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MASS TRANSFER DUE TO AN IMPINGING SLOT JET

JACOB H. MASLIYAH
Department of Chemical Engineering, University of Alberta, Edmonton, Alberta, Canada

and

TRUNG T. NGUYEN
Department of Chemistry and Chemical Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

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Abstract—Local mass-transfer coefficients resulting from the impingement of a two-dimensional laminar air jet on a flat surface have been measured using a holographic technique. The regression equation, in terms of the local Sherwood number, *Sh*, for a Schmidt number of 2.85 was found to be

$$Sh = 0.7(x/B)^{-0.73}Re^{0.55}$$

for $180 \leqslant Re \leqslant 600$ and $1 \leqslant x/B \leqslant 30$ where x is the distance measured from the jet centre, along the flat surface, and B is the slot width. The characteristic length for *Sh* and *Re* is $2B$. The regression equation represents the best available correlation to date.

NOMENCLATURE

- A, constant;
- B, slot width [m];
- D, diffusion coefficient [m^2/s];
- d_e, equivalent diameter [m $(=2B)$];
- k, local mass-transfer coefficient [m/s];
- Mw, molecular weight of swelling agent;
- N, mass flux [$Kg/m^2 s$];
- n, fringe order;
- P, total pressure [mm Hg];
- P^0, vapour pressure of swelling agent [mm Hg];
- p_s, partial vapour pressure of swelling agent at the polymer surface [mm Hg];
- p_∞, partial vapour pressure of swelling agent in the ambient air;
- Re, Reynolds number, $\frac{\bar{U}d_e}{\nu}$;
- S, plates span length [m];
- Sc, Schmidt number, D/ν;
- Sh, Sherwood number, kd_e/D;
- t, time of mass-transfer experiment [s];
- $\bar{U}$, mean velocity of jet at nozzle exit [m/s];
- u_x, fluid velocity in x-direction;
- u_y, fluid velocity in y-direction at the nozzle exit;
- x, streamwise coordinate [m].

Greek symbols

- ν, kinematic viscosity [m^2/s];
- $\bar{\rho}$, molar density of air–swelling agent gas mixture.

INTRODUCTION

HEAT transfer due to impinging jets on flat surfaces has received much attention in the literature in the last decade. Such impinging jets are utilized in drying of paper and in cooling of metal sheets and glass.

Theoretical and experimental studies of fluid flow and heat transfer or mass transfer due to impinging axisymmetric jets (issuing from circular tubes) and two-dimensional slot jets (issuing from parallel plates) have been presented in the literature [1–7]. Such studies were made either for the impinging jet region or at a distance far away from the jet centre. Due to the relatively large errors involved in the heat-transfer sensors, it is more convenient to resort to mass-transfer studies rather than heat-transfer experimentation and to interchange Sherwood number and Schmidt number with Nusselt number and Prandtl number, respectively. Such a direct interchange is usually permissible when one deals with a low mass-transfer rate where the normal surface velocity is very nearly zero. Such mass-transfer studies have been carried out using solid sublimation techniques for the case of a circular jet and a slot jet [1, 3].

A novel technique using laser holography coupled with a swollen polymer method has been used by Kapur and Macleod [2] to study mass transfer due to the impingement of axisymmetric jets. Masliyah and Nguyen [8, 9] utilized the holographic method to study mass transfer under laminar conditions for jets issuing from square and rectangular tubes. Their studies showed that the local mass-transfer coefficient is a strong function of radial and azimuthal positions.

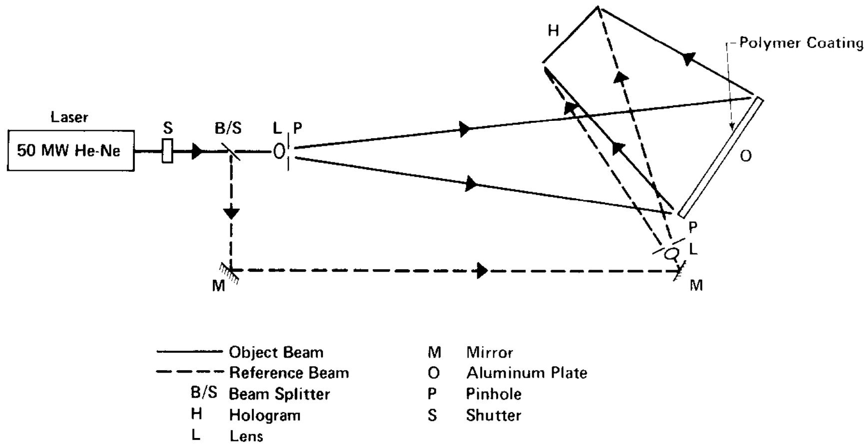

FIG. 1. Holographic arrangement.

Data in the literature indicate that heat and mass transfer due to axisymmetric jets has been extensively studied and is well correlated. However, heat or mass transfer due to slot jets requires further studies as has been indicated by Sparrow and Wong [3].

This work is directed towards more documentation of the local Sherwood number (i.e. local mass-transfer coefficient) due to impingement of a slot jet on a flat surface. Initially the slot jet is laminar and a swollen polymer method coupled with a laser interferometric technique are used in this study.

EXPERIMENTAL PROCEDURE

Details of the swollen polymer method to measure local mass-transfer coefficients have already been given by Macleod and Todd [10], Kapur and Macleod [2] and Masliyah and Nguyen [8]. The essence of this technique is to coat the flat surface under study with a thin silicone polymer and to swell this coating (to equilibrium) with a swelling agent. In this case, swelling is achieved simply by immersing the coating in a bath of ethylsalicylate. When the swollen polymer coating is subjected to an air jet, the swelling agent diffuses out from the polymer coating to the main air stream. This migration causes the polymer coating to shrink. The local coating recession is a measure of the local mass of the swollen agent that has left the polymer coating. It has been shown that this local coating recession is directly proportional to the amount of mass transferred and that mass transfer occurs within the "constant rate period" [2, 8, 10].

The value of the coating shrinkage has been measured using double exposure holographic interferometry. In this method, the flat coated surface was "photographed" before and after subjecting the coating to an air jet. When the resulting hologram is reconstructed, bright and dark fringes are observed to be super-imposed on the polymer coating. These fringes are contours of equal surface recession or equal mass transfer. From the geometry of the optical set-up it is possible to evaluate the coating shrinkage between two consecutive dark (or bright) fringes [2, 8]. Figure 1 shows the holographic arrangement used in this study.

An aluminum plate 0.3 × 0.3 m having a thickness of 0.01 m was coated with silicone rubber and was swollen to equilibrium using ethylsalicylate. Three slot tubes were constructed; two brass tubes with dimensions 0.36 × 0.075 × 0.00075 m and 0.35 × 0.075 × 0.001 m and a Plexiglass tube with dimensions 0.35 × 0.076 × 0.0015 m.

The equivalent diameter of a rectangular tube is given by:

$$d_e = 4SB/[2(S+B)]$$

and due to the small ratio of plates spacing, B, to the plates span, d_e is approximately given by $d_e \simeq 2B$, where B is the width of the slot. The large ratio of plates span to slot width minimizes end effects and leads to a situation of truely two-dimensional jet. In all our calculations d_e was taken as $2B$. The mass-transfer experiments were conducted with the flat plates subjected to the air jet for a period ranging from 120 s to 480 s. The runs for the various mass-transfer experiments (different slots and duration of mass-transfer experiment), for a given Reynolds number, were combined in terms of Sherwood number, defined by:

$$Sh = \frac{kd_e}{D} \tag{1}$$

where k is defined by:

$$N = k(p_s - p_\infty)\bar{\rho}Mw/P \tag{2}$$

and D is the diffusion coefficient.

N is mass flux, kg/m^2 s, $\bar{\rho}$ is the molar density of the gas mixture, Mw is the molecular weight of the swelling agent, P is the total pressure and p_s and p_∞ are the partial vapour pressure of the swelling agent at the coating surface and in the ambient air, respectively. Assuming that p_∞ is negligible and that the partial vapour pressure of the swelling agent at the surface is that of its vapour pressure, equation (2) becomes

$$N = kP^0\bar{\rho}Mw/P \tag{3}$$

where P^0 is the vapour pressure of the swelling agent.

The mass flux could also be given as

$$N = A(n/t) \quad (4)$$

where t is the time of the mass-transfer experiment and n is the fringe order, A is a constant for a given mass-transferring system and optical arrangement. It is given as:

3.39×10^{-4} kg/m^2 fringe [8].

Combining equations (1), (3) and (4), yields:

$$Sh = APnd_e/tDP^0\bar{\rho}Mw. \quad (5)$$

By simply determining the fringe order, i.e. counting the fringes with the outer bright fringe being the zeroth fringe, Sherwood number could be evaluated [8].

RESULTS AND DISCUSSION

The Schmidt number of ethylsalicylate–air system is 2.85. The diffusion coefficient of ethylsalicylate was taken as 5.4×10^{-6} m^2/s at 24°C. The experiments were conducted at 23–25°C. All the experimental data reported here were taken with the distance between the tip of the slot tube and the coating surface being 4B. Experimental work with a gap of 8B gave similar results.

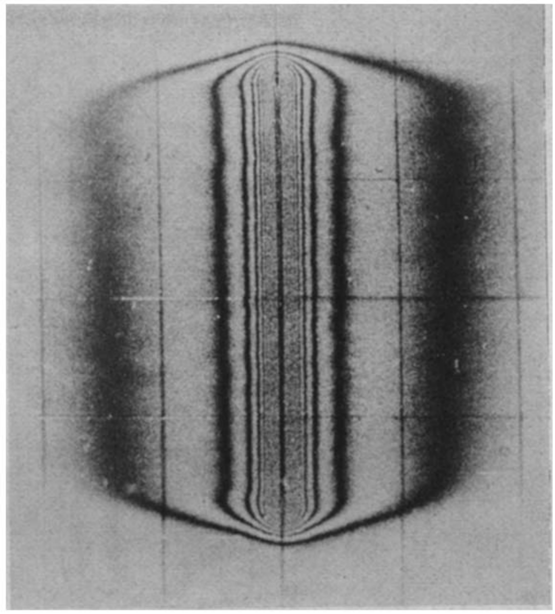

FIG. 2. Contours of equal mass transfer for Re = 180.

Permanent photographs were made of the reconstructed holograms. Such photographs are shown in Figs. 2–4. They show the fringe pattern obtained with the Plexiglass slot jet for Reynolds numbers 180, 400 and 600, respectively. The fringes as shown

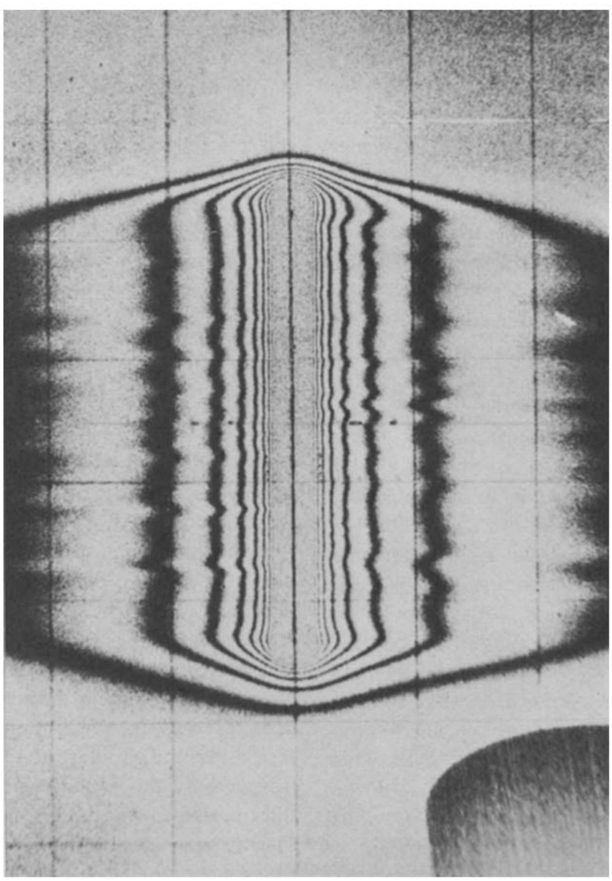

FIG. 3. Contours of equal mass transfer for Re = 400.

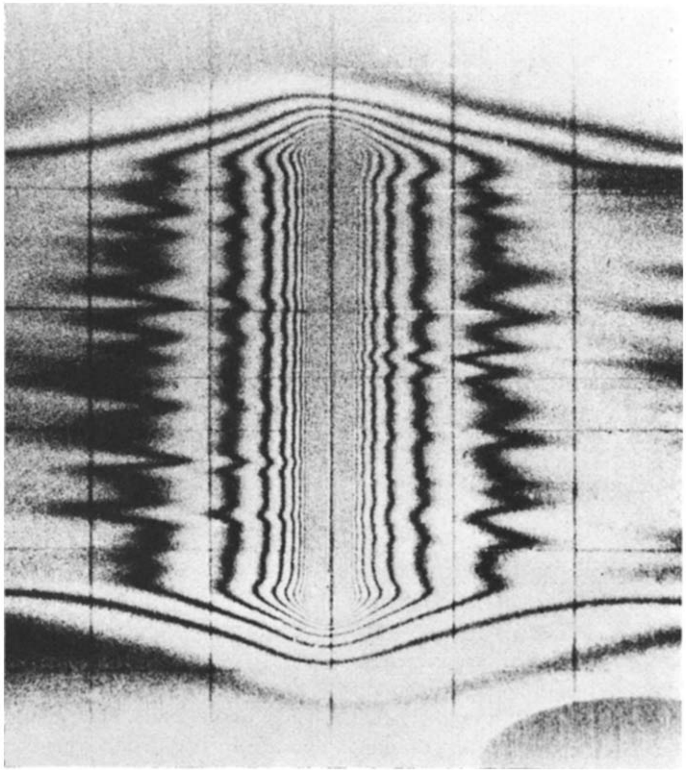

FIG. 4. Contours of equal mass transfer for $Re = 600$.

give an overall picture of the spatial variation of mass transfer. Figure 2 shows that the fringes are parallel to the plates and that the slot jet acts as a two-dimensional jet. The influence of the parallel plates ends (corners) is clearly seen and this influence is limited to a very short distance along the slot spanwise direction. It is of interest to note that as Reynolds number is increased, the fringes are no longer smooth but exhibit spanwise fluctuations. The intensity of such fluctuations increased with Reynolds number. These fluctuations are due to the presence of very slight roughness at the edge of the parallel plates and their pattern is very much the same for $Re = 400$ and 600. When the parallel plates edge was polished to produce a very smooth surface no such spanwise fluctuations were observed. This phenomenon is rather surprising as for laminar flow slight surface roughness does not normally affect the fluid flow. In the studies with circular jets the fringes were smooth and for these studies no special attention was taken to produce a highly polished tube tip. It is of interest to note that at the parallel plates ends (corners) the fringes do not exhibit any fluctuations. It might be conjectured that a two-dimensional slot jet is more apt to be affected by surface roughness than a three-dimensional jet. This type of spanwise mass-transfer fluctuations could be the reason for the difficulties experienced by previous workers to obtain reliable mass-transfer data, [3].

Figure 5 shows the variation of Sherwood number with the dimensionless distance from stagnation point (streamwise coordinate), x/B. The linearity of the logarithmic plot indicates that $\ln Sh$ is proportional to $\ln(x/B)$.

Regression analysis was made to obtain a correlation for Sherwood number with the jet Reynolds number and streamwise coordinate, x/B. In the regression analysis a variable weighting factor was used so that each data point has approximately the same influence. A total of 664 data points were used. The regression equation is given by:

$$Sh = 0.7(x/B)^{-0.73}Re^{0.55} \qquad (6)$$

for $180 \leqslant Re \leqslant 600$ and $1 \leqslant x/B \leqslant 30$.

A plot to test the applicability of equation (6) is shown in Fig. 6. For a perfect fit with zero experimental error, all data points should lie on a straight line having a slope of unity. It is observed that the data points are scattered about the line with the slope of unity and consequently no segregation is observed. The correlation obtained for the local Sherwood number is valid for x/B as low as unity where $\ln Sh$ varies linearly with $\ln(x/B)$. For the case of circular jets, the linearity of the relationship $\ln Sh$–$\ln(x/B)$ does not extend below $x/B = 5$, where B becomes the circular tube radius.

Sparrow and Wong were not able to correlate their mass-transfer data because of a large spread in their experimental data. However, they did indicate that the exponents of Reynolds number and x/B are in the neighborhood of 1/2 and $-1/2$, respectively.

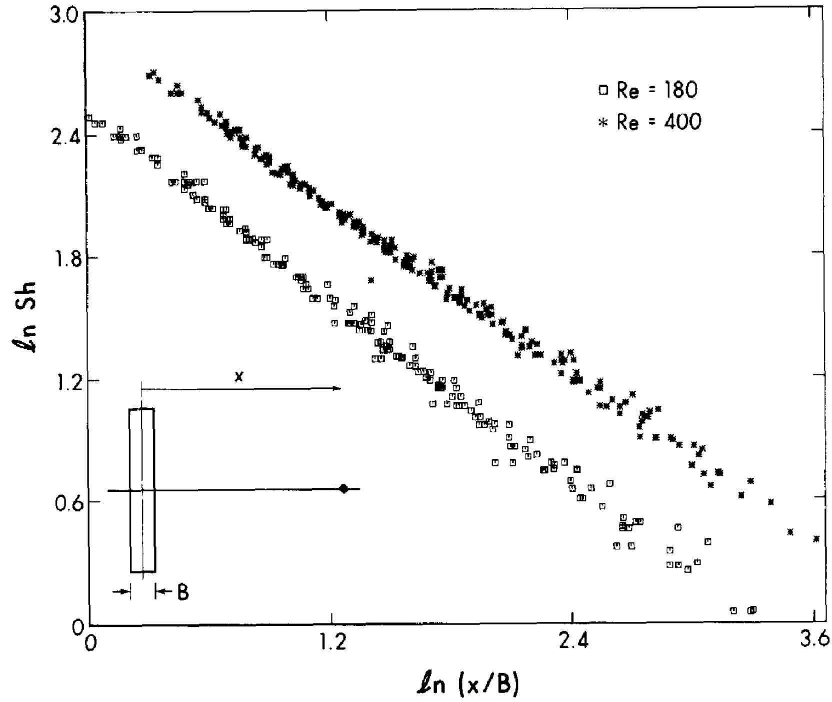

FIG. 5. Variation of local Sherwood number with dimensionless streamwise distance.

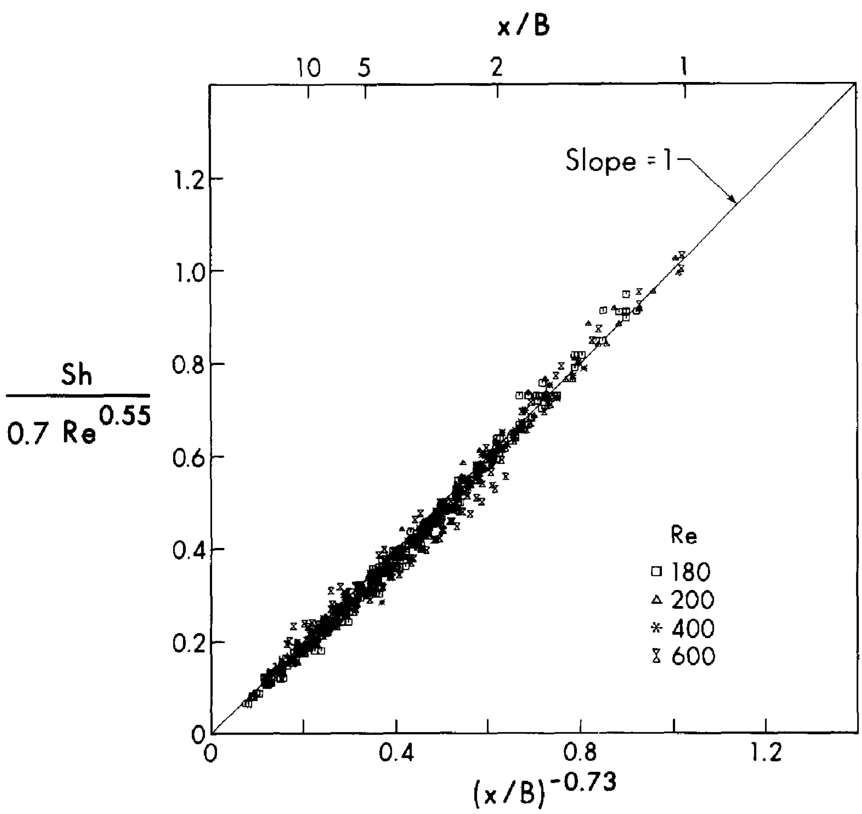

FIG. 6. Test for goodness of fit.

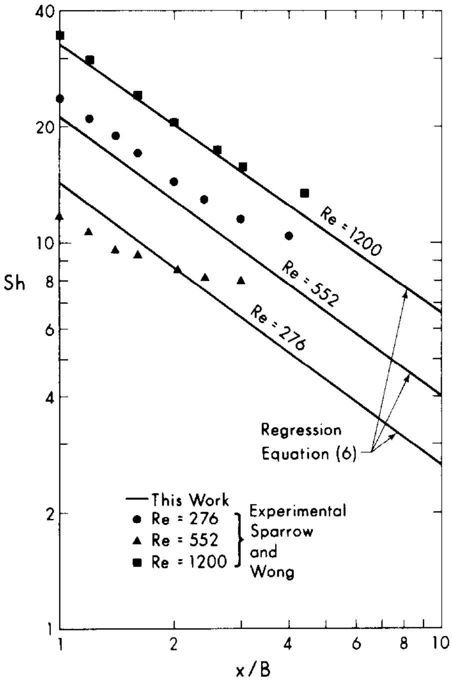

FIG. 7. Comparison with literature mass-transfer data.

Figure 7 compares the data of Sparrow and Wong with the regression equation obtained in this study. As their data were obtained for a slightly different Schmidt number, a correction was made using $(Sc)^{0.4}$ as the correction factor. An overall general agreement between their experimental work and our analysis was obtained. The range of the regression correlation presented here was extended to $Re = 1200$ and good agreement with Sparrow and Wong's data was obtained. Although such an agreement could be considered fortuitous, at least it indicates that the present correlation could be extended beyond $Re = 600$.

Schwarz and Caswell [5] using the flow equations for a wall jet as developed by Glauert [11] obtained, in terms of mass-transfer variables,

$$k = D\left(\frac{5F}{32\nu^3(x+l)^3}\right)^{1/4} \frac{\Gamma(Sc+1/3)}{\Gamma(Sc)\Gamma(1/3)} \tag{7}$$

where

$$F = \int_0^\infty u_x^2 \int_0^\infty u_x \,\mathrm{d}y\,\mathrm{d}y \tag{8}$$

u_x is the velocity in x-direction and y is the coordinate normal to the plate. The mass transferring plate coincides with the x coordinate and l is a length variable to be determined. It has been suggested [5] that F could be estimated at the nozzle exit, hence:

$$F = \int_0^{B/2} u_y^2 \int_0^{B/2} u_y \,\mathrm{d}x\,\mathrm{d}x$$

leading to:

$$F = \tfrac{3}{10}B^2\bar{U}^3 \tag{9}$$

where $u_y = \frac{3}{2}\bar{U}[1-(2x/B)^2]$ at the nozzle exit.

The flow geometry is given in Fig. 8. For $Sc \simeq 2.85$ and using equation (9), equation (7) can be rearranged to give:

$$Sh = \frac{k}{D}d_e = 0.281Re^{0.75}[(x+l)/B]^{-0.75}. \tag{10}$$

Schwarz and Caswell suggested that l/B is proportional to Re^m where m is either 1/3 or 1. For large values of x/B and low values of Reynolds number, equation (10) gives:

$$Sh = 0.281Re^{0.75}(x/B)^{-0.75}. \tag{11}$$

The exponent of x/B as given by the theoretical analysis of Schwarz and Caswell is in fair agreement with the experimental findings of this study. However, the exponent of Reynolds number does not agree with our experimental work as given by the regression analysis of equation (6).

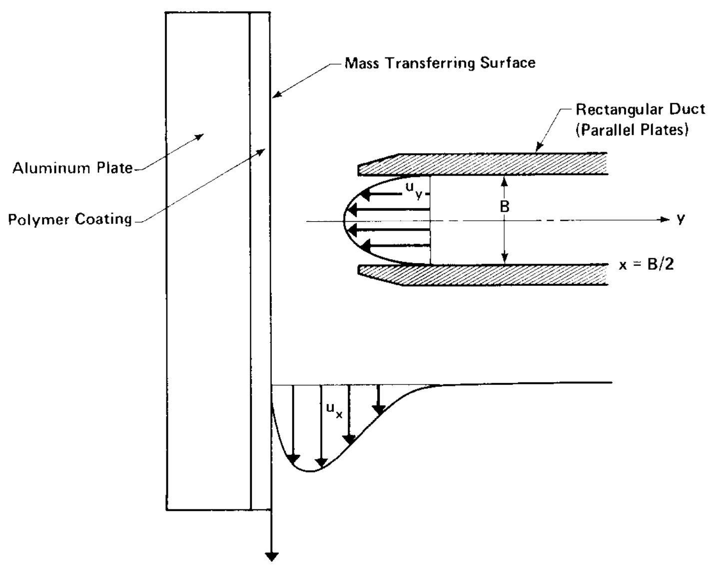

FIG. 8. Flow configuration.

CONCLUDING REMARKS

Mass transfer due to impinging slot jets on a flat surface was successfully studied using laser interferometric technique. A regression equation defining Sherwood number in terms of the jet Reynolds number and downstream distance was presented. The holographic approach was found to be very useful in detecting spanwise variation of Sherwood number. It appears that any slight roughness at the tip of the slot jet nozzle leads to spanwise fluctuations in the mass-transfer coefficient.

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TRANSFERT MASSIQUE DU A UN JET INCIDENT TRIDIMENSIONNEL

Résumé—On mesure les coefficients locaux de transfert massique qui résultent de l'impact d'un jet laminaire d'air, bidimentionnel, sur une surface plane, en utilisant une technique holographique. On donne la formule du nombre de Sherwood local Sh pour un nombre de Schmidt égal à 2,85:

$$Sh = 0{,}7\,(x/B)^{-0{,}73}\,Re^{0{,}55}$$
$$\text{pour } 180 < Re < 600$$
$$\text{et } \quad 1 \leqslant x/B \leqslant 30$$

où x est la distance mesurée à partir du centre du jet le long de la surface de la plaque et B la largeur de la fente. La longueur caractéristique pour Sh et Re est $2\,B$. Cette équation de régression représente la meilleure formule disponible actuellement.

STOFFÜBERGANG BEI ANSTRÖMUNG DURCH EINEN EBENEN FREISTRAHL

Zusammenfassung—Es wurden unter Verwendung einer Halographietechnik örtliche Stoffübergangskoeffizienten bei der Anströmung einer ebenen Fläche durch einen zweidimensionalen laminaren Luftstrahl gemessen. Die Regressionsgleichung für die örtliche Sherwood-Zahl wurde für eine Schmidt-Zahl von 2,85 gefunden zu

$$Sh = 0{,}7 \cdot (x/B)^{-0{,}73} \cdot Re^{0{,}55}$$
$$\text{für } 180 \leqslant \text{Re} \leqslant 600$$
$$\text{und } \quad 1 \leqslant \text{x/B} \leqslant 30,$$

worin x die Entfernung—gemessen vom Strahlmittelpunkt—parallel zur ebenen Oberfläche und B die Schlitzbreite ist. Die charakteristische Länge für Sh und Re ist $2B$. Die Regressionsgleichung stellt die z. Z. beste vorhandene Korrelation dar.

ПЕРЕНОС МАССЫ ПРИ ИСТЕЧЕНИИ СТРУИ ИЗ ЩЕЛИ

Аннотация — С помощью голографического метода измерены локальные коэффициенты переноса массы при натекании двумерной ламинарной струи воздуха на плоскую поверхность. Найдено, что уравнение регрессии, выраженное через локальное число Шервуда *Sh* при числе Шмидта, равном 2,85, имеет вид

$$Sh = 0{,}7(x/B)^{-0.73}Re^{0.55}$$

в диапазоне $180 \le Re \le 600$ и $1 \le x/B \le 30$, где x — расстояние от оси струи вдоль плоской поверхности, а B — ширина щели. Характерный размер для вычисления *Sh* и *Re* принят $2B$. Уравнение регрессии лучше других известных соотношений коррелирует имеющиеся данные.