Int. J. Heat Mass Transfer. Vol. 16, pp. 385–393. Pergamon Press 1973. Printed in Great Britain

CONVECTIVE MASS TRANSFER FROM STATIONARY AND MOVING SURFACES USING A MERCURY EVAPORATION TECHNIQUE

R. W. MAXWELL and K. L. NASH*

Engineering Department, University of Leicester, Leicester, England

(*Received* 19 *June* 1971 *and in revised form* 2 *June* 1972)

Abstract—The analogy between heat and mass transfer is applied to various systems, and the results of mass transfer tests on the evaporation of mercury vapour from amalgamated surfaces are compared with published data on heat transfer in systems where the mechanics of the processes are similar. Experimentally measured mass transfer rates from stationary and rotating cylinders in transverse air streams, and from rotating cylinders and stationary flat surfaces due to the action of an impinging jet of air, are related to the corresponding heat transfer process.

NOMENCLATURE

A,	heat or mass transfer area;
d,	diameter;
c,	molar density of solution of mercury vapour and air;
c_p,	specific heat at constant pressure;
D,	diffusivity of mercury vapour in air;
h,	heat transfer coefficient;
k,	thermal conductivity;
k_x,	mass transfer coefficient;
p_v,	partial pressure of mercury vapour;
r,	radius or radial distance;
v,	linear velocity;
W_A,	molar rate of addition of species A;
x_A,	mole fraction of species A in a given phase;
α,	thermal diffusivity;
ν,	kinematic viscosity;
ω,	rotational speed;
ρ,	fluid density;
μ,	fluid viscosity;
Nu,	Nusselt number, hd/k;
Sc,	Schmidt number, ν/D;
Sh,	Sherwood number, $k_x d/cD$, based on the test cylinder diameter;
Sh_j,	Sherwood number based on the jet nozzle diameter;
Re,	Reynolds number, vd/ν;
Re_r,	rotational Reynolds number, $\omega r^2/\nu$;
Re_F,	Reynolds number based on main flow velocity and cylinder diameter;
Re_j,	Reynolds number based on jet velocity and jet nozzle diameter;
Pr,	Prandtl number, $c_p\mu/k$;
j_H,	heat transfer j-factor, $Nu\,Re^{-1}\,Pr^{-\frac{1}{3}}$;
j_D,	mass transfer j-factor, $Sh\,Re^{-1}\,Pr^{-\frac{1}{3}}$.

* Now at Mechanical Engng Dept, Hendon College of Technology, London.

1. INTRODUCTION

PROBLEMS involving the estimation of convective heat and mass transfer rates from stationary and moving surfaces arise in connection with a wide range of industrial processes. The present experimental method, initiated by Maxwell and Storrow [1], eliminates difficulties associated with accurate measurement of heat transfer coefficients in systems where mathematical modelling becomes cumbersome or imprecise due to the complex nature of the fluid flow patterns.

In the present study, rates of mass transfer of mercury evaporating from amalgamated surfaces were experimentally determined by means of a mercury detection meter [2]. Using the Chilton–Colburn analogy [3] between heat and mass transfer, the results were then related to those in the corresponding heat transfer process.

The mercury vapour technique of mass transfer analysis has the advantage that surfaces of various shapes can be readily formed from the material used (copper insets in perspex), and that highly accurate measurements are possible due to the sensitivity of mercury detection meters. As a means of predicting heat transfer rates, the method offers the further advantage of eliminating problems associated with accurate temperature measurement in analogous heat transfer tests.

The objects of the experiments were:

(a) to investigate the use of the mercury evaporation technique as a means of predicting mass and heat transfer rates from stationary and rotating cylinders in cross flow and from rotating cylinders and stationary flat surfaces due to the action of impinging jets;
(b) to obtain transfer data applicable to rotating cylinders, and to a jet of fluid impinging on both stationary and moving surfaces, for use in an associated research project.

The analogy method requires, in addition to geometrical and bulk fluid flow similarity, correspondence of heat and mass transfer boundary conditions. For the mass transfer experiments performed, the boundary conditions comprised a constant mercury vapour pressure at the solid–fluid interface and negligible mercury vapour pressure in the incoming fluid. These conditions correspond to a constant surface temperature and fluid inlet temperature in the heat transfer case.

The ability of amalgamated surfaces, with a copper or brass substrate, to retain a mercury film for a sufficient period of time was demonstrated in preliminary tests [4]. It is, however, vital that in the experiments the surface and fluid temperatures should be virtually identical to allow accurate determination of the saturated vapour pressure at the surface. As explained in the next section, this requirement was shown to be satisfied during the tests.

2. EXPERIMENTAL PROCEDURE

The arrangement of the equipment used in the tests is shown in Fig. 1. Compressed air was passed from a receiver through a battery of parallel mounted Rotometers, thence through a calming section into the test section of the duct, and finally through a mixing section to exhaust into the atmosphere. The air flow rate was controlled by adjustment of valves at the

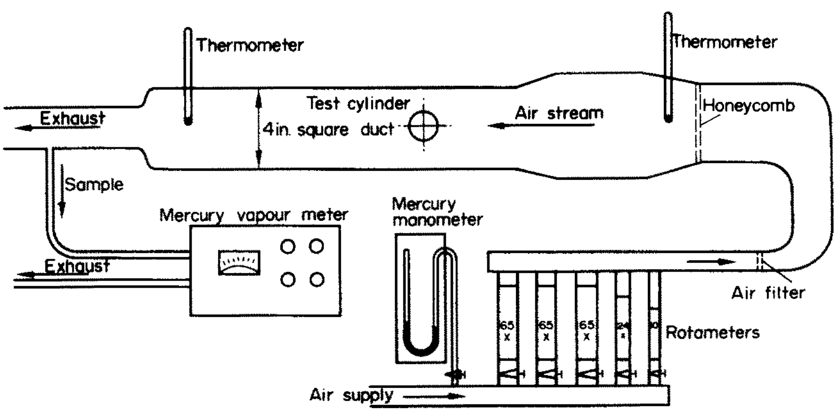

FIG. 1. Schematic arrangement of evaporation test rig.

inlet to each Rotameter, to give a range of mean test section velocity of between 0·6 and 6·5 ms^{-1}. The pressure of the air entering the Rotameters was measured by a mercury manometer adjacent to the inlet manifold. Air temperatures were measured by two mercury-in-glass thermometers mounted respectively upstream and downstream of the test section and sufficiently remote from it to prevent disturbance of the air stream around the specimen.

of mercury concentration measurement. Prior to test runs, readings were taken with a transversing sampling probe to ensure that the samples obtained in the tests were representative of the mercury concentration in the duct.

As part of the preliminary testing, an investigation of the comparative temperature of the test surface and of the air stream was carried out. For this investigation, a special specimen fitted with thermistors beneath the test surface was used,

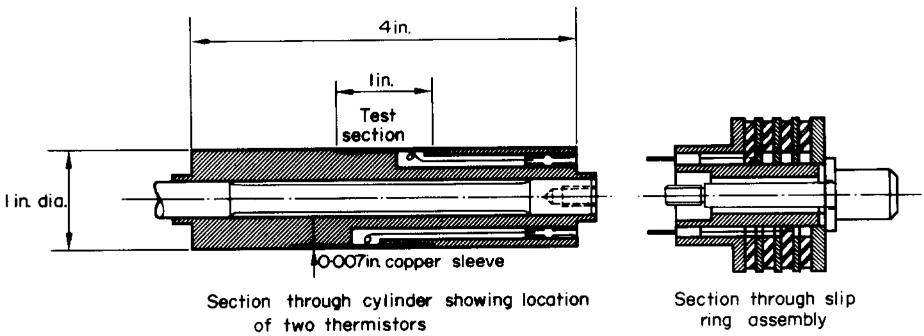

FIG. 2. Arrangement of thermistors in a special test cylinder.

Two specimens of identical dimensions were used at different times during each series of tests. One specimen had a copper test surface which was covered with a thin film of mercury during tests. The surface was cleansed with nitric acid and recoated with mercury before each test run. The second specimen had a lacquered surface and was used to obtain readings of zero mass transfer at the mercury vapour meter. A maximum duration of two minutes was allowed for each test run, preliminary work [4] having shown that no appreciable decay in the rate of mass transfer would occur during this period.

The rate of mercury evaporation during the tests was evaluated by measurements of mercury evaporation in samples of air taken from the mixing section of the duct. The meter depended for its operation on the difference in the absorption of ultra-violet radiation by the sample in question and by filtered mercury free air. It provided a highly sensitive and accurate means

as shown in Fig. 2. No significant differences in temperature were found during the tests.

The final series of experiments was designed to determine the effect on the mass transfer rate of a jet of air impinging normally onto the test surface. For these tests it was desirable to eliminate mass transfer due to the main air stream sweeping across the test surface; nevertheless, a flow greater than that provided by the jet was needed for the mercury concentration meter. The test section was accordingly modified by the addition of a perspex guard, mounted upstream of the test specimens, incorporating bye-pass slots to direct the main air stream well clear of the specimens, see Fig. 3. The jet nozzle directed air from a separate supply onto the test surfacēs.

3. EVALUATION OF THE OVERALL MASS TRANSFER COEFFICIENT

For mass transfer in a closed channel with known interfacial area and composition,

$$dW_A = k_{x\mathrm{loc}}(x_{A0} - x_{Ab}) + x_{A0}(dW_A + dW_B) \tag{3.1}$$

where $k_{x\mathrm{loc}}$ is the local mass transfer coefficient, x_{A0} and x_{Ab} are the local cup-mixing mole fractions of the species A in the given phase, in the element of area dA, and dW_A and dW_B are the elemental molar rates of addition of the species A into the species B, and of species B into species A, respectively [5].

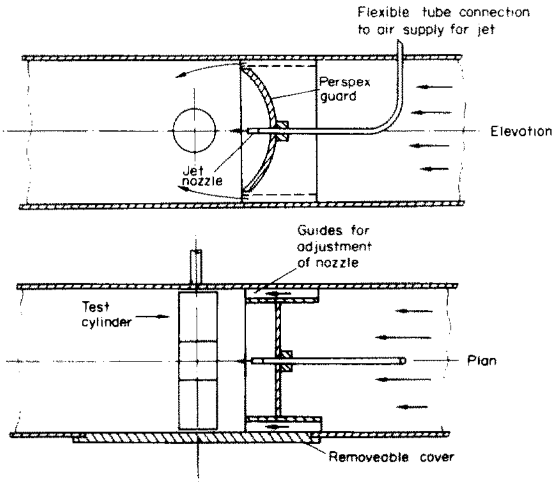

FIG. 3. Sectional views through duct showing nozzle and guard.

For mass transfer between a submerged object and a surrounding fluid, mass transfer coefficients are reported for the entire surface area A. If the fluid concentration next to the surface is uniform, equation (3.1) is rewritten,

$$W_A = k_x A(x_{A0} - x_{A\infty}) + x_{A0}(W_A + W_B) \tag{3.2}$$

in which $x_{A\infty}$ is the uniform composition of the fluid approaching the object.

If mercury be species A and air is species B, the solubility of air in mercury may be neglected, so that $W_B = 0$. Therefore,

$$W_A = k_x A \frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \tag{3.3}$$

or,

$$k_x = \frac{W_A}{A}\frac{1 - x_{A0}}{x_{A0} - x_{A\infty}}. \tag{3.4}$$

In computing x_{A0}, ideal gas behaviour is assumed, i.e. the mole fraction x_{A0} is proportional to the vapour pressure of mercury at the interphase temperature and pressure. If the operating pressure of the air within the closed channel remains at one atmosphere, and since the mercury concentration in the approaching air stream is negligible, from equation (3.4),

$$k_x = \frac{W_A}{A}\frac{1 - p_v}{p_v} \tag{3.5}$$

where p_v is the vapour pressure of mercury expressed in atmospheres.

4. THE CHILTON–COLBURN ANALOGY

Chilton and Colburn [3] postulated the theory that the processes in which a material is transferred by diffusion are closely related to a heat transfer process, since the latter can be considered merely as the diffusion of hot molecules into a region of cold ones and a corresponding diffusion of cold molecules in the reverse direction. Through a method which has as its basis the Reynolds analogy between heat transfer and fluid friction, a correlation between j-factors, defined as

$$j_H = Nu\,Re^{-1}\,Pr^{-\frac{2}{3}} \quad \text{Heat Transfer} \tag{4.1}$$

and

$$j_D = Sh\,Re^{-1}\,Sc^{-\frac{2}{3}} \quad \text{Mass Transfer} \tag{4.2}$$

is obtained of the form

$$j_H = j_D = \tfrac{1}{2}f. \tag{4.3}$$

The relationship agrees closely with the predictions of boundary layer theory for a flat plate, when Pr and Sc exceed 0·5, but in flow over curved boundaries where form drag occurs, $\frac{1}{2}f$ may exceed j_H and j_D considerably. However, the more limited empirical analogy,

$$j_H = j_D = \text{a function of } Re, \text{ geometry and boundary conditions} \tag{4.4}$$

has proved useful for a number of flow situations. Equation (4.4) is the usual form of the Chilton–Colburn analogy.

5. PRESENTATION AND DISCUSSION OF RESULTS

5.1 *Stationary cylindrical surfaces*

The experimental results for mass transfer from stationary cylinders in a transverse air stream are shown in Fig. 4, in comparison with

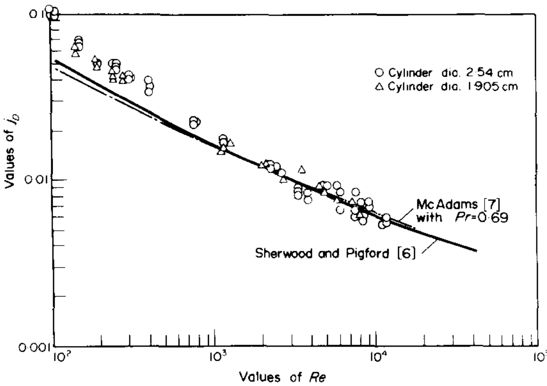

FIG. 4. Stationary plot of j_D versus Re.

heat transfer data taken from Sherwood and Pigford [6] and McAdams [7] as representative of a large collection of data. Whilst the difference between the results and the heat transfer data is less than 2 per cent at $Re = 10^4$, a wider difference is indicated at the lower range of Reynolds number values up to a maximum of 32 per cent at $Re = 10^2$.

Since the results of the mass transfer tests are here compared with heat transfer data for cylinders in a free stream, additional tests were conducted to determine the effect due to the constraints of the duct walls. The mass transfer rates from four cylinders of different diameter were measured and the results were collated in the form of Sherwood number versus the ratio of cylinder diameter to height of duct (d/h), for constant Reynolds number values. The effect of the proximity of the duct walls to the surface of the cylinders, at the lower air flow rates, is shown by the two curves in Fig. 5. For the extreme case of $d/h = 0{\cdot}25$, the Sherwood number value is approximately 34 per cent above that for the corresponding free stream condition, obtained from the extrapolated value

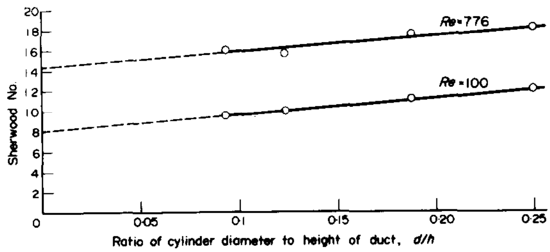

FIG. 5. Cylinders with transverse flow—effect of dimensions of duct on Sherwood number.

at $d/h = 0$. The tests also showed that a progressively smaller correction was required as the Re values increase. For air flow rates in excess of $Re = 2 \times 10^3$, the effect of the duct wall constraints was minimal.

5.2 *Rotating cylinders*

A comparison between the averaged results, obtained by drawing the estimated best line through the plotted values, for tests on rotating cylinders and stationary cylinders in a transverse air stream is shown in Fig. 6.

In similar tests on heat transfer from rotating cylinders, Bjorklund [8] found that his results can be correlated to within $\pm$ 15 per cent by the equation $Nu = 0{\cdot}18[(2Re_r^2 + Re_F^2 + Gr)Pr]^{0{\cdot}315}$, which is based on Etemad's [9] empirical method of correlation, valid up to 10^9 of the bracketed group $(2Re_r^2 + Re_F^2 + Gr)\,Pr$. Bjorklund's equation can be simplified for comparison by assuming that $Pr = 1{\cdot}0$ for air and that $Gr = 0$ for isothermal boundary conditions. The derived relationship then becomes

$$j_H = 0{\cdot}18Re_F^{-1}(2Re_r^2 + Re_F^2)^{0{\cdot}315}.$$

The curves of this relationship are shown plotted in Fig. 6, for values of Re_r of 633 and 5064. The difference between the derived relationship and the results of the mass transfer tests is 55 per cent at $Re_F = 10$ and a maximum of 60 per cent at $Re_F = 10^4$. It is significant to note, however, that the values of j_H, for $Re_r = 633$, from the derived relationship are less than those for stationary cylinders for $Re_F > 10^3$.

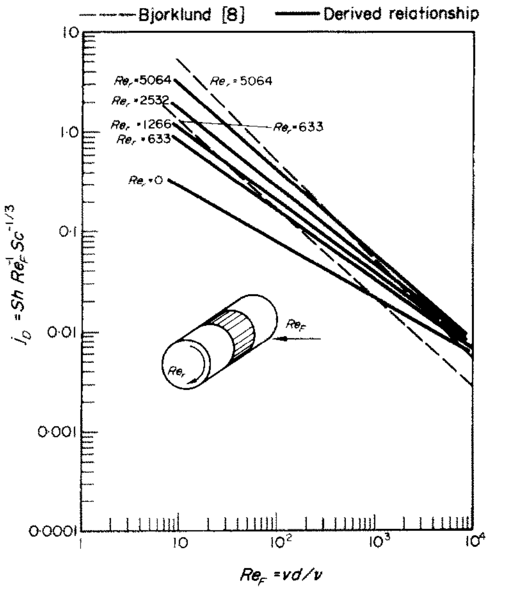

FIG. 6. Averaged results of tests on rotating cylinders in a transverse air stream.

The flow pattern that exists about a rotating cylinder placed in a transverse air stream is explained by Schlichting [10]. On the upper side in the present tests, where the flow was opposite to the direction of movement of the cylinder wall, separation is developed only incompletely. On the lower side, where the flow and the cylinder move in the same direction, separation is completely eliminated.

5.3 *Impingment of jets on stationary and rotating cylinders*

The results of this particular series of tests proved to be far more satisfactory in respect of the degree of fluctuation of the mass transfer rate than other tests and, because the average temperature of the air stream varied by only three degrees C during the test period, an extremely good correlation of results is obtained on a basis of Sh_j vs. Re_j. The results also tend to confirm the original assumption that the mass transfer rate is a function of the cross-sectional area of the jet nozzle, which value was used in the evaluation of Sh_j.

The effect on the mass transfer rate due to a variation in the distance from the jet orifice to the cylindrical surface is illustrated by Figs. 7 and 8. The results indicate that the mass

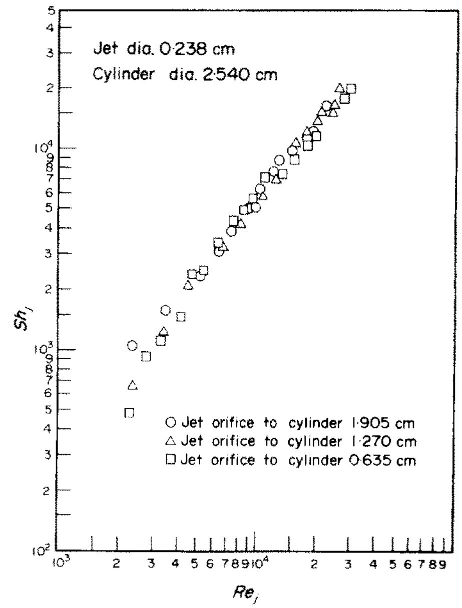

FIG. 7. Effect on Sherwood number due to a variation of distance from jet orifice to cylinder.

transfer rate remains unaffected for distances of up to eight diameters of the jet nozzle, from a minimum spacing of slightly less than three nozzle diameters.

In tests to determine the effect on the mass transfer rate due to a variation in the rotational speed of the cylinders, the distance from the orifice to the cylindrical surfaces was kept at a constant eight nozzle diameters. The results are shown in Figs. 9 and 10. They indicate that the effect is negligible for rotational speeds of between 500 and 5000 rpm, and for average

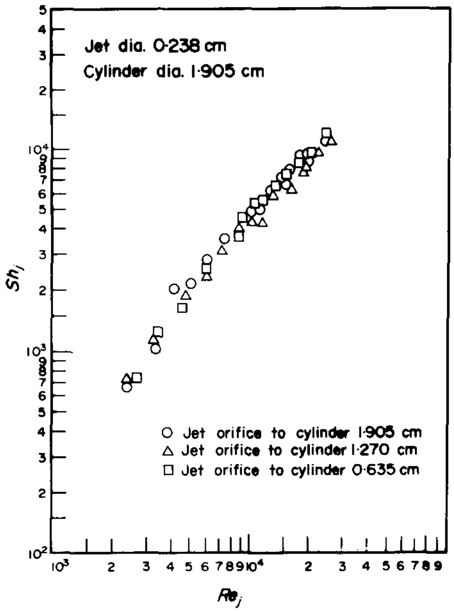

FIG. 8. Effect on Sherwood number due to a variation of distance from jet orifice to cylinder.

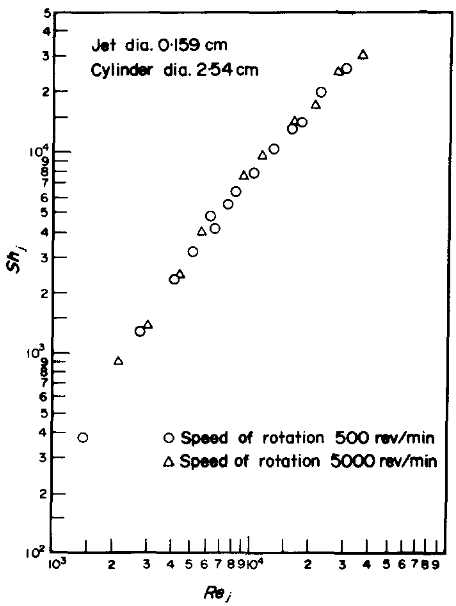

FIG. 9. Effect on Sherwood number due to a variation of rotational speed of test cylinder.

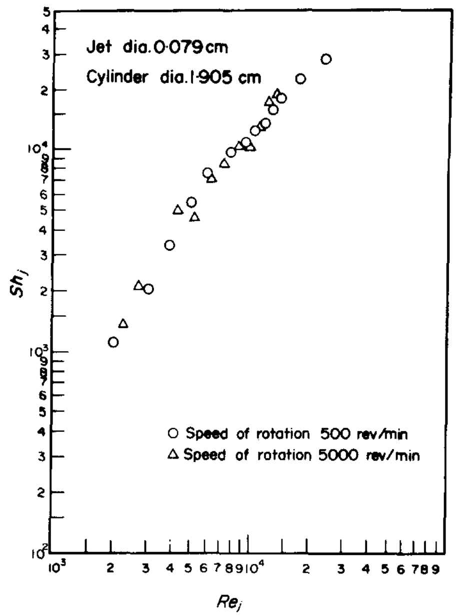

FIG. 10. Effect on Sherwood number due to a variation of rotational speed of test cylinder.

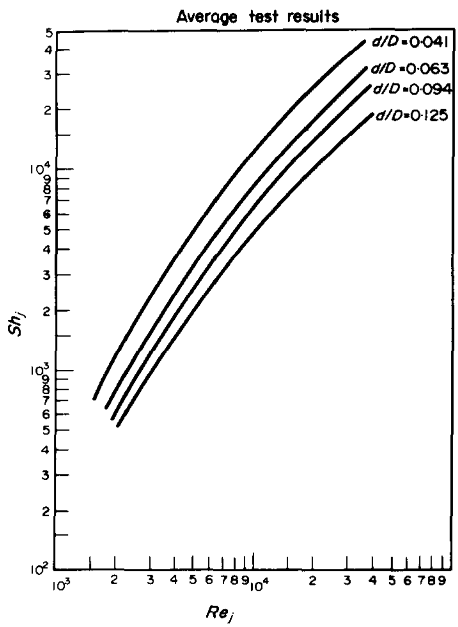

FIG. 11. Effect on Sherwood number due to a variation of ratio of nozzle diameter to test cylinder diameter.

air jet velocities of between 1500 and 18750 cm/s.

The averaged results are shown in Fig. 11, which illustrates the effect on the Sherwood number values due to a variation in the ratio of jet diameter to test cylinder diameter (d/D).

6. CONCLUSIONS

The results of the experiments demonstrate that the mercury evaporation technique is a valuable method of determining mass transfer rates and predicting heat transfer data for similar systems. The mechanism of diffusion of mercury vapour into air has been shown to agree closely with established correlations of mass transfer data from a variety of different techniques, and the method can be used to predict heat transfer data from similar geometrical configurations and with constant surface temperature in the heat transfer situation. The sensitivity of the mercury detection meter is such that the survey of mass transfer of mercury from amalgamated surfaces is more versatile than other mass transfer techniques, and provides a powerful tool for fundamental studies.

7. FUTURE WORK

Development work is in progress to design a mercury vapour detection meter capable of the accurate measurement of mercury concentrations to within one microgramme of mercury per cubic meter of air. Such an instrument would make possible the measurement of local mass transfer rates from extremely small amalgamated surfaces of precise geometry.

REFERENCES

1. R. W. MAXWELL and J. A. STORROW, *Chem. Engng Sci.* **6**, 204 (1957).
2. Mercury Vapour Detection Meter, Type E 3472, Serial No. HRL 1066-1, Columbia Instruments Ltd., Slough, Bucks., England.
3. T. H. CHILTON and A. P. COLBURN, *Ind. Engng Chem.* **26**, 1183 (1934).
4. R. W. MAXWELL and K. L. NASH, University of Leicester Eng. Dept. Report, 69-26 (Oct. 1969).
5. R. B. BIRD, W. E. STEWART and E. N. LIGHTFOOT, *Transport Phenomena*, pp. 636–648, John Wiley, New York (1966).
6. T. K. SHERWOOD and R. L. PIGFORD, *Absorption and Extraction*, p. 70. McGraw-Hill, New York (1952)
7. W. H. MCADAMS, *Heat Transmission*, p. 259. McGraw-Hill, New York (1942).
8. I. S. BJORKLUND, Heat transfer from rotating bodies, single cylinders and concentric cylinders, Ph.D. thesis, Stanford Univ. (1958).
9. G. A. ETEMAD, Free convection heat transfer from a rotating horizontal cylinder to ambient air, with interferometric study of flow, *Trans. Am. Soc. Mech. Engrs* **7**, 1283 (1955).
10. H. SCHLICHTING, *Boundary Layer Theory*, p. 363. McGraw-Hill, New York (1968).

TRANSFERT MASSIQUE PAR CONVECTION DEPUIS DES SURFACES STATIONNAIRES OU MOUVANTES AVEC UTILISATION D'UNE TECHNIQUE D'EVAPORATION DE MERCURE

Résumé—L'analogie entre les transferts thermiques et massiques est appliquée à différents systèmes et les résultats des essais de transfert massique sur l'évaporation de mercure à partir de surfaces amalgamées sont comparés à des résultats publiés concernant le transfert thermique dans des systèmes où les mécanismes des processus sont similaires. Les flux massiques mesurés expérimentalement à partir de cylindres stationnaires ou tournants dans des courants d'air transversaux, à partir de cylindres tournants et des surfaces planes stationnaires attaqués par un jet d'air sont reliés au processus correspondant du transfert thermique.

KONVEKTIVER STOFFTRANSPORT VON RUHENDEN UND BEWEGTEN OBERFLÄCHEN BEI QUECKSILBERVERDAMPFUNG

Zusammenfassung—Es wurde die Analogie zwischen Wärme- und Stoffübertragung auf verschiedene Systeme angewandt Die Ergebnisse der Versuche für den Stoffübergang bei Quecksilberverdampfung von amalgamierten Oberflächen wurden verglichen mit veröffentlichten Daten des Wärmeübergangs in Systemen mit den gleichen Bedingungen. Die experimentell bestimmten Stoffübergangsraten von ruhenden

und rotierenden, von Luft quer angeströmten Zylindern und von rotierenden Zylindern und ruhenden ebenen Platten bei Anströmung durch einen Luftstrahl wurden mit den entsprechenden Wärmeübergangsvorgängen verglichen.

ИССЛЕДОВАНИЕ КОНВЕКТИВНОГО МАССОПЕРЕНОСА ОТ СТАЦИОНАРНЫХ И ДВИЖУЩИХСЯ ПОВЕРХНОСТЕЙ С ПОМОЩЬЮ МЕТОДИКИ ИСПАРЕНИЯ РТУТИ

Аннотация—Аналогия между тепло-и массопереносом применяется к различным системам. Экспериментальные результаты по массопереносу при испарении паров ртути с амальгированных поверхностей сравниваются с опубликованными данными по теплопереносу в системах с аналогичной механикой процессов. Экспериментально измеренные скорости массопереноса от стационарных и вращающихся цилиндров, поперечно обтекаемых потоками воздуха, и от вращающихся цилиндров и стационарных плоских поверхностей под действием падающей струи воздуха, отнесены к соответствующему процессу теплопереноса.