is the same as the curve for $Re_j = 2.8\times10^5$ in Fig. 4 and was discussed previously.

From unsystematic variation of $\overline{Sh}$ with $d/D$ it may be possible to conclude that increasing $d/D$ affects the mass transfer from the jet flow in two ways; an increase in $d/D$ from 3.333 to 7.5 causes a decrease in the mass transfer for all the jet to cylinder distances, whereas a further increase from 7.5 to 15.0 causes a significant increase in the mass transfer for $L/D \leqslant 10$. The higher mass transfer at $d/D = 15$ may indicate that the turbulence generated by the shear stress between the jet flow and the stationary surrounding air, into which the jet flow emerges, is possibly more severe than that at $d/D = 3.333$ and 7.5

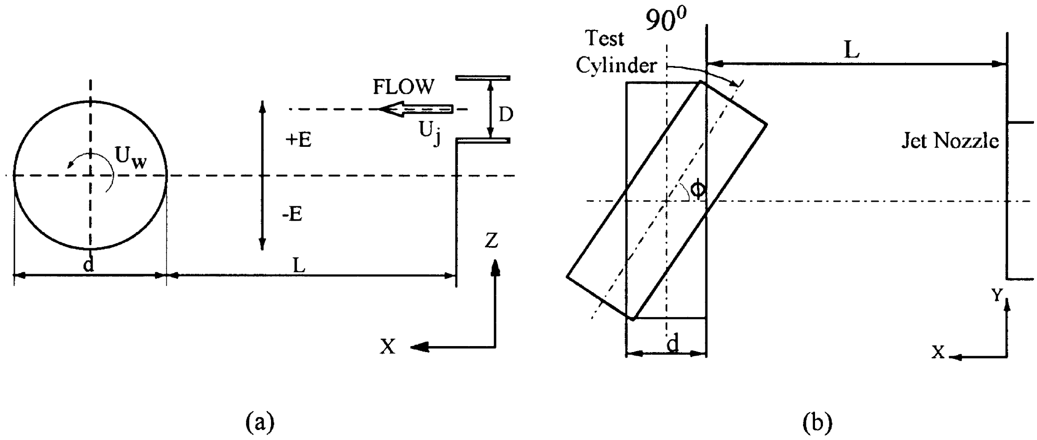


Fig. 6. Definition of geometrical parameters.

for $L/D \leqslant 10$. But it is smaller at $d/D = 7.5$ than at $d/D = 3.333$ for all $L/D$ studied. This means that the turbulence due to the mixing in the jet flow perhaps first decreases with an increase in $d/D$, then it increases with further increase in $d/D$. Unfortunately there is not any available flow field data to support these variations in the jet flow field with varying $d/D$ inferred from mass transfer rate measurements. Without flow field data, it is not plausible to make a generalising conclusion. For a more definitive conclusion it is suggested that some flow field measurements to be made for $d/D$ ratios varying in a wide range.

At $d/D = 15.0$ $\overline{Sh}$ first decreases with increasing $L/D$ up to $L/D = 4$ then it increases and another maximum occurs at $L/D = 6$ and thereafter it decreases first sharply and later gradually. This behaviour indicates that the effect of the velocity decay overcomes the effect of the increase in the turbulence with increasing $L/D$ for $L/D \leqslant 4$. Then the further turbulence increase in the jet flow in the range of $4 < L/D \leqslant 6$ may be the reason for the increase in the mass transfer. For $L/D > 6$ the continuous decrease in the mass transfer indicates that the turbulence increase in the jet flow is not as such to overcome the effect of the further mean jet flow velocity decay.

At $d/D = 7.5$, $\overline{Sh}$ first slowly increases with increasing $L/D$ up to $L/D = 6$ and then remains constant between $L/D = 6$ to 10. Hereafter it decreases gradually due to the velocity decay and the variation in the turbulence distribution in the jet flow in the corresponding ranges of $L/D$ with increasing distance from the jet exit.

### 3.3. *The effect of the ratio of* E/D (*off-set*)

The effect of the off-set of the cylinder axis from the jet centreline was investigated in the range $-0.555 \leqslant E/D \leqslant 2.133$ for $Re_j = 1.7 \times 10^5$, $Re_w = 1.6 \times 10^4$, $d/D = 3.333$, $L/D = 6$, and $\phi = 90^\circ$ (for a fixed distance from the jet exit ($L/D = 6$) in order to isolate the effect of $L/D$). The result of these measurements is shown in Fig. 8. It is seen from the figure that the highest $\overline{Sh}$ is obtained at $E/D = -0.555$. The reason for this may be that for this $E/D$ a larger portion of the jet flow impinges on the side of the cylinder where the surface motion is opposite to the oncoming flow. It is then possible that this opposing motion pushes the jet flow to the other side of the cylinder where the surface motion is in the same direction as the oncoming flow. Thus the amount of fluid interacting with the cylinder surface may be larger than that of non-off-set case ($E/D = 0$) and hence leads to an increase in the mass transfer. At $E/D = 0.555$ $\overline{Sh}$ is also higher than that of $E/D = 0$ but less than that for $E/D = -0.555$. This may be explicable in terms of bending of the jet flow from its origin, as reported by Sparrow and Alhomoud [9]. At small off-set, because of the bending character of the jet flow, it impinges head on the cylinder and thus creates higher mass transfer than that of $E/D = 0$. As the off-set increases further, $\overline{Sh}$ decreases with the increasing off-set as a result of the fact that a smaller portion of the cylinder remains in the jet flow with increasing off-set. At the extreme conditions the mean mass transfer from the off-set cylinder is approximately 31% less than that of the non off-set cylinder confirming results of Sparrow and Alhomoud [9] where a 51% reduction in the mass transfer is reported for a stationary cylinder in a jet flow with larger off-sets.

### 3.4. *The effect of the impingement angle* ($\phi$)

The effect of the impingement angle, $\phi$, was investigated in the range $20^\circ \leqslant \phi \leqslant 90^\circ$ for $Re_j = 1.7 \times 10^5$, $Re_w = 1.6 \times 10^4$, $d/D = 3.333$, $L/D = 6$, and $E/D = 0.0$. Figure 6(b) shows the geometrical definitions related to the inclined jet systems. An impingement angle of 90° is

(a)

(b)

(c)

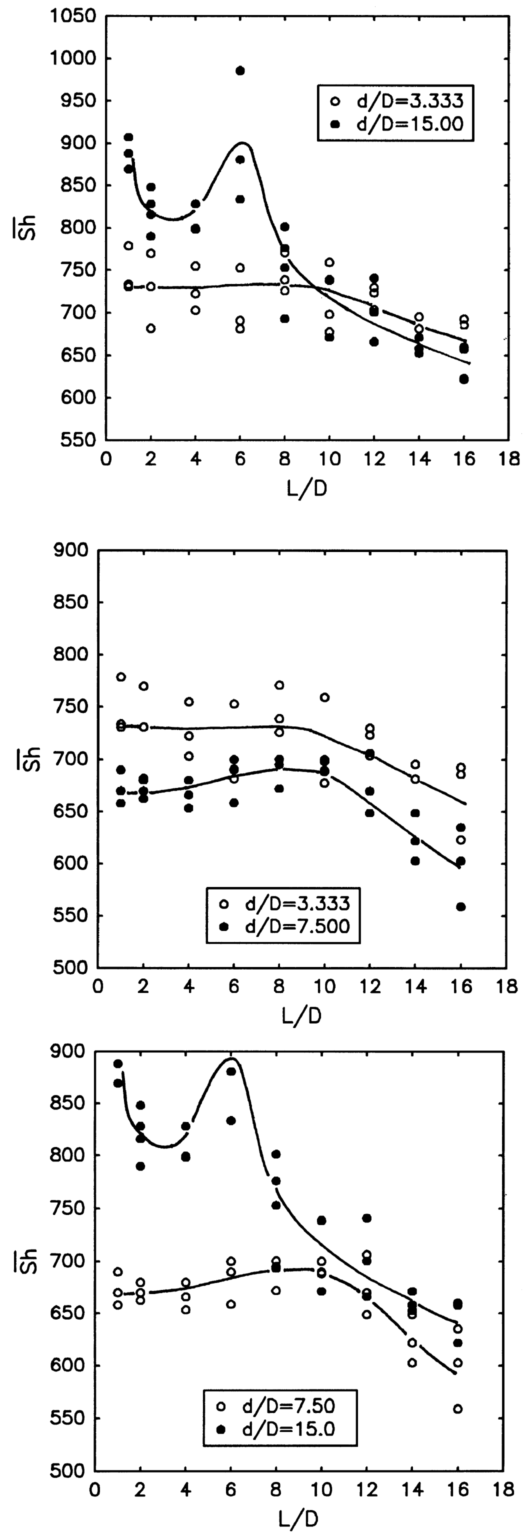


Fig. 7. The effect of $L/D$ on $\overline{Sh}$ as function of $d/D$ for $Re_j = 2.8\times10^5$, $E/D = 0.0$, and $\phi = 90^\circ$.

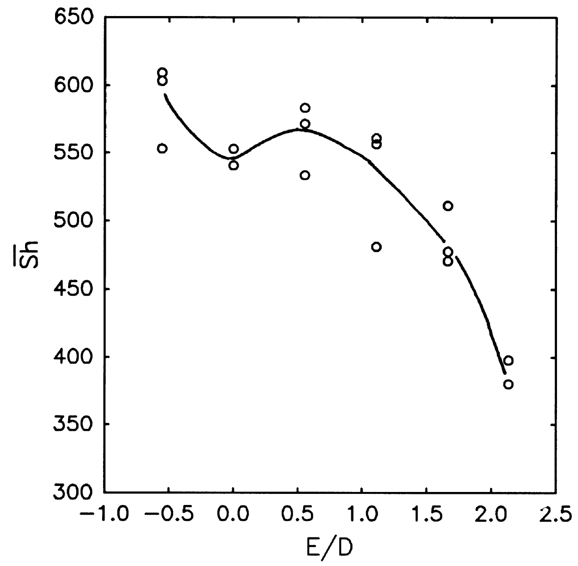


Fig. 8. The effect of $E/D$ on $\overline{Sh}$ for $Re_w = 1.6\times10^4$, $Re_j = 1.7\times10^5$, $L/D = 6$, $d/D = 3.333$, and $\phi = 90^\circ$.

actually normal impingement. The inclination was provided by adjusting the orientation of the cylinder with respect to the jet nozzle. Figure 9 shows the variation of $\overline{Sh}$ with $\phi$. $\overline{Sh}$ remains constant for $90^\circ \leqslant \phi \leqslant 60^\circ$ and then it decreases with further increase in the inclination, confirming the results obtained from flat plates in jet flows by Sparrow and Lovell [17] and Davies et al. [18].

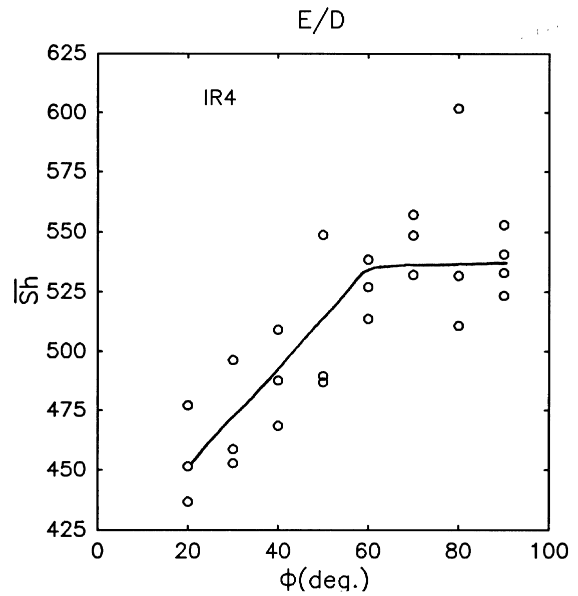


Fig. 9. Variation of $\overline{Sh}$ with the impingement angle for $Re_w = 1.6\times10^4$, $Re_j = 1.7\times10^5$, $L/D = 6$, $d/D = 3.333$, and $E/D = 0.0$.

The reason for this behaviour may be that as the inclination increases, the flow over the cylinder surface becomes more and more parallel to the cylinder axis, i.e. the flow over the cylinder will be changing from crossflow dominant to the parallel flow dominant. Thus, only the front section of the cylinder will be in contact with a flow associated with high mass transfer coefficient, whereas the rest of the cylinder will be in contact with a weak crossflow and the flow generated by the rotation. The rotation may also cause a destruction in the boundary layer development in the radial direction depending on the rotational speed. Hence the mean mass transfer from the cylinder will be decreasing with an increase in the inclination beyond a critical angle and depending on rotational speed.

### 3.5. Correlations of the mean mass transfer

$\overline{Sh}$ obtained from a rotating cylinder in a two dimensional slot jet flow for $0.057 \geqslant Re_w/Re_j \leqslant 0.333$ and $1 \leqslant L/D \leqslant 16$ were correlated as a function of these parameters. Because of the limited amount of data obtained for varying $d/D$, $E/D$ and $\phi$, $\overline{Sh}$ was not correlated as a function of these parameters. Thus the evaluated correlation equations are valid only for fixed values of these parameters, i.e. $d/D = 3.333$, $E/D = 0.0$ and $\phi = 90°$. Moreover, the results presented in earlier sections (see Fig. 4), showed that the effect of $L/D$ on $\overline{Sh}$ varied depending on its range: (i) $\overline{Sh}$ slightly increases with increasing $L/D$ in the range $L/D < 8$, and (ii) $\overline{Sh}$ decreases with increasing $L/D$ in the range $L/D \geqslant 8$. Thus two correlation equations, for one each $L/D$ range, were evaluated (Fig. 10). For $1 \leqslant L/D < 8$, it is apparent that $\overline{Sh}$ is a very weak function of $L/D$ and decreases with increasing $Re_w/Re_j$. On the other hand, for $8 \leqslant L/D \leqslant 16$, $\overline{Sh}$ decreases as both $Re_w/Re_j$ and $L/D$ increase.

### 3.6. Comparisons of the mass transfer in different flow systems

Figure 11 shows a comparison of the variation of the mean mass transfer with the free stream Reynolds number for a stationary cylinder in a crossflow, a stationary cylinder in a jet flow, and a rotating cylinder in a jet flow. The free stream Reynolds number ($Re_f$) refers to both crossflow Reynolds number and jet exit Reynolds number, i.e.;

$$Re_f = \frac{u_j\,d\rho}{\mu} = \frac{u_c\,d\rho}{\mu} \quad (2)$$

where $u_c$ is the crossflow velocity. It is seen from Fig. 11 that for $Re_f < 6.0 \times 10^4$, a rotating cylinder with a higher rotational speed (1000 rpm) exposed to a jet flow system gives higher mass transfer than other flow systems. As the free stream Reynolds number increases, this behaviour is reversed—and for $Re_f \geqslant 1.3 \times 10^5$ it gives the smallest mass transfer.

In general, for $Re_f \geqslant 6.0 \times 10^4$, the mean mass transfer performance decreases in the order of a stationary cylinder in a crossflow, a stationary cylinder in a jet flow and a rotating cylinder in a jet flow. This means that although the jet flow systems give higher local transport coefficients in the impingement region, their overall mass transfer performance is lower than that of uniform crossflow. The result at first sight may seem to be contradicting the findings of Kumada et al. [7] and Schuh and Person [8], where it is reported that the jet flow enhances the heat transfer by up to 30% over that of a uniform crossflow when the turbulence level in the crossflow is negligible, while it is the same when the turbulence is higher than 2% in the crossflow. But it should be remembered here that Schuh and Person's heat transfer measurements were made for a Reynolds number range of $2.0 \times 10^4 \leqslant Re_j \leqslant 5.0 \times 10^4$ (below $6.0 \times 10^4$) and for which they reported a 30% increase in the heat transfer from a cylinder over that in a low turbulence uniform

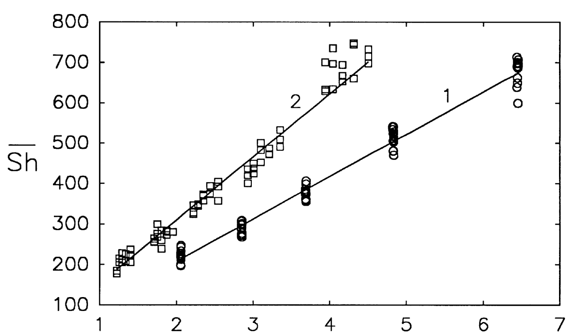


Fig. 10. Correlations of $\overline{Sh}$ with $Re_w/Re_j$ and $L/D$ for a rotating circular cylinder interacting with a two-dimensional slot jet.

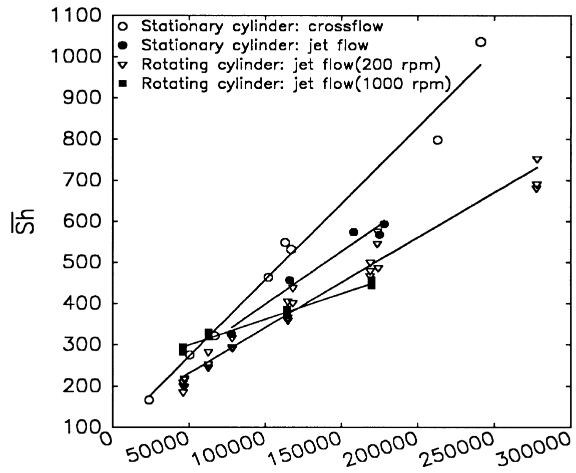


Fig. 11. A comparison of $\overline{Sh}$ for a stationary cylinder in a crossflow, a stationary cylinder in a jet flow, and a rotating cylinder of various rotational speeds in a jet flow.

crossflow. Although Kumada et al.'s mass transfer measurements covered a larger Reynolds number range ($4.4 \times 10^4 \leqslant Re_j \leqslant 2.0 \times 10^5$), by comparing their measurements made at $Re_j = 5.0 \times 10^4$ with that of Schuh and Person, and from the close agreement between them, they concluded that with a jet flow, about 30% higher mass transfer could be obtained compared with a low turbulence uniform flow of the same Reynolds number. Therefore considering their Reynolds number range and about the same turbulence level in the present crossflow studies and in the present jet flow studies at the jet exit (around 6%, determined by hot wire anemometry), the extension of the lines in Fig. 11 to the lower free stream Reynolds number will give about same mass transfer for present jet and crossflow systems. Thus, the present result is consistent with those from the literature.

It is also observed from Fig. 11 that the rotation of the cylinder in the jet flow causes a further decrease in the mass transfer performance of jet flow system beyond a critical jet exit Reynolds number. This phenomenon can be seen more clearly in Fig. 12 where $\overline{Sh}$ from a rotating cylinder at various rotational speeds is plotted against the jet exit Reynolds number. At smaller jet exit Reynolds numbers the smaller rotational speeds give lower $\overline{Sh}$ while at higher jet exit Reynolds numbers this behaviour is reversed. These results are in agreement with the predictions of Chiou and Lee [13] and the experimental results of Polat et al. [14] who made heat transfer measurements over a moving belt exposed to a confined slot jet flow. Thus it is concluded from Fig. 12 that for a higher $Sh$ from a rotating cylinder the rotational speed should be adjusted according to the range of the jet exit Reynolds number.

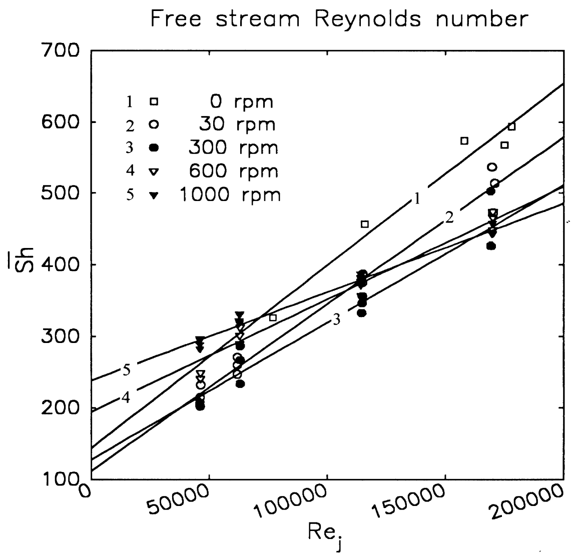


Fig. 12. The effect of the rotational speed on $\overline{Sh}$ for a rotating cylinder in a jet flow for $L/D = 6$, $d/D = 3.333$, $E/D = 0.0$ and $\phi = 90^\circ$.

## 4. Conclusions

Mass transfer characteristics of a rotating cylinder in a two dimensional slot jet of air have been investigated as function of the flow and geometrical parameters. The results indicated that:

(1) The mass transfer variation with $Re_w$ for a sufficiently small $Re_j$ undergoes three different stages. (i) at $(Re_w/Re_j) \leqslant 0.15$, $\overline{Sh}$ decreases with increasing $Re_w$; (ii) at $0.15 < (Re_w/Re_j) \leqslant 0.55$, $\overline{Sh}$ is independent of $Re_w$; (iii) in the range $(Re_w/Re_j) > 0.55$, $\overline{Sh}$ increases with increasing $Re_w$.

(2) At smaller jet exit Reynolds numbers, the smaller rotational speeds provide lower mass transfer rate, while at higher jet exit Reynolds numbers, this behaviour is reversed. Thus, for higher mass transfer rate from rotating cylinders, it is suggested that the rotational speed is adjusted according to the range of the jet exit Reynolds number.

(3) In general, for $Re_j \geqslant 6.0 \times 10^4$, the mean mass transfer performance decreases in the order of a stationary cylinder in a uniform crossflow with a turbulence of 0.6%, a stationary cylinder in a jet flow, and a rotating cylinder in a jet flow. This means that although the jet flow systems provide higher local transport coefficients in the impact zone, the overall mass transfer performance is lower than that of a uniform crossflow with 0.6% turbulence.

(4) The mean Sherwood number has been correlated as function of $Re_j$ for $3.3 \times 10^3 \leqslant Re_w \leqslant 2.29 \times 10^4$, $L/D = 6$, $d/D = 3.333$, $\phi = 90^\circ$, and $E/D = 0.0$. The resultant eqns were: $\overline{Sh} = 0.357 Re_j^{0.598}$ for $Re_j < 1.7 \times 10^5$, $\overline{Sh} = 0.0323 Re_j^{0.617}$ for $Re_j \geqslant 1.7 \times 10^5$.

(5) Some other correlation equations for the mean Sherwood number at different position along the cylinder axis have been obtained as function of $Re_w/Re_j$ and $L/D$ for $0.057 \leqslant Re_w/Re_j \leqslant 0.333$, $d/D = 3.333$, $1 \leqslant L/D \leqslant 16$, $\phi = 90^\circ$, and $E/D = 0.0$. Correlation equations for a position in the mid section of the cylinder and in the jet nozzle projected area were shown to be:

$$\overline{Sh} = 105(Re_w/Re_j)^{-0.65}(L/D)^{0.0015} \quad \text{for } 1 \leqslant L/D < 8$$

$$\overline{Sh} = 156(Re_w/Re_j)^{-0.67}(L/D)^{-0.1948} \quad \text{for } 8 \leqslant L/D \leqslant 16$$

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