Int. J. Heat Mass Transfer. Vol. 23, pp. 355–361.
Pergamon Press Ltd. 1980. Printed in Great Britain.

AN EXPERIMENTAL INVESTIGATION OF MASS TRANSFER FROM A GAS FLOW TO LIQUID JETS

H. T. KARLSSON, S. ÅBERG and I. BJERLE

Division of Chemical Technology, Department of Chemical Engineering, Chemical Center, Lund Institute of Technology, P.O.B. 740, S-220 07 Lund 7, Sweden

(*Received* 20 *November* 1978 *and in revised form* 23 *April* 1979)

Abstract – The mass-transfer factor, for flow perpendicular to varying configurations of liquid jets, has been experimentally determined. For the range $10 \leq Re \leq 200$, the following dependency was obtained $j_d = 1.13\,Re^{-0.60}$ where the usual definition of j_d has been slightly modified. At $Re = 10$ the result lies about 30% above data for heat and mass transfer to a stationary cylinder placed normal to the flow. The deviation decreases with increasing *Re* number and for comparison, ten expressions from the literature were adapted. The deviation was discussed in terms of the laminar film generated parallel to the jets and the wake flow generated behind each jet. Obviously, one can predict approximately mass transfer to liquid jets placed normal to the flow by using an expression for a stationary cylinder under similar conditions. The result can be improved by correcting for the effect caused by the wake flow and the parallel film, together with a geometric factor. For this purpose a semi-empirical model is suggested.

NOMENCLATURE

- a, spacing between centre of two jets in flow direction [m];
- A, mass-transfer area [m^2];
- b, spacing between centre of two jets normal to flow direction [m];
- c, specific heat of fluid [J/kg K];
- d, jet diameter, cylinder diameter [m];
- D, diffusion coefficient in fluid [m^2/s];
- f, configuration factor;
- G, gas flow [m^3/s];
- h, heat-transfer coefficient [J/K m^2 s];
- j, heat- and mass-transfer factor;
- k, thermal conductivity of fluid [J/K m s];
- k, mass-transfer coefficient [m/s];
- l, spacing between centre of a jet and wall [m];
- m, constant;
- n, constant;
- p, partial pressure of sulphur dioxide [Pa];
- t, time [s];
- U, superficial velocity [m/s].

Subscripts

- d, mass transfer;
- e, without jets;
- h, heat transfer;
- in, inflow;
- j, with jets;
- out, outflow;
- p, specific heat at constant pressure.

Superscript

- $*$, residence time of liquid jets.

Greek symbols

- α, increase in heat- and mass-transfer rate due to the wake flow;
- ν, kinematic viscosity of fluid [m^2/s];
- ρ, density of fluid [kg/m^3].

Dimensionless groups

- Nu, $= hd/k$, Nusselt number;
- Pr, $= c_p\nu\rho/k$, Prandtl number;
- Re, $= dU/\nu$, Reynolds number;
- Sc, $= \nu/D$, Schmidt number;
- Sh, $= k_d d/D$, Sheerwood number;
- Tr, $= d^2/t^*\nu$, residence-time number.

INTRODUCTION

AN ATTRACTIVE alternative to conventional gas cleaners is the multi-jet absorber. Among its advantages are its good mass-transfer properties, extremely low pressure drop and lack of need for any separation equipment for the two phases. No packing is needed for holding the liquid and its contact time is very short, which is sometimes good from the viewpoint of selectivity. The multi-jet absorber can also be used for laboratory investigations. The principle of a multi-jet absorber is shown in Fig. 1.

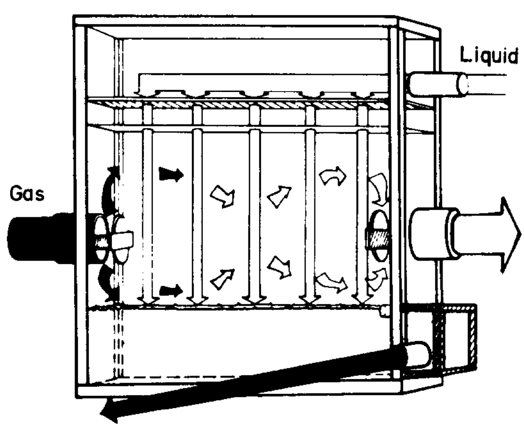


FIG. 1. The principle of a multi-jet absorber.

One of the main problems with the multi-jet absorber is to determine the mass-transfer coefficient, in the gas phase, for the liquid jets. Several important aspects are involved, such as the velocity of the perpendicular gas flow, the velocity of the liquid jets and the configuration of the jets.

Heat and mass transfer to a stationary cylinder can be shown to have similarities with mass transfer to liquid jets. In the literature it is possible to find mass- and heat-transfer factors, represented by an equation of the type

$$j = mRe^{-n} \tag{1}$$

For mass transfer, the following definition is conventional

$$j_d = \frac{Sh}{ReSc^{1/3}} \tag{2}$$

and for heat transfer

$$j_h = \frac{Nu}{RePr^{1/3}}. \tag{3}$$

In this investigation, the mass-transfer coefficient, for the gas phase, was experimentally determined for a gas flowing perpendicular to varying configurations of liquid jets. In the test runs sulphur dioxide was absorbed in a small multi-jet absorber, with sodium hydroxide as the scrubbing agent. The results were compared with data valid for flow perpendicular to a stationary cylinder. Based on this comparison, a general model for predicting mass transfer to liquid jets was proposed.

APPARATUS AND EXPERIMENTS

The absorber was 0.4 m long and 0.04 m wide, with jets about 0.08 m long. Generation of the jets was carried out with perforated steel plates. Air was passed, via a distributor, through the smallest cross-section.

The mass transfer was simulated by absorption of sulphur dioxide in a 0.2 M sodium-hydroxide solution. The air contained about 2000 vpm sulphur dioxide, and the reaction was infinitely fast at the interface, so the whole concentration distribution was located in the gas phase. The concentration in the gas was measured at the entrance to and the exit from the absorber, both in the presence and absence of jets, using a continuous IR-spectrophotometer. The mass-transfer coefficient was calculated using

$$k_d = \frac{G}{A}\left\{\ln\left(\frac{p_{in}}{p_{out}}\right)_j - \ln\left(\frac{p_{in}}{p_{out}}\right)_e\right\} \tag{4}$$

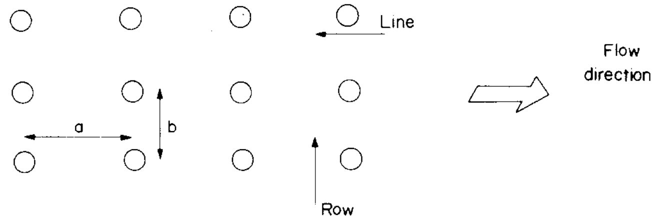
where G is the gas flow and A is the total mass-transfer area of the liquid jets. p_{in} and p_{out} are the partial pressure of sulphur dioxide in the entrance and exit flows, respectively. The subscripts j and e indicate measurements with and without jets in the absorber. Equation (4) assumes that the same amount is absorbed by the bottom surface with and without jets. This is a rather good approximation, because the contribution from the bottom surface is relatively small.

Three different kinds of jet configurations, as shown in Fig. 2, were examined. Ninety-five jets, with a diameter of 10^{-3} m, were used in all experiments. The absorber void fraction was >0.99 and the maximum velocity exceeded superficial velocity by less than 15% in the most extreme case.

The 0.08 m long jets had a mean velocity of 3 m/s, corresponding to a residence time of 0.027 s, if acceleration is taken into consideration.

The Re number ranged from 10 to 200, and was based upon the superficial velocity. At Re numbers higher than 200, a bending of the jets could be observed. At Re numbers below 10, it was difficult to analyze the gas concentration in the exit flow due to high absorption efficiency.

During the experiments the temperature was 30 ± 2°C. The diffusion coefficient for sulphur dioxide was calculated from Hirschfelder's equation to be 1.30 × 10^{-5} m^2/s at this temperature, corresponding to Sc = 1.25. Hirschfelder's equation can be found in any standard text treating the subject of diffusion. The value was checked using other equations and the same result was obtained.



Config	$a \times 10^3$ (m)	$b \times 10^3$ (m)	Lines × rows	
1	3.5	∞	1	95
2	11.0	12.5	3	32
3	20.0	6.7	5	19

FIG. 2. The jet configurations investigated. For configuration 2, the middle line constitutes only 31 jets.

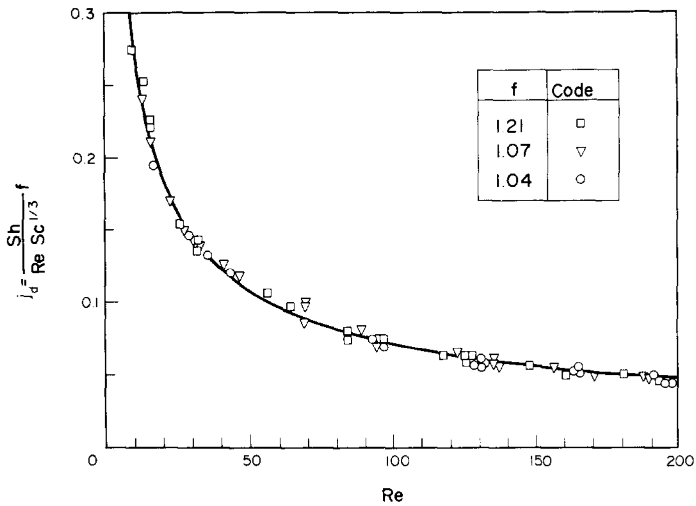


FIG. 3. A plot of the experimental data and the fitted curve. The mass-transfer factor as a function of the *Re* number.

EXPERIMENTAL RESULTS

Basic data, corresponding to 80 test runs, are plotted in Fig. 3. Some of the points in the figure are based on more than one run. By introducing a factor f, it was possible to represent data for all configurations with one relationship

$$j_d = 1.13\,Re^{-0.60} \tag{5}$$

where

$$j_d = \frac{Sh}{ReSc^{1/3}} f \tag{6}$$

and

$$f = (1 + d/a)^{3/4} \tag{7}$$

d and a are respectively the jet diameter and the spacing between the centre of two adjacent jets in the flow direction lines (see Fig. 2). The presented form of the mass-transfer factor is similar to that conventionally used for a single stationary cylinder, with the exception of the factor f. This factor is explained later on in the theoretical discussion.

LIQUID JETS COMPARED TO A SINGLE CYLINDER

In Fig. 4 equation (5) is compared with some data for heat and mass transfer adapted from the literature. The equations plotted are valid for flow perpendicular to a single tube, cylinder or wire. Furthermore, it has been assumed that heat and mass transfer are analogous, and therefore $j_d = j_h$. As can be seen, transfer to liquid jets in general is faster than to a stationary cylinder, and this effect is slightly enhanced with decreasing *Re* number. The difference observed is due to the film generated along the jets and the disturbance of the flow pattern by upstream jets which will affect

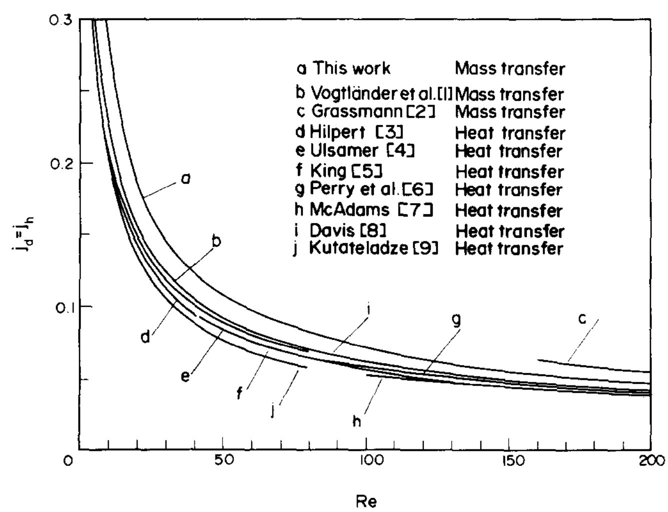


FIG. 4. A survey of heat- and mass-transfer data, for flow perpendicular to a cylinder, wire or tube. The mass-transfer factor as a function of the *Re* number.

the flow field of downstream jets. Parameters of importance for the latter phenomenon are mainly of geometric origin.

Geometric aspects

Johansson [10] investigated flow around a cylinder between two plates with $l/d = 5$, where l is the spacing between the major axis of the cylinder and the wall and d is the cylinder diameter. According to Johansson the wall effects are of no significance at $Re \geq 10$. Since $l/d \geq 6.6$ in this investigation, the influence of the walls on the flow around the jets was neglected. The same was true for adjacent lines of jets because $b/d \geq 6.6$, where b is the spacing between the centres of two jets normal to the flow direction.

When the superficial velocity was chosen as the basis for the Re number, j_d did not vary with b/d and this is in agreement with the previous discussion.

The jets placed in the same line are assumed to interact with each other in two ways. First an arbitrary jet is shadowing other jets downstream. According to Sissom *et al.* [11] it is possible, at $b/d > 1.5$, to increase the efficiency by increasing a/d. In this investigation a factor f was therefore introduced, and it was suggested that f should vary with a power of $(1 + d/a)$. According to Jakob [12] a similar factor is recommended, with the power of 1/2, for tubular heat-exchangers. In this investigation the best fit was obtained with the power 3/4, resulting in equation (7). With no shadowing it was assumed that $f \rightarrow 1$.

The second phenomenon is due to the wake flow generated behind each jet. The wake flow is assumed to prevail a certain distance after the jet, and thus affect downstream jets. It is expected that this phenomenon would be largely independent of the ratio a/d, since the wake length is much larger than a. Very little data is available for predicting this influence. However, some data have been given for heat transfer from bundles of tubes. According to Sissom *et al.*, the heat-transfer rate is increased by a factor $\alpha = 1.56$, if the bundle is 10 rows or more deep. However, it should be noted that the above mentioned α-factor is valid only for Re numbers from 500 to 20000.

The film generated by the jets

The film generated along the jets enhances the mass-transfer rate. When there is no cross flow, this film is laminar. The phenomenon can be considered as a flow parallel to a cylinder or as a moving continuous cylinder and theories for both cases are similar. When a cross flow is introduced, a wake will be generated behind each jet, due to separation. For a smooth tube Johansson calculated the angle of separation by solving the Navier–Stokes equation. From his results the wake can be calculated to affect 22% of the whole cylinder surface at $Re = 10$ and to increase with increasing Re number. Schlichting [13] followed the same procedure by means of Blausius's series. In his case the wake affects 40% of the cylinder area, independent of the Re number. Probably small ripples on the jet surface are enough to decrease strongly the affected part.

The part corresponding to the wake therefore will give a turbulent film but this is difficult to take into account. However, with data taken from Bennet *et al.* [14] it can be shown that the mass-transfer rate for a laminar and turbulent film will have the same magnitude.

The Sh number depends on the Sc and Tr numbers, where

$$Tr = \frac{d^2}{t^* \nu} \tag{8}$$

d is the jet diameter, ν is the kinematic viscosity of the gas and t^* is the residence time of the liquid jets. The Sh number discussed here is a mean value. In Fig. 5, the group $Sh/Sc^{1/3}$ is displayed as a function of Tr according to various models. Experimental data from Bjerle *et al.* [15] have been included for comparison. The data are based on absorption of sulphur dioxide in a NaOH solution by means of a single laminar jet. Figure 5 is valid for $Sc = 1.25$, but from an investigation by Karnis *et al.* [16], it can be concluded that the group $Sh/Sc^{1/3}$ is almost independent of Sc, if common gases are utilized. Data for the models were taken from Eichhorn *et al.* [17] and Sherwood *et al.* [18] (model 1), Crank [19] (model 2), Karnis *et al.* [16]

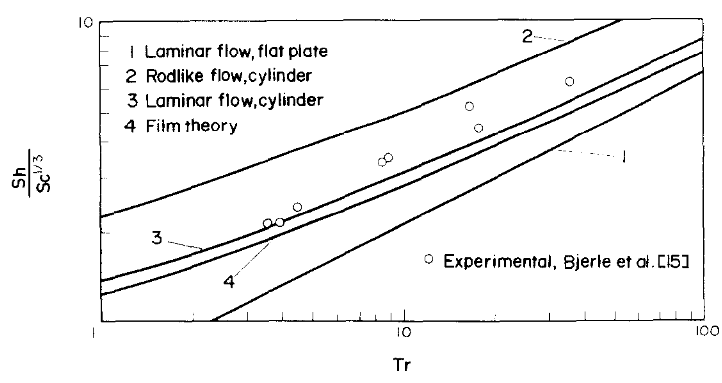


FIG. 5. The average Sh number for flow along a cylinder, or for a continuous moving cylinder, according to various models, at $Sc = 1.25$. $Sh/Sc^{1/3}$ as a function of the Tr number.

(model 3) and Sakiadis [20] (model 4).

In this investigation $Tr = 2.3$ was utilized in all test runs.

A GENERAL MODEL

The model proposed provides that the estimation of mass transfer to liquid jets can be based on a relationship valid for a stationary cylinder. In the following outline the data of Davis [8] have been chosen. The data can be described by

$$Sh/Sc^{1/3} = 0.86\, Re^{0.43} \quad (9)$$

$$Re \leq 200.$$

Equation (9) thus describes mass transfer to a single jet, in the limiting case where the jet residence-time is infinite. In the general case equation (9) predicts a too small a value for a single jet, since the film generated by the jet enhances mass transfer, as previously mentioned.

The problem can be regarded as two perpendicular flows over a curved surface. For the hypothetical case where the surface is flat, the estimation can simply be carried out by utilizing the resultant of the *Re* numbers for the two flows. Since the flows over the curved surface are governed by one *Re* number and one *Tr* number, the difference in influence on mass transfer of these two numbers is not known. However, it was found from Fig. 6, that equation (9) can be used for estimation of the group $Sh/Sc^{1/3}$ for a single jet with no cross flow, by replacing the *Re* number with the *Tr* number multiplied by the constant 2.5. By applying the analogy with the flat surface, the estimation of mass transfer to a single jet with cross flow can be carried out, utilizing

$$Sh/Sc^{1/3} = 0.86\{\sqrt{[Re^2 + (2.5\, Tr)^2]}\}^{0.43}. \quad (10)$$

A similar problem is that of a rotating cylinder with cross flow. Kays *et al.* [21] investigated this problem experimentally for three different values for the rotating *Re*-number. They suggested an equation analogous to equation (10). The constant corresponding to 2.5 in equation (10), was in their case obtained intuitively and not through a fit of the experimental data. However, by applying the method proposed here to the test runs by Kays *et al.*, a constant similar to that found by them intuitively was obtained.

Since equation (10) was developed for a single jet, the previous reasoning concerning the wake flow has to be taken into account, when a line of jets is considered. Comparing equations (5) and (10), for $f = 1$, an α-factor similar to that proposed by Sissom *et al.*, can be obtained. Equation (5) gave values larger by a factor ranging from 1.18 to 1.12. By utilizing a mean value, the final formula became

$$Sh/Sc^{1/3} = 0.98(Re^2 + 6.3\, Tr^2)^{0.215} f^{-1}. \quad (11)$$

Limitations

For application to the design of a multi-jet absorber, certain limitations have to be set for preventing or minimizing the following effects;

(1) Liquid entrainment.
(2) Coalescence of the jets.
(3) Formation of drops instead of jets.
(4) Bending of the jets, due to the gas flow.
(5) High liquid recirculation ratio.

The following geometric limitations are recommended

$a/d,\ b/d \geq 3.5$
$0.5 \leq d \leq 2$ mm (suggested choice: 1 mm)
Jet length ≤ 0.15 m.

The parameters governing equation (11) should lie in the following ranges

$Re \leq 200$
$0.5 \leq Tr \leq 5$
$1 \leq f \leq 1.21$

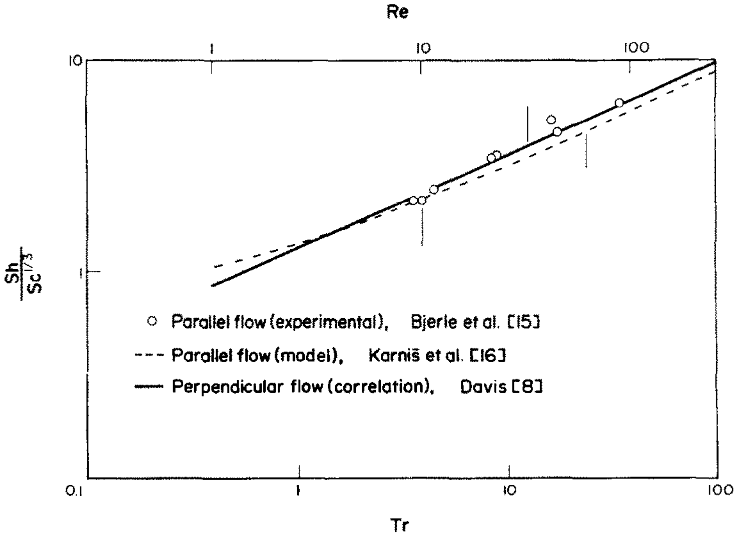


FIG. 6. $Sh/Sc^{1/3}$ as a function of the *Re* and *Tr* numbers, for flow perpendicular and parallel to a cylinder, respectively. The same equation can be used for parallel and perpendicular flow by putting $Re = 2.5\ Tr$.

Table 1. The k_dA value for various types of absorbers

Type of absorber	k_dA (1/s)	Investigator
Multi-jet absorber	1 - 30	This work
Packed tower	0.01 - 10	Kwanten et al. [22]
Plate tower	0.5 - 30	Kwanten et al. [22]
Spray scrubber	0.3 - 2	Mehta et al. [23]
Bubble column	2 - 4	Dankwerts [24]

The multi-jet absorber compared with commercial absorbers

In the table, the magnitude of the k_dA value for the multi-jet absorber is shown. As a comparison, data for different types of absorbers are included.

CONCLUSIONS

Mass transfer to liquid jets can be determined by the equation

$$Sh/Sc^{1/3} = 0.98(Re^2 + 6.3\, Tr^2)^{0.215} f^{-1} \quad (11)$$

Equation (11) is valid for

$$Re \leq 200 \quad f \leq 1.21 \quad b/d \geq 5$$

REFERENCES

1. P. H. Vogtländer and C. A. P. Bakker, An experimental study of mass transfer from a liquid flow to wires and gauzes, *Chem. Engng Sci.* **18**, 383–389 (1963).
2. P. Grassmann, Elektrochemiche Messung von Stoffübergangzahlen, *Chemie-Ingr-Tech.* **8**(33), 529–533 (1961).
3. R. Hilpert, Wärmeabgabe von geheizten Drähten and Rohren im Luftstrom, *Forsch. Geb. Ing Wes.* **4**, 215–224 (1933).
4. J. Ulsamer, Die Wärmeabgabe eines Drahtes oder Rohres an einen senkrecht zur Achse strömenden Gas – oder Flüssigkeitsstrom, *Forsch. Geb. Ing Wes.* **3**, 94–98 (1932).
5. W. J. King, The basic laws and data of heat transmission, *Mech. Engng* **54**, 410–414, 426 (1932).
6. R. H. Perry and C. H. Chilton, *Chemical Engineers Handbook*, 5th edn, pp. 10–13. McGraw-Hill, New York (1973).
7. W. H. McAdams, *Heat Transmission*, 3rd edn, p. 259. McGraw-Hill, New York.
8. A. H. Davis, Convective cooling of wires in streams of viscous liquids, *Phil. Mag.* **47**, 1057–1092 (1924).
9. S. S. Kutateladze, *Fundamentals of Heat Transfer*, 2nd edn, p. 247. Edward Arnold, New York (1963).
10. H. Johansson, A numerical solution of the flow around a circular cylinder between two parallel plates, Report no. 74-F-2, p. 32. Dept. of Chem. Engng, Lund Inst. of Techn. (1974).
11. L. E. Sissom and D. R. Pitts, *Elements of Transport Phenomena*, pp. 499–506. McGraw-Hill, New York (1972).
12. M. Jakob, *Heat Transfer*, Vol. 2, p. 254. John Wiley, New York (1949).
13. H. Schlichting, *Grenzschicht-Theorie*. 3rd edn, p. 145. G. Braun, Karlsruhe (1965).
14. C. O. Bennett and J. E. Myers, *Momentum, Heat, and Mass Transfer*, 2nd edn, pp. 333, 367. McGraw-Hill, New York (1974).
15. I. Bjerle, S. Bengtsson and K. Färnkvist, Absorption of SO_2 in $CaCO_3$-slurry in a laminar jet absorber, *Chem. Engng Sci.* **27**, 1853–1861 (1972).
16. J. Karnis and V. Pechoc, The thermal laminar boundary layer on a continuous cylinder, *Int. J. Heat Mass Transfer* **21**, 43–47 (1978).
17. R. Eichhorn, E. R. G. Eckert snd A. D. Anderson, An experimental study of nonuniform wall temperature on heat transfer in laminar and turbulent axisymmetric flow along a cylinder, *J. Heat Transfer* **82C**, 353 (1960).
18. T. K. Sherwood, R. L. Pigford and C. R. Wilke, *Mass Transfer*, p. 80. McGraw-Hill, New York (1975).
19. J. Crank, *The Mathematics of Diffusion*, 2nd edn, pp. 87–88. Clarendon Press, Oxford (1975).
20. B. C. Sakiadis, Boundary-layer behavior on continuous solid surfaces—III. The boundary layer on a continuous cylindrical surface, *A.I.Ch.E.Jl* **3**, 467–472 (1961).
21. W. M. Kays and I. S. Bjorklond, Heat transfer from a rotating cylinder with and without cross flow, ASME paper 56-A-71 (1956).
22. F. J. G. Kwanten and J. Huiskamp, *Gas Purification Processes for Air Pollution Controll* (edited by G. Nonhebel) 2nd edn, pp. 101–103. Newness–Butterworths, London (1972).
23. K. C. Mehta and M. M. Sharma, Mass transfer in spray columns, *Br. Chem. Engng* **15**(11), 1440–1444 (1970).
24. P. V. Dankwerts, *Gas–Liquid Reactions*, McGraw-Hill, New York (1970).

ETUDE EXPERIMENTALE DU TRANSFERT MASSIQUE ENTRE UN GAZ EN MOUVEMENT ET DES JETS LIQUIDES

Résumé — On a déterminé expérimentalement le coefficient de transfert massique pour des écoulements perpendiculaires à des jets liquides. Dans le domaine $10 < Re < 200$, on obtient la relation $j_d = 1{,}13\, Re^{-0{,}60}$ où la définition habituelle de j_d est légèrement modifiée. A $Re = 10$, les résultats sont de 30% supérieurs à ceux du transfert de chaleur et de masse à un cylindre fixe placé normalement à l'écoulement. L'écart décroit quand le nombre Re augmente et on adapte dix expressions antérieures. L'écart est discuté à partir du film laminaire généré et parallèle aux jets et du sillage formé derrière chaque jet. On peut prévoir approximativement le transfert massique pour des jets liquides perpendiculaires à l'écoulement, en utilisant une expression pour un cylindre fixe dans des conditions semblables. Le résultat peut être amélioré en le corrigeant des effets provoqués par le sillage et le film parallèle, à l'aide d'un facteur géométrique. On suggère un modèle semi-empirique.

EINE EXPERIMENTELLE UNTERSUCHUNG DES STOFFÜBERGANGS VON EINER GASSTRÖMUNG AN FLÜSSIGKEITSSTRAHLEN

Zusammenfassung—Stoffübergangszahlen für die Strömung normal zu unterschiedlichen Anordnungen von Flüssigkeitsstrahlen wurden experimentell untersucht. Für den Bereich $10 < Re < 200$ wurde die folgende Abhängigkeit $j_d = 1{,}13\,Re^{-0{,}60}$ erhalten, wobei die übliche Definition von j_d leicht modifiziert wurde. Bei $Re = 10$ liegt das Ergebnis etwa 30% über Werten für Wärme- und Stoffübergang an einem ruhenden Zylinder, der normal zur Strömung angeordnet ist. Die Abweichung nimmt mit zunehmender *Re*-Zahl ab, und zum Vergleich wurden 10 Beziehungen aus der Literatur herangezogen. Die Abweichung wurde hinsichtlich des parallel zu den Strahlen erzeugten laminaren Films und der hinter jedem Strahl erzeugten Nachlaufströmung diskutiert. Offensichtlich kann man näherungsweise den Dtoffübergang an Flüssigkeitsstrahlen vorhersagen, die normal zur Strömung angeordnet sind, indem man einen Ausdruck für stationäre Zylinder unter ähnlichen Bedingungen verwendet. Das Ergebnis kann verbessert werden durch Korrektur für den Einfluß der Nachlaufströmung und des parallelen Films sowie durch einen geometrischen Faktor. Zu diesem Zweck wird ein halb-empirisches Modell vorgeschlagen.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ МАССОПЕРЕНОСА ОТ ПОТОКА ГАЗА К СТРУЯМ ЖИДКОСТИ

Аннотация — Экспериментально определен коэффициент массопереноса для потока газа, направленного перпендикулярно струям жидкости переменной конфигурации. Для диапазона значений числа Рейнольдса $10 \leq Re \leq 200$ получена следующая зависимость $j_d = 1{,}13\,Re^{-0{,}60}$ где общепринятое определение j_d несколько модифицировано. При $Re = 10$ получаемый результат на 30% выше данных для неподвижного цилиндра, расположенного перпендикулярно направлению потока. С увеличением числа *Re* это расхождение уменьшается. Для сравнения использованы десять зависимостей, взятых из опубликованных источников. Расхождение в значениях объясняется наличием ламинарной пленки, образующейся параллельно струям, и следным течением, индуцированным каждой струей. Перенос массы к струям жидкости, направленным перпендикулярно потоку, вероятно, можно приближенно рассчитать с помощью выражения для неподвижного цилиндра в аналогичных условиях. Более точный результат можно получить за счёт введения поправки на влияние течения в следе и в параллельной пленке, а также введения геометрического фактора. Для этой цели предложена полуэмпирическая модель.