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MASS-TRANSFER COEFFICIENT IN IMPINGEMENT FLOW FROM SLOTTED NOZZLES

M. KORGER and F. KŘÍŽEK
National Research Institute of Heat Engineering, Běchovice, Prague

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Abstract—A determination of the local coefficients of mass transfer in impingement flow of air issuing from slotted nozzles was made using the technique of sublimation from experimental naphthalene plates. The determination was carried out in two regions with different characters of β_l variations, covering relative distances above and below $(s/b) = 8{\cdot}5$. Relationships for the maximum and mean values of mass-transfer coefficient were established in both regions, and a criterion equation was derived for the mean mass-transfer coefficient in the region of $(s/b) > 8{\cdot}5$. The results were also verified for a group of parallel slotted nozzles and the possibilities of application of the derived relations outlined.

NOMENCLATURE

L, width of plate in the direction of spreading flow (m);
b, width of slot (mm, m);
s, distance between slot orifice and surface (mm, m);
w_0, maximum flow velocity measured in slot orifice (m/s).

Dimensionless criteria
Re_0, $(b.w_0/\nu)$;
Re_s, $= (w_0.L/\nu\sqrt{(s/b)})$;
Sh, $= (\beta.L/D)$;
Sc, $= (\nu/D)$.

Subscripts
0, refers to points on stream centre line;
l, refers to local values;
ϕ, refers to mean values.

INTRODUCTION

THE SO-CALLED impingement flow has been increasingly utilized in recent years for enhancing the intensity of heat and mass transfer of heat-transfer media. Conditions corresponding to such flows are encountered in engineering practice whenever free streams of air issuing from circular or slot nozzles impinge upon a wall.

The majority of studies on the relationships that govern the heat and mass transfer in impingement flow has concentrated on flows issuing from circular nozzles. The number of papers dealing with the conditions that arise when a flat stream impinges upon a wall, has been relatively limited so far, the problem of the relationships defining the values of local heat or mass coefficients receiving the least attention of all. Yet the knowledge of the variations of local coefficients, especially of their maximum values, is eminently important in view of the fact that impingement flows have found their widest field of application in cases when increased intensity of heat and mass transfer is to be achieved even at the price of considerably higher power costs.

SELECTION OF METHODS AND RANGE OF EXPERIMENTS

The selection of the method range of our experimental investigations has been influenced by the final aims of our studies which are directed towards obtaining data applicable to impingement drying [1]. The following two aspects of the problem were given consideration when choosing the experimental method: (1) The intensity of evaporation particularly below the nozzle centre line, is very high in impingement drying. Unless it is known, the choice of material whose properties would reliably ensure moisture conductivity corresponding to the maximum intensity of evaporation, is very difficult.

(2) The intensity of evaporation rapidly decreases in the direction away from the nozzle centre line (in the direction of the spreading

flow) in impingement drying. Such intensity variations occurring in the course of evaporation could produce a moisture gradient in the direction of the spreading flow, and this fluid flow in the plane of the experimental plate could considerably distort the final results.

These considerations led us to a decision to model the fluid evaporation by the sublimation of naphthalene, a substance which had been successfully used before for analogous purposes and whose thermophysical properties in such applications had been verified by several investigators (see, for example, reference [2]). A split naphthalene plate consisting of narrow prisms, enabled us to determine the local values of mass-transfer coefficient by weighing and later on by measuring the decrease in the plate thickness with the aid of a dial gauge.

For the chosen widths of the slot b = 5–40 mm and the nozzle efflux velocity w = 10–40 m/s, the range of experiments may be characterized by $Re_0 = 6{\cdot}04 \times 10^3$ to $3{\cdot}78 \times 10^4$. The distance between the nozzle orifice and the plate surface was varied between 10 and 360 mm, the dimensionless distance s/b ranging between 0·25 and 40. Prior to the tests proper the effectiveness of the selected method was verified on a simpler case of longitudinal flow past a flat plate [3]. In view of the simplifying conditions adopted for the evaluation of the tests, care was taken to ensure that the model tests be conducted at low temperature gradients between the stream of air and the wall (conditions of isothermal diffusion), as well as at low partial pressures. Since all tests were made at approximately equal temperatures, the effect of the diffusion coefficient (D m^2/h) variations could be neglected and the values of β_l compared directly. Systematic errors produced by natural sublimation taking place during determination of the decrease in the plate weight or height, were taken care of by a suitable correction whose value, differing from one experiment to another, was $\beta_l = 1{\cdot}9$ m/h on the average. The reliability interval of the results ranged around ±1·0 m/h on the average when using test $t_{0{\cdot}001}$.

RESULTS OF TESTS

The curves of local coefficients of mass transfer, β_l, for various values of the variable parameters (b, s, w_0) were obtained through the evaluation of experimental results.

The curves were essentially of two types; their character is well evident from Fig. 1 which shows the local coefficient of mass transfer β_l below the slot nozzle. Further processing of the experimental results enabled us to establish the conditions under which the respective type of

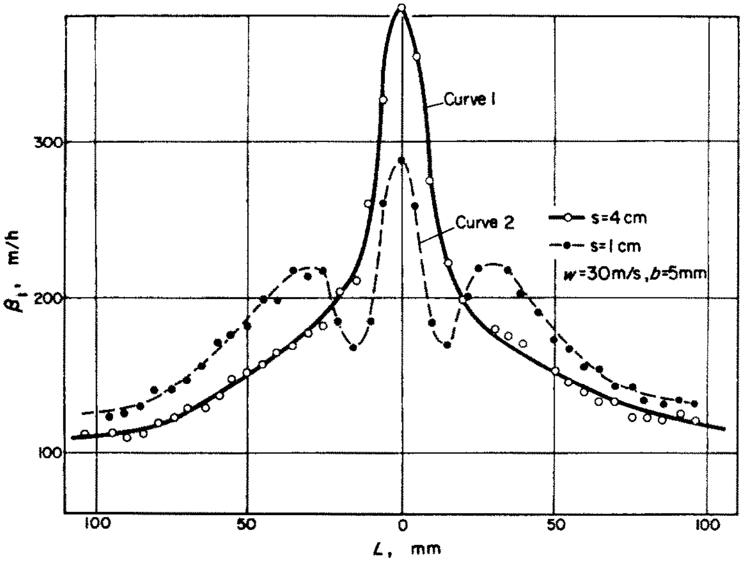

FIG. 1. Variations of local mass-transfer coefficients β_l below slot nozzle.

curve occurs. As the variations of β_l indicate, the maximum values $\beta_l = \beta_0$ lie on the nozzle centre line. This applies with the exception of very small distances between the nozzle orifice and the wall surface (range of $s \leqq b$). At small distances the flow in question impinges no longer perpendicularly to the wall but proceeds more or less parallel to it (the so-called wall flow).

An analysis of the curves of local mass-transfer coefficient was started by studying a simpler limit case (with the coefficient of mass transfer corresponding to a point below the nozzle centre line) for which *Sh* is not defined (for $L \to 0$; $Sh \to 0$).

As the curves obtained indicate, the values of β_0 are not exclusively in inverse proportion to the

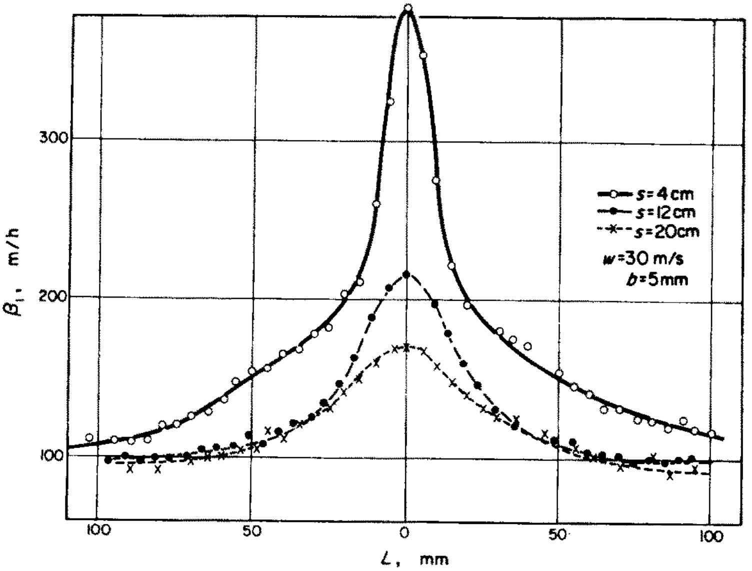

FIG. 2. Variations of local mass-transfer coefficients β_l below slot nozzle for various distances.

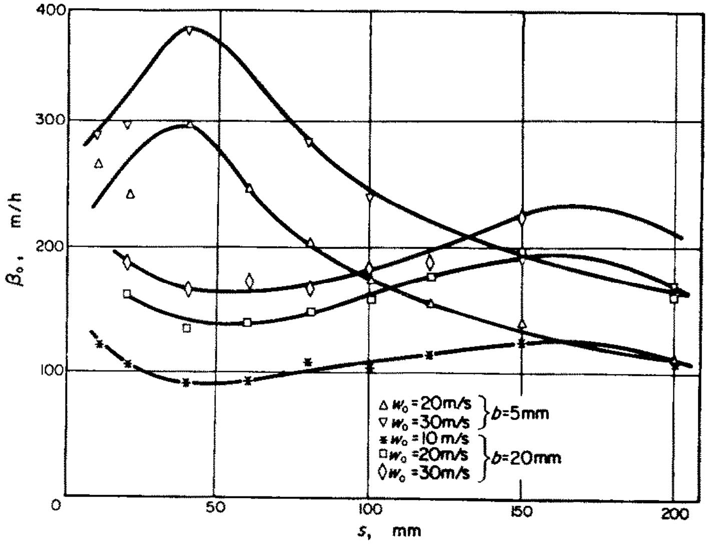

FIG. 3. Variations of β_0 vs. distance between nozzle orifice and surface.

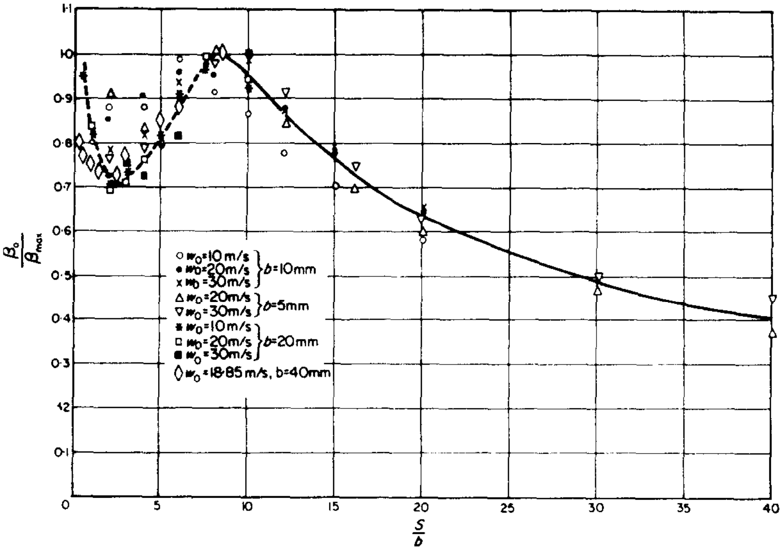

FIG. 4. $\beta_0/\beta_{0\max}$ vs. ratio s/b.

distance between the nozzle orifice and the material surface (Fig. 2) but continuously decrease to some minimum with decreasing distance. As the nozzle orifice further approaches the material surface, β_0 again rises. The values of β_0 at various orifice-surface distances are plotted in Fig. 3.

The seeming diversity of the curves of β_0 can be brought to order by the introduction of ratio s/b, the so-called dimensionless distance between the nozzle orifice and the effective surface. On relating the respective values to this dimensionless distance we obtain mutually similar curves for all the cases under study. Two extremes exhibited by all curves are found in the neighbourhood of $s/b = 2{\cdot}5$ (minimum) and $s/b = 8{\cdot}5$ (maximum). In the discussion that follows, β_0 corresponding to the maximum, is designated as $\beta_{0\max}$ and all experimental values are plotted as relation $(\beta_0/\beta_{0\max}) = f(s/b)$ (Fig. 4).

The points thus obtained are distributed in a manner that permits fitting of curves common to all tests.

Since the scatter of $\beta_0/B_{0\max}$ is far greater in the region of $s/b < 8{\cdot}5$ than at higher values of s/b, the curve is difficult to fit in this region. In view of the fact that the coefficients of mass transfer were determined from prisms with $c = 5$ mm, the curve of $\beta_0/\beta_{0\max}$ was plotted from the results of tests in which wider slots enabled us to establish the local β_l at points below the nozzle with greater accuracy. The curve of $\beta_0/\beta_{0\max}$ thus obtained for $s/b < 10$ is shown in Fig. 5.

As the character of the curve indicates, maximum values of β_0 may be expected first for

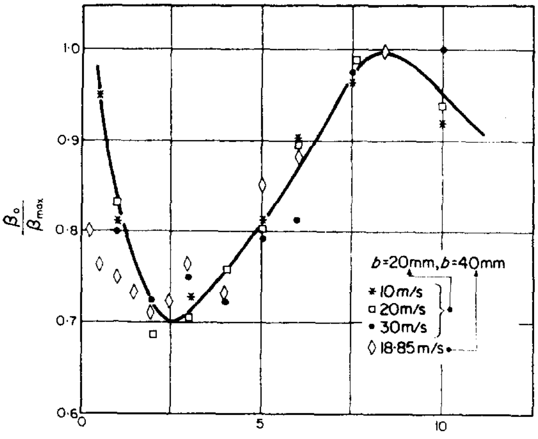

FIG. 5. $\beta_0/\beta_{0\max}$ vs. ratio s/b for tests with 20–40 mm slot width.

$s/b = 8{\cdot}5$ and then for $s/b < 1$. But curves obtained for s/b less than 1 are of no interest for technical applications because at small nozzle-to-surface distances mass transfer is accompanied by increased power costs owing to higher aerodynamic resistance. In addition, practical considerations demand that a certain distance between the nozzles and the material to be dried be maintained in order to permit guiding of the material between nozzles (height of strips of netting, take-up chains, etc.) as well as to take care of the natural creasing of the material.

Two regions with different character of mass transfer below the nozzle can be distinguished when analysing the curve shown in Fig. 4.

The first region covers the range of dimensionless distances $s/b < 8{\cdot}5$, the other that of $s/b > 8{\cdot}5$.* In view of what has been said in the foregoing, we concentrated on the second region.

For this region we were able to write the following relation

$$\frac{\beta_0}{\beta_{0\max}} = 4{\cdot}1 \left(\frac{s}{b}\right)^{-0{\cdot}66}; \tag{1}$$

further study of the dependence of β_0 on w_0 and b resulted in relation

$$\beta_0 = 29{\cdot}9 . w^{0{\cdot}66} . \left(\frac{s}{b}\right)^{-0{\cdot}66} b^{-0{\cdot}33} \tag{2}$$

which applies to the diffusion of naphthalene vapours to air. For other diffusing substances, relation (2) can be recalculated with the aid of equation

$$\beta_l = \frac{D}{D_{C_{10}H_8}} \left(\frac{Sc}{Sc_{C_{10}H_8}}\right)^{1/3} . \beta_{l C_{10}H_8}$$

The experimental values processed according to relation (2) over the given range, are plotted in Fig. 6. The result is interesting inasmuch as it establishes the dependence of β_0 on the ratio $w_0/(s/b)$, a characteristic quantity of the efflux of free streams from nozzle, from the variations of β_l in an experimental way.

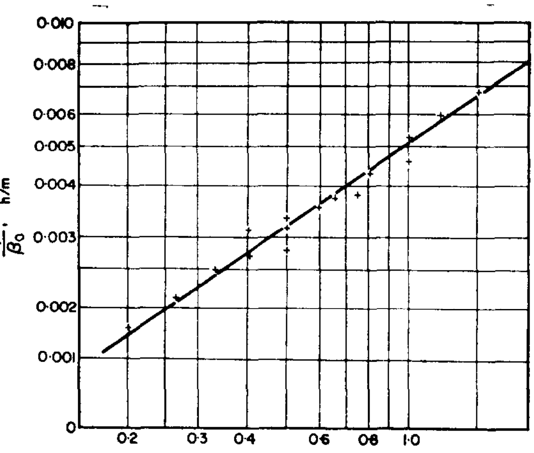

FIG. 6. Dependence of $1/\beta_0$ on $(s/b)^{0{\cdot}66} \cdot w^{-0{\cdot}66}$ for $b = 10$ mm and $w_0 = 10$–40 m/s.

The value of $s/b = 8{\cdot}5$ which separates the two regions, has also become the limit value for distinguishing between the types of curves No. 1 and No. 2 (Fig. 1).

To obtain the mean coefficients of mass transfer, we measured the areas of curves β_l (Fig. 2) with a planimeter in strips of length $L = 0{\cdot}05$, $0{\cdot}08$, $0{\cdot}1$ and $0{\cdot}15$ m which correspond to a range of L/b from $1{\cdot}25$ to 30. The dependence of the dimensionless criterion on various parameters was studied with the aid of relation $Sh = (\beta_0 . L/D)$.

The result of our analysis can be expressed as follows:

$$Sh = kL^{0{\cdot}714} \left(\frac{s}{b}\right)^{-0{\cdot}392} \tag{3}$$

which can, on introducing a common exponent and

$$Re_s = \frac{b . w_s}{\nu} = \frac{b . w_0}{\nu\sqrt{(s/b)}}$$

be rewritten with some approximation in the form of

$$Sh = k . Re^{0{\cdot}77} . Sc^{1/3}. \tag{4}$$

Here again, the effect of ratio $w_0/(s/b)$, well known from relations defining the velocity at the centreline of free flat streams [4–6] comes into

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* The relation established for the first region is in the form of a cubic parabola:

$$\frac{\beta_0}{\beta_{0\max}} = -\,0{\cdot}00284 \left(\frac{s}{b}\right)^3 + 0{\cdot}04897 \left(\frac{s}{b}\right)^2 - 0{\cdot}2078 \left(\frac{s}{b}\right) + 0{\cdot}97108.$$

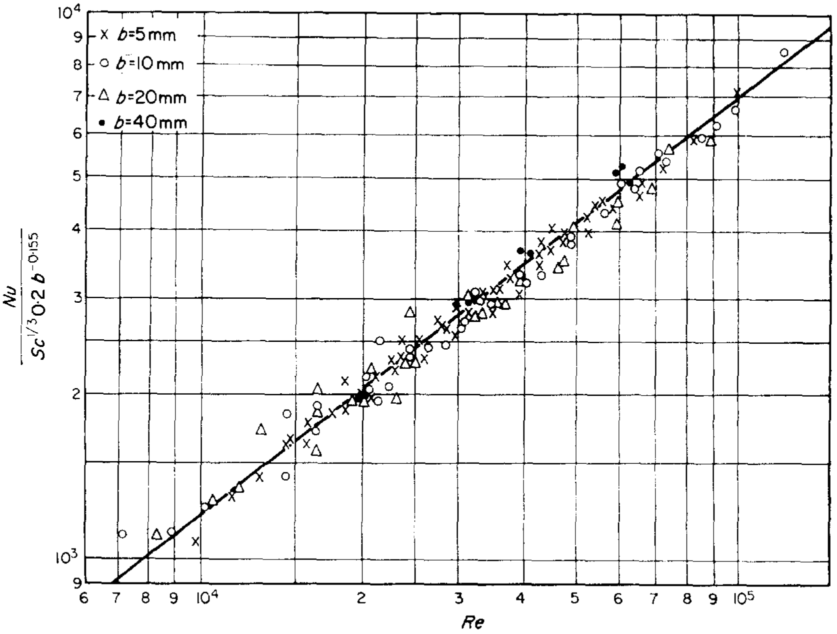

FIG. 7. Dependence of $Sh/Sc^{1/3}$. k on Re.

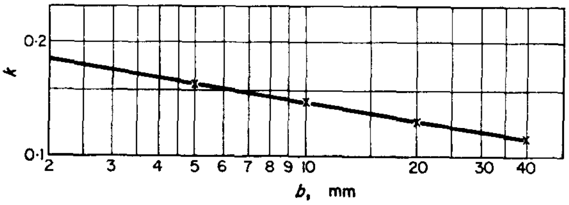

FIG. 8. Dependence of k on nozzle width b.

play; the mean quadratic velocity of free streams has been used before in the determination of the mean values of Sh [7].

Values of Sh processed according to relation (4) are shown in Fig. 7. It is evident that the results are in good accord with the functional relation obtained above. The experimental data plotted in Fig. 8 indicate that the value of k varies also with the width of the nozzle. Analogous results are reported in [8] for circular nozzles.

Since in practical applications of impingement drying the case of an isolated nozzle is a very rare one, relation (4) was further verified for a system of three nozzles where mass transfer may be affected by interaction of the adjacent nozzles. The variations of the mass-transfer coefficient decisive for a system of three nozzles, were determined from data obtained for the central nozzle.

The pitch of the nozzles with width $b = 5$ mm was varied between 50 and 330 mm; this range virtually covers all the cases commonly encountered in drying practice.

The results processed in the manner outlined above enabled us to arrive at conclusions similar to those drawn for the case of an isolated nozzle. The maximum values ranged over an interval of $s/b = 8{\cdot}0$–$9{\cdot}5$, the minimum ones in the region of $s/b = 3{\cdot}5$–$4{\cdot}5$. The effect of the nozzle pitch

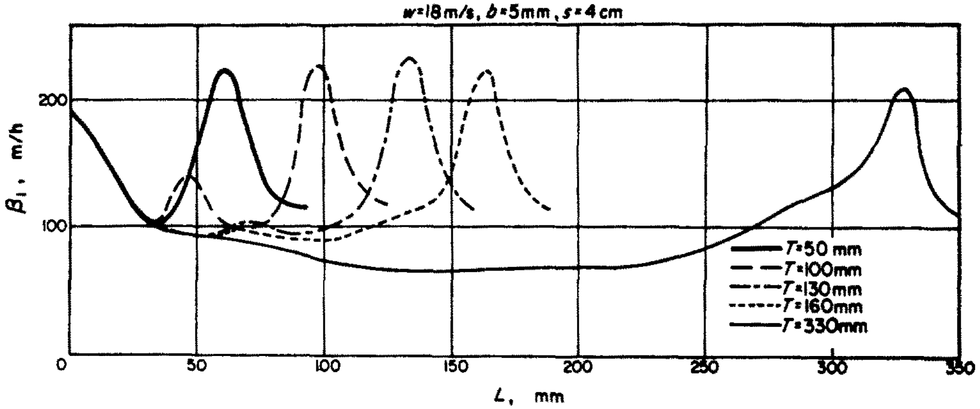

FIG. 9. Variations of β_l for group of nozzles with different pitch.

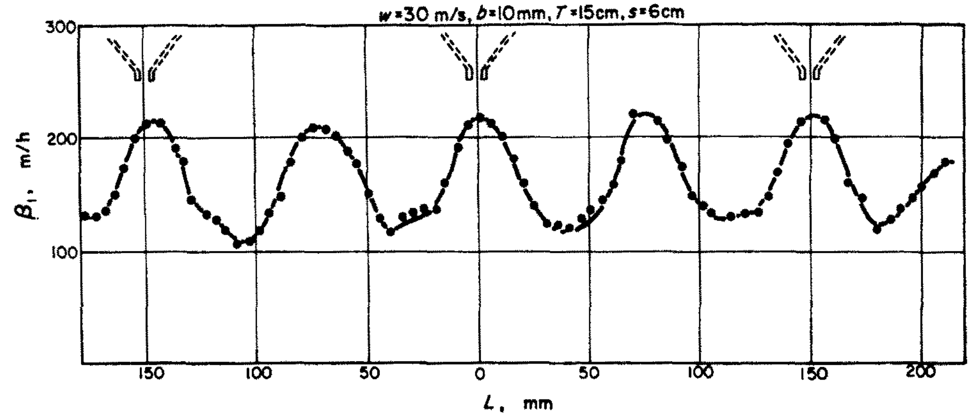

FIG. 10. Variations of local mass-transfer coefficient β_l for one arrangement of three nozzles.

on local mass-transfer coefficient is evident from Fig. 9.

As the variations of the local values of β_l indicate, the curve of β_l is for $s/b \geqslant 8{\cdot}0$ about the same as that for an isolated nozzle. This finding enables us to use relation (4) also for groups of nozzles (Fig. 9). One or more points with increased mass transfer are again observed on the curve of β_l for $s/b < 8{\cdot}0$. Figure 10 illustrates a case when points with higher mass-transfer coefficient are equivalent to those below the nozzle centre line.

CONCLUSION

As our results suggest two regions of mass-transfer differing in the critical ratio s/b must be distinguished in impingement flow. So far as the mean values of β_ϕ and Sh are concerned, the problem is amenable to treatment with the aid of dimensionless criteria in the form of

$$Sh = kRe^{0{\cdot}77}.Sc^{1/3};$$

this relation has been verified for the following ranges: w_0 = 10–40 m/s, b = 5–40 mm, L/b = 1·25–20 and s/b = 8·5–80. The value of $s/b = 8{\cdot}5$ constitutes the lower limit of application of the equation as well as of the treatment outlined.

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Résumé—On a déterminé les coefficients locaux de transport de masse dans l'écoulement normal d'air sortant de tuyères bidimensionnelles en employant la technique de la sublimation à partir de plaques expérimentales en naphtalène. Cette détermination a été faite dans deux régions avec des variations de β_l de caractère différent, le long de distances relatives inférieures et supérieures à $(s/b) = 8{,}5$. On a établi dans les deux régions des relations pour les valeurs maximales et moyennes du coefficient de transport de masse, et l'on a obtenu un critèrie pour le coefficient moyen de transport de messe dans la région où $(s/b) > 8{,}5$. On a également vérifié les résultats pour un groupe de tuyères bidimensionnelles parallèles et souligné les applications possibles des relations obtenues.

Zusammenfassung—Der örtliche Stoffübergangskoeffizient beim Aufprall eines Luftstromes der von Schlitzdüsen ausgeht wurde mit Hilfe der Sublimation von Versuchspaltten aus Naphtalin bestimmt. Diese Bestimmung wurde in zwei Bereichen mit unterschiedlichem Charakter der β_l Änderung durchgefürht für relative Abstände oberhalb und unterhalb $(s/b) = 8{,}5$. Beziehungen für den Grösstwert und den Mittelwert des Stoffübergangskoeffizienten wurden für beide Bereiche ermittelt und eine Kriteriumsgleichung für den mittleren Stoffübergangskoeffizienten im Bereich $(s/b) > 8{,}5$ abgeleitet. Die Ergebnisse wurden auch für eine Gruppe paralleler Schlitzdüsen nachgeprüft und die Anwendungsmöglichkeiten der abgeleiteten Beziehungen gezeigt.

Аннотация—Методом сублимации экспериментальных плиток из нафталина определены локальные коэффициенты массопереноса при ударном истечении воздуха из щелевых сопел. Определение проведено в двух областях с различным характером изменения β_l и относительными расстояниями выше и ниже $(s/b) = 8{,}5$. Для обеих областей получены соотношения для максимальных и средних значений коэффициента массопереноса. Выведено критериальное уравнение для среднего значения коэффициента массопереноса в области $(s/b) > 8{,}5$. Результаты проверены на группе параллельных щелевых сопел и намечена возможность применения выведенных соотношений.