Int. J. Heat Mass Transfer. Vol. 7, pp. 283–291. Pergamon Press 1964. Printed in Great Britain

THERMAL AND MATERIAL TRANSFER IN TURBULENT GAS STREAMS—A METHOD OF PREDICTION FOR SPHERES

T. R. GALLOWAY† and B. H. SAGE‡

Chemical Engineering Laboratory, California Institute of Technology, Pasadena, California

(*Received* 20 *August* 1963)

Abstract—The thermal and material transport from spheres in turbulent air streams have been reduced to analytical expressions taking into account the Reynolds number of the flow, the level of turbulence of the air stream, and the diameter of the sphere. The coefficients for these expressions are based upon experimental work ranging from drops to spheres of about 1 ft in diameter. The range of Reynolds numbers involved extends from 2 to $1{\cdot}33 \times 10^6$. The standard error of estimate for all the experimental measurements was about 15 per cent, while the standard error of estimate for measurements for a much smaller range of sphere diameters was approximately 4 per cent.

NOMENCLATURE

A, A_1, A_2, B, C,	coefficients;
d,	diameter, in;
D_{Mk},	Maxwell diffusion coefficient of component k, lb/s;
Gr,	Grashof number;
h,	heat-transfer coefficient, Btu/s ft² degF;
k,	thermal conductivity, Btu/s ft degF;
N,	number of points;
Nu_i^*,	macroscopic Nusselt number for conditions at interface;
P,	pressure, lb/ft² absolute or lb/ft²;
Pr_∞,	molecular Prandtl number for conditions of stream;
Re_∞,	Reynolds number for conditions of stream;
s,	average deviation;
Sc_∞,	molecular Schmidt number for conditions of stream;
Sh_i^*,	macroscopic Sherwood number for conditions at interface;
U,	velocity, ft/s;
$\bar{u}_{xf}$,	mean longitudinal local fluctuating velocity, ft/s;
x,	coefficient of standard deviation.

Greek symbols

a_t,	apparent level of turbulence, fraction;
β,	normalized transport;
K,	thermometric conductivity, ft²/s;
ν,	kinematic viscosity, ft²/s;
σ,	standard error of estimate.

Subscripts

c,	calculated;
e,	experimental;
i,	condition at interface;
M,	material transfer;
T,	thermal transfer;
T_M,	simultaneous thermal and material transfer;
x,	longitudinal direction of flow;
∞,	stream condition.

Superscript

o,	limiting value.

† Graduate research student in Chemical Engineering.
‡ Professor of Chemical Engineering.

INTRODUCTION

MANY investigations have been made of thermal and material transport from spheres located in turbulently flowing gas streams. In most instances, however, the experimental information did not include the level or the scale of the turbulence in the gas stream, and the behavior was correlated on the basis of linear theory.

A few investigators [1–4] observed a nonlinear

U

relationship between the Nusselt or the Sherwood number and the square root of the Reynolds number, and attempted to take such behavior into account by increasing the exponent of the Reynolds number above 0·5. The results, based upon the assumption that the Nusselt number was a single-valued function of the square root of the Reynolds number, were not entirely satisfactory, as illustrated in Fig. 1. Average deviations of 60 per cent from the correlation shown in the figure were encountered. For this reason a systematic program of measurement was carried out for thermal and material transfer from small spheres in flowing air streams of varying levels of turbulence [3, 5–11]. Recently Kinard, Manning and Manning [12] prepared a correlation of the material transfer from spheres taking into account separately the effects of transport front and aft of the zone of boundary-layer separation. The behavior with respect to the several variables was similar to that found in the present review, except that no regard was taken by Kinard and co-workers of the level of turbulence or of other than the first order effects of diameter.

The purpose of this review is to present the available experimental data in a form useful to the engineer for the prediction of transport behavior. In this work the influence of Reynolds number, size of sphere, and level of turbulence has been taken into consideration. The effect of the scale of turbulence has not been included, since the experimental data contained little information about this variable.

ANALYTICAL CONSIDERATIONS

It is beyond the scope of this paper to review the details of the radial conduction and radial diffusion, in connexion with boundary layer theory, which form the basis of much of the theoretical treatment of thermal and material transfer from spheres. For thermal transport the limiting value of the Nusselt number for radial conduction is given by:

$$(Nu_i^*)_{Re_\infty = Gr = 0} = 2. \quad (1)$$

A similar analysis for the limiting value of material transport involving only radial diffusion results in:

$$(Sh_i^*)_{Re_\infty = Gr = 0} = 2. \quad (2)$$

The details of this development are described by Frössling [13] and Langmuir [14]. Most of the more recent work in this field [1, 3, 4, 15] has verified the theoretical limit which is shown in Fig. 1.

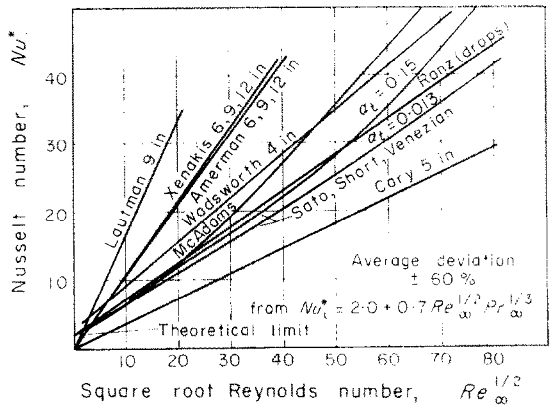

FIG. 1. Conventional presentation of convective thermal transport from spheres.

Frössling [13] carried out a satisfactory analysis of the convective macroscopic transfer from spheres, and predicted that at zero level of turbulence the Nusselt number would be a single-valued function of the Reynolds and Prandtl numbers. The results of his analysis are as follows:

$$Nu_i^* = 2{\cdot}00 + 0{\cdot}552\, Re_\infty^{1/2}\, Pr_\infty^{1/3}. \quad (3)$$

A similar line of reasoning leads to the following relationship for the Sherwood number:

$$Sh_i^* = 2{\cdot}00 + 0{\cdot}552\, Re_\infty^{1/2}\, Sc_\infty^{1/3}. \quad (4)$$

It should be noted that this expression does not take into account the effect of the level of turbulence.

In the present development the Reynolds, Prandtl, and Schmidt numbers were defined in the following way:

$$Re_\infty = dU_\infty/\nu_\infty \quad (5)$$

$$Pr_\infty = \nu_\infty/K_\infty \quad (6)$$

$$Sc_\infty = P\nu_\infty/D_{Mk}. \quad (7)$$

The Nusselt number corresponding to the space average properties at the interface was evaluated from:

$$Nu_i^* = h_i\, d/k_i. \quad (8)$$

The Sherwood number was defined in terms of the space average properties at the interface in the following way:

$$Sh_i^* = h_{Mi}d/k_i. \quad (9)$$

For present purposes the longitudinal level of turbulence was defined by:

$$a_t = a_{tx} = (\bar{u}_{xf}^2)^{1/2}/U. \quad (10)$$

In most of the experimental work the level of turbulence was varied by changing the axial position of the sphere in the wake of a grid or a perforated plate. For the recent investigations with small spheres [6, 7, 8, 10, 11], the detailed experimental measurements of Davis [16, 17] were employed to relate the longitudinal level of turbulence to the position in the wake of an identical perforated plate. The work of Davis can be used to establish the level of turbulence in an apparatus of similar geometry from a knowledge of the grid mesh size and the distance downstream to the sphere. Where there is a turbulence-inducing grid, predictions of the level of turbulence can be made in a manner similar to that shown in Fig. 2. Wadsworth [18] measured the level of longitudinal turbulence with a hot-wire anemometer.

Since it is difficult to determine the level of turbulence experimentally, the level of turbulence established in these investigations is subject to some uncertainty. It might therefore be preferable to define this quantity in terms of

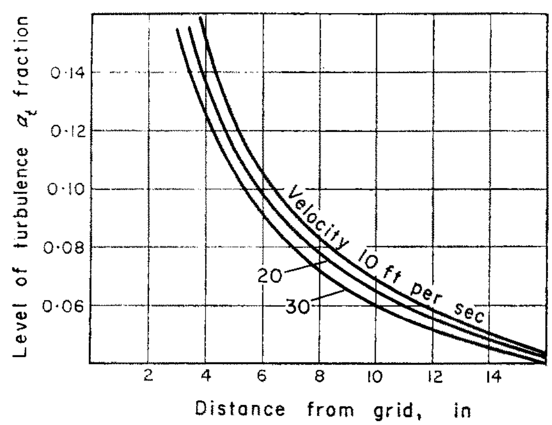

FIG. 2. Effect of position in wake of grid upon longitudinal level of turbulence.

the sphere diameter, the mesh size, and the longitudinal sphere position in the wake of the perforated plate. However, in the interest of simplicity in interpreting the results, the term "apparent level of turbulence", designated as a_t, will be employed. The results indicate good agreement with measurements of the level of turbulence reported by different investigators. Such agreement confirms the fact that the position in the wake of the perforated plate is a satisfactory indication of the local level of turbulence.

In the present development the primary variables were defined as

$$\beta_T = (Nu_i^* - 2{\cdot}000)/(Re_\infty^{1/2}\, Pr_\infty^{1/3}) \quad (11)$$

for thermal transfer, and

$$\beta_M = (Sh_i^* - 2{\cdot}000)/(Re_\infty^{1/2} Sc_\infty^{1/3}) \quad (12)$$

for material transport. These dependent variables are designated as β_T and β_M, respectively, throughout the following discussion. Simple boundary layer theory with no turbulence indicated that these quantities should be invariant with respect to Reynolds number and sphere diameter. In the limit, as the Reynolds number approaches zero the values β_T and β_M become indeterminate. The experimental data may be extrapolated to zero Reynolds number, and the limiting values of these quantities may then be established with some certainty.

The effect of the apparent level of turbulence and the sphere diameter on the thermal transport variable β_T was approximated in the following way:

$$\beta_T = A_1 + A_2 d^{1/2} + Ba_t(a_t + C)\, Re_\infty^{1/2} \quad (13)$$

From equation (13) it is evident that at zero Reynolds number this quantity would be a function of the sphere diameter alone. An analogous expression with constants having different values, was employed for material transport. Earlier experimental work [5, 6, 10, 11] indicated that the value of the Nusselt number for thermal transfer was not equal to the value of the Nusselt number for simultaneous thermal and material transport at the same Reynolds number and molecular Prandtl number.

A summary of the experimental data utilized

Table 1. Summary of experimental conditions for data employed†

Description of sphere	Number of data points	Range of Conditions: Apparent level of turbulence‡	Reynolds number	Nusselt or Sherwood number	Reference
		Thermal and simultaneous thermal and material transport			
0·5 in porous sphere	95	0·013–0·15	820–7250	18–49	[6, 10]
1·0 in porous sphere	21	0·013–0·15	1820–7300	27–59	[11]
0·5 in silver sphere	40	0·013–0·15	900–7260	16–48	[7, 8]
1·0 in silver sphere	14	0·013–0·15	1800–7500	22–48	[11]
0·07 in *n*-heptane drops	32	0·013	66–319	6–13	[3]
6·0 in copper sphere	7	0·02	176000–1330000	420–1418	[21]
9·0 in copper sphere	7	0·008	263000–975000	513–987	[21]
12·0 in copper sphere	12	0·01	177000–1330000	420–1418	[21]
5·0 in Armco-iron sphere	5	0·01	44000–150000	107–206	[22]
0·02 in water drops	6	0·01	48–1040	7–32	[13]
0·279 in steel sphere	7	0·01	190–1460	12–26	[2]
0·496 in steel sphere	4	0·01	540–2100	17–30	[2]
0·787 in steel sphere	5	0·01	210–1340	12–24	[2]
9·0 in copper sphere	8	0·02	129600–1020000	628–2010	[19]
0·0375 in water drops	18	0·01	2–195	3–10	[15]
4·0 in copper sphere	30	0–0·066	22600–246000	148–540	[18]
6·0 in copper sphere	8	0·02	87000–667000	301–927	[20]
9·0 in copper sphere	8	0·008	130000–975000	374–1217	[20]
12·0 in copper sphere	8	0·01	177000–1330000	480–1418	[20]
		Material transport			
0·5 in porous sphere	95	0·013–0·15	820–7250	21–78	[6, 10]
0·07 in *n*-heptane drops	32	0·013	66–319	7–13	[3]
0·02 in water drops	6	0·01	48–1040	7–32	[13]
0·0375 in water drops	18	0·01	2–195	3–9	[15]

† All transport to air.
‡ Apparent turbulence level defined by equation (10).

in this review, covering the range of conditions, is set forth in Table 1.

In order to illustrate the nature of the behavior, there is shown in Fig. 3 the effect of the Reynolds number upon the Nusselt number associated with thermal transfer from a 1·0 in silver sphere [11], and upon the Nusselt number associated with simultaneous thermal and material transport from a 0·5 in [6, 10] and a 1·0 in porous sphere [11]. Fig. 4 shows the effect of the apparent level of turbulence directly for a series of Reynolds numbers for these same data. Results for material transfer from the 0·5 in porous sphere appear in Fig. 5, which depicts the effect of the square root of the Reynolds number and the apparent level of turbulence upon the Sherwood number. The trends visible in these figures were also found by Wadsworth [18], Powell [1], and others.

RESULTS

In order to show the behavior reported by the several investigators, the results for thermal transfer and for combined thermal and material transfer are depicted in Fig. 6. The marked influence of the apparent level of turbulence upon the variation in the parameter β with Reynolds number is evident. Similar information for the Sherwood number associated with material transport is given in Fig. 7.

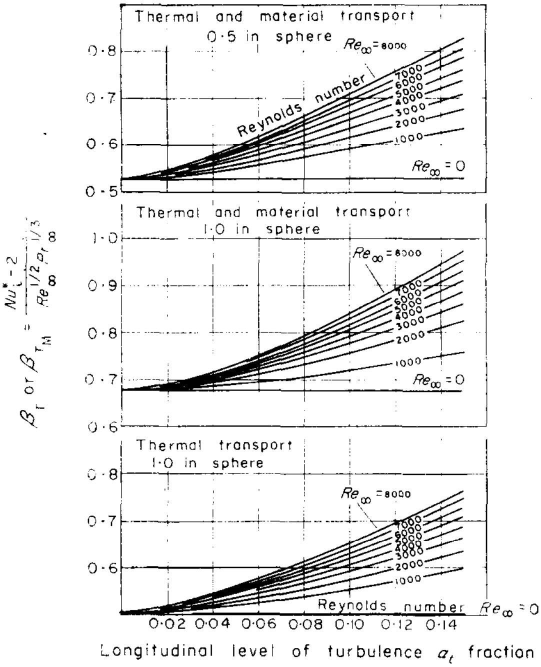

FIG. 3. Effect of Reynolds number upon macroscopic thermal transport from spheres.

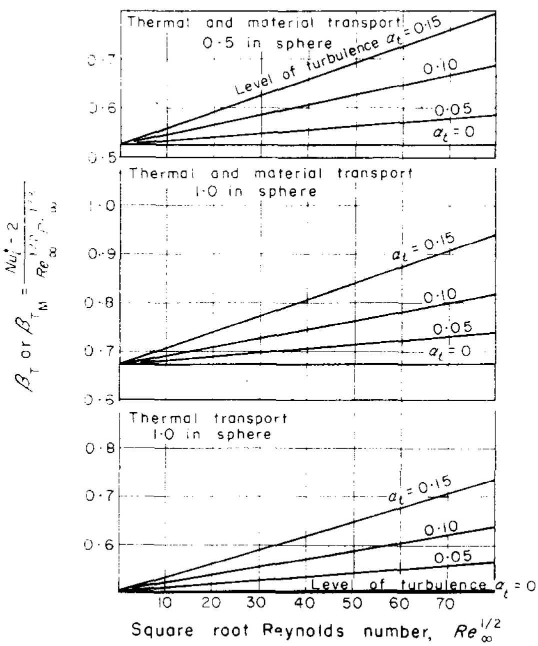

FIG. 4. Effect of level of turbulence upon macroscopic thermal transport from spheres.

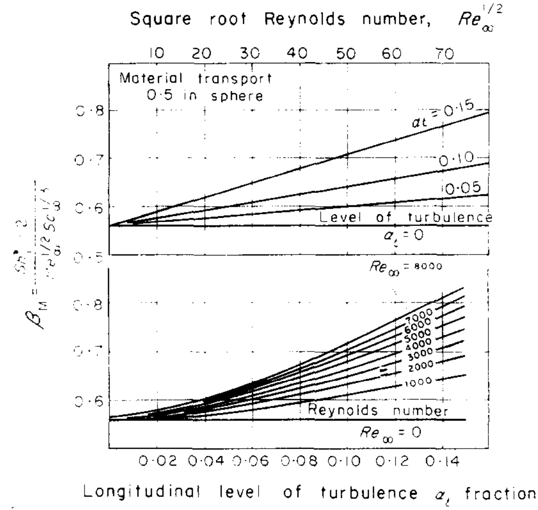

FIG. 5. Effect of Reynolds number and level of turbulence upon macroscopic material transport from spheres.

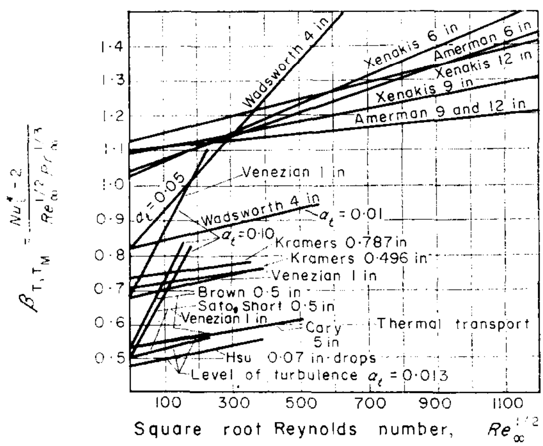

FIG. 6. Summary of macroscopic thermal transport from spheres.

The information presented in Figs. 6 and 7 serves to illustrate the range of conditions covered. These data indicate a much more rapid change in the values of β with Reynolds number at the higher apparent levels of turbulence. Insofar as could be ascertained by a careful evaluation of the experimental data, the variations in these values were linear with respect to the square root of the Reynolds number, as was indicated in equation (13).

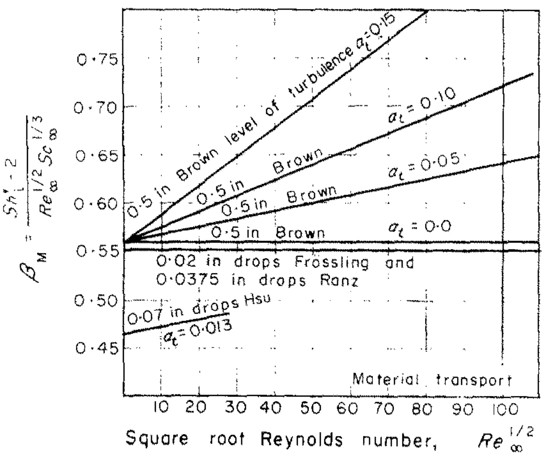

FIG. 7. Effect of Reynolds number on macroscopic material transport from spheres and drops.

Selected experimental data [3, 6, 7, 8, 10, 11, 18] were reduced to the values of β as functions of the three independent variables: Reynolds number, sphere diameter, and apparent level of turbulence. Each set of data was subjected to a linear regression analysis of conventional least squares approach with respect to the three independent variables. The coefficients for equations resulting from these calculations are set forth in Table 2, which also records the number of experimental points in each data set, the average deviation, and the standard error of estimate. These data follow experimental conditions as given for each set of data in Table 1. The detailed experimental data obtained by the authors and employed in this review are available.†

It is apparent that the recent measurements with 0·5 in and 1·0 in spheres [6, 7, 8, 10, 11] yield relatively small standard errors of estimate from the relationship described by equation (13). Slightly larger standard errors of estimate were

† Tabular material has been deposited as Documents No. 5600, No. 7159 and No. 6682 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D.C.

Table 2. Coefficients for equations†

Description of sphere	Number of data points		Coefficients			Average deviation§ (per cent)	Standard error of estimate¶ (per cent
	used	rejected‡	*A*	*B*	*C*		
			Thermal and simultaneous thermal and material transport				
0·5 in porous sphere	87	8	0·530	0·0271	−0·0321	0·38	2·1
1·0 in porous sphere	20	1	0·603	0·0134	0·0349	−1·30	3·2
0·5 in silver sphere	36	4	0·453	0·567	0·0210	0·03	4·0
1·0 in silver sphere	14	0	0·448	0·0119	0·0405	0·41	4·1
4·0 in copper sphere‖	28	2	0·727	0·0194	0·0001	−1·35	11·7
			Material transport				
0·5 in porous sphere	86	9	0·717	0·01201	0·0345	0·80	3·7

† Coefficients for equations as follows:

$$(Nu_i^* - 2)/Re_\infty^{1/2} \text{ or } (Sh_i^* - 2)/Re_\infty^{1/2} = A + Ba_t(a_t + C)\,Re_\infty^{1/2}.$$

Data based on measurements in air stream only, where $Pr_\infty^{1/3} = 0·8926$ and $Sc_\infty^{1/3} = 1·281$.

‡ Statistically rejected when deviation exceeds $x(\sigma)$, where $x = 2$.

§ Average deviation defined by:

$$s = 100\,\{[\sum_1^N (Nu_{ie}^* - Nu_{ic}^*)]/N\} \quad \text{or} \quad s = 100\,\{[\sum_1^N (Sh_{ie}^* - Sh_{ic}^*)]/N\}.$$

¶ Standard error of estimate defined by:

$$\sigma = 100\,\{\sum_1^N [(Nu_{ie}^* - Nu_{ic}^*)/Nu_{ie}^*]^2/(N-1)\}^{1/2} \quad \text{or} \quad \sigma = 100\,\{\sum_1^N [(Sh_{ie}^* - Sh_{ic}^*)/Sh_{ie}^*]^2/(N-1)\}^{1/2}.$$

‖ Wadsworth [18].

Table 3. Recommended coefficients for equations†

Nature of transport	Number of data points		Coefficients				Average deviation§ (per cent)	Standard error of estimate¶ (per cent)
	used	rejected‡	A_1	A_2	B	C		
Thermal, Nu_i^*	121	24	0·538	0·181	0·328	0·0405	−4·7	14·6
Simultaneous thermal and material, Nu_i^*	140	11	0·562	0·181	0·0672	0·0500	−2·8	4·2
Material, Sh_i^*	132	13	0·439	0·181	0·234	0·0500	2·1	6·6

† Coefficients for equations as follows:

$$Nu_i^* = 2{\cdot}000 + (A_1 + A_2 d^{1/2})\, Re_\infty^{1/2} Pr_\infty^{1/3} + B\alpha_t(\alpha_t + C)\, Re_\infty Pr_\infty^{1/3}$$

$$\text{or } Sh_i^* = 2{\cdot}000 + (A_1 + A_2 d^{1/2})\, Re_\infty^{1/2} Sc_\infty^{1/3} + B\alpha_t(\alpha_t + C)\, Re_\infty Sc_\infty^{1/3}.$$

‡ Statistically rejected when deviation exceeds $x(\sigma)$ where $x = 2$.

§ Average deviation defined by:

$$s = 100\,\{[\sum_1^N (Nu_{ie}^* - Nu_{ic}^*)]/N\} \quad \text{or} \quad s = 100\,\{[\sum_1^N (Sh_{ie}^* - Sh_{ic}^*)]/N\}.$$

¶ Standard error of estimate defined by:

$$\sigma = 100\,\{\sum_1^N [(Nu_{ie}^* - Nu_{ic}^*)/Nu_{ie}^*]^2/(N-1)\}^{1/2} \quad \text{or} \quad \sigma = 100\,\{\sum_1^N [(Sh_{ie}^* - Sh_{ic}^*)/Sh_{ie}^*]^2/(N-1)\}^{1/2}.$$

found for Wadsworth's measurements [18] while the data of some of the earlier investigators [2, 3, 19, 20] yielded much larger standard errors of estimate. It should be noted that Table 2 is based only on the detailed experimental data for 0·5 in, 1·0 in and 4·0 in spheres [6, 7, 8, 10, 11, 18] and does not represent correlations between the several sets of data.

The final values of the constants based upon the regression analysis of all the available experimental data are recorded in Table 3. If it is assumed that the effect of sphere diameter is the same for material transport, for thermal transport alone, and for thermal transport associated with simultaneous material transport, then the coefficient A_2 of equation (13) is the only term associated with sphere diameter. The following relatively simple relationship was obtained between the diameter of the sphere and the intercept of curves corresponding to zero Reynolds number for thermal transport alone:

$$\beta_T^o \equiv \lim_{Re_\infty \to 0} \beta_T = A_1 + A_2 d^{1/2}. \qquad (14)$$

Included in the data used in the development of Table 3 are measurements for drops [3, 13, 15], for 0·5 in and 1·0 in silver and porous spheres [6, 7, 8, 10, 11], and for larger metallic spheres [18–22]. The actual limiting value of β for the thermal transfer associated with simultaneous material transfer at zero Reynolds number was dependent upon the extent of the material transport, since a blowing boundary layer was present. For the material transport of n-octane and n-heptane the following relationship was obtained:

$$\beta_T^o = \beta_{T_M}^o - 0{\cdot}024. \qquad (15)$$

On the basis of the limited data available, it has been assumed in Fig. 8 that the influence of diameter was the same for the case of simultaneous thermal and material transfer as for thermal transfer alone. Higher limiting values of β were obtained for simultaneous thermal and material transfer than for thermal transfer alone. Similarly, the value β_M^o was smaller than the value $\beta_{T_M}^o$, as shown in the following expression:

$$\beta_M^o = \beta_{T_M}^o - 0{\cdot}123. \qquad (16)$$

It is again emphasized that insufficient data are available to establish with certainty the influence of size of the sphere upon the value of β for material transfer or for the thermal transfer associated with simultaneous material transfer. The effect upon $\beta_{T_M}^o$ of different absolute rates of material transfer under comparable Reynolds numbers is not known. However, by assuming

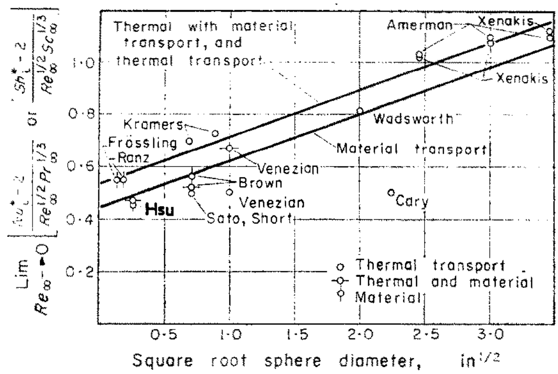

FIG. 8. Effect of sphere diameter upon limit of thermal and material transport.

that the relationships set forth in equation (13) describe the limiting value of β, this equation may be combined with equations (14) and (15) to yield the following relationships:

$$\beta_{T} = 0{\cdot}538 + 0{\cdot}1807\, d^{1/2} + 0{\cdot}328\, a_t \quad (a_t + 0{\cdot}0405)\, Re_\infty^{1/2} \qquad (17)$$

$$\beta_{T_M} = 0{\cdot}562 + 0{\cdot}1807\, d^{1/2} + 0{\cdot}0672\, a_t \quad (a_t + 0{\cdot}0500)\, Re_\infty^{1/2} \qquad (18)$$

$$\beta_M = 0{\cdot}439 + 0{\cdot}1807\, d^{1/2} + 0{\cdot}234\, a_t \quad (a_t + 0{\cdot}0500)\, Re_\infty^{1/2}. \qquad (19)$$

These expressions, together with definitions of β, permit the direct evaluation of the Nusselt and Sherwood numbers from a knowledge of the Reynolds number of the flow, the Prandtl or Schmidt number of the fluid, and the diameter of the sphere and the apparent level of turbulence. These expressions yield good agreement with Wadsworth's measurements [18] and with the more recent data for 0·5 in and 1·0 in spheres [6, 7, 8, 10, 11].

CONCLUSION

Equations (17), (18), and (19) permit a reasonable description of the effect of flow conditions and sphere diameter upon thermal, material, or simultaneous thermal and material transport over a wide range of sphere diameters, Reynolds numbers, and levels of turbulence. Since nearly all the data used in this discussion were taken with respect to the flow of air at atmospheric pressure past spheres of varying sizes, there is no certainty that the results apply over a range of Prandtl and Schmidt numbers. Such measurements were, however, in agreement with the earlier forms of correlation [23]. They were also in agreement with the analysis of thermal and material transport from spheres as developed by Frössling [13, 24]. Additional investigations with the liquid metals and with petroleum oils at elevated pressures would establish with greater certainty the generality of equations (17), (18), and (19).

It is apparent from the present review that the effects of level of turbulence and sphere diameter on the parameters β_T, β_M and β_{T_M} are marked, and it is most worthwhile to take these variables into account in expressions predicting convective thermal transport and material transport from spheres.

ACKNOWLEDGEMENT

Hilda Hager assisted in the preparation of the manuscript and Virginia Berry contributed to the calculations.

REFERENCES

1. R. W. POWELL, Further experiments on the evaporation of water from saturated surfaces, *Trans. Inst. Chem. Engrs Lond.* **18**, 36–50 (1940).
2. H. A. KRAMERS, Heat transfer from spheres to flowing media, *Physica* **12**, 61–80 (1946).
3. N. T. HSU, K. SATŌ and B. H. SAGE, Material transfer in turbulent gas streams. Influence of shape on evaporation of drops of *n*-heptane, *Industr. Engng Chem.* **46**, 870–876 (1954).
4. R. L. STEINBERGER and R. E. TREYBAL, Mass transfer from a solid soluble sphere to a flowing liquid stream, *A.I.Ch.E. J.* **6**, 227–232 (1960).
5. N. T. HSU and B. H. SAGE, Thermal and material transfer in turbulent gas streams: local transport from spheres, *A.I.Ch.E. J.* **3**, 405–410 (1957).
6. R. A. S. BROWN, K. SATŌ and B. H. SAGE, Material transfer in turbulent gas streams. Effect of turbulence on macroscopic transport from spheres, *Industr. Engng Chem., Chem. Engng Data Series*, **3**, 263–272 (1958).
7. K. SATŌ and B. H. SAGE, Thermal transfer in turbulent gas streams—Effect of turbulence on macroscopic transport from spheres, *Trans. Amer. Soc. Mech. Engrs., J. Appl. Mech.* **80**, 1380–1388 (1958).
8. W. W. SHORT, R. A. S. BROWN and B. H. SAGE, Thermal transfer in turbulent gas streams. Effect of turbulence on local transport from spheres, *Trans. Amer. Soc. Mech. Engrs, J. Appl. Mech.* Ser. E, **27**, 393–402 (1960).
9. L. N. BATHISH and B. H. SAGE, Thermal transfer in turbulent gas streams: temperature distribution in

boundary flows about spheres, *A.I.Ch.E. J.* **6**, 693–697 (1960).
10. R. A. S. BROWN and B. H. SAGE, Material transfer in turbulent gas streams. Effect of turbulence on local transport from spheres, *J. Chem. Engng Data* **6**, 355–359 (1961).
11. E. VENEZIAN, M. J. CRESPO and B. H. SAGE, Thermal and material transfer in turbulent gas streams: one-inch spheres, *A.I.Ch.E. J.* **8**, 383–388 (1962).
12. G. E. KINARD, F. S. MANNING and W. P. MANNING, A new correlation for mass transfer from single spheres, *Brit. Chem. Engng* **8**, 326–327 (1963).
13. N. FRÖSSLING, Über die Verdunstung fallender Tropfen, *Beitr. Geophys.* **52**, 170–216 (1938).
14. I. LANGMUIR, The evaporation of small spheres, *Phys. Rev.* **12**, 368–370 (1918).
15. W. E. RANZ and W. R. MARSHALL JR., Evaporation from drops, *Chem. Engng Progr.* **48**, 141–146, 173–180 (1952).
16. L. DAVIS, Measurements of turbulence decay and turbulent spectra behind grids, *Report* 3–17, Jet Propulsion Lab., Pasadena, Calif. (June, 1952).
17. L. DAVIS, Measurements of turbulence level behind a set of square-mesh grids and correlation with grid pressure loss. Report 3–22, Jet Propulsion Lab., Pasadena, Calif. (November, 1950).
18. J. WADSWORTH, The experimental examination of the local heat transfer on the surface of a sphere when subjected to forced convective cooling. Report No. MT-39, National Research Council of Canada, Division of Mech. Engng. (September, 1958).
19. L. G. LAUTMAN and W. C. DROEGE, Thermal conductances about a sphere subjected to forced convection. Serial No. AIRL A6118 50-15-3, Air Materiel Command (August, 1950).
20. G. XENAKIS, A. E. AMERMAN and R. W. MICHELSON, An investigation of the heat-transfer characteristics of spheres in forced convection. WADC Tech. Rept. 53-117, Wright Air Development Center, Wright–Patterson Air Force Base, Ohio (April, 1953).
21. A. E. AMERMAN, An investigation of the heat-transfer characteristics of spheres in forced convection. WADC Tech. Report 53-117, Suppl. 1, Wright Air Development Center, Wright–Patterson Air Force Base, Ohio (December, 1953).
22. J. R. CARY, The determination of local forced-convection coefficients for spheres, *Trans. Amer. Soc. Mech. Engrs* **75**, 483–487 (1953).
23. W. H. MCADAMS, *Heat Transmission*, 3rd Ed. McGraw-Hill, New York (1954).
24. N. FRÖSSLING, Evaporation, heat transfer, and velocity distribution in two-dimensional and rotationally symmetrical laminar boundary-layer flow *NACA* TM 1432, Washington, D.C. (1958).

Résumé—On a mis sous la forme d'expressions analytiques les transferts de chaleur et de masse à partir de sphères dans des écoulements turbulents, en tenant compte du nombre de Reynolds de l'écoulement et du niveau de turbulence, ainsi que du diamétre de la sphère. Les coefficients pour ces expressions sont basés sur une recherche expérimentale allant de gouttes à des sphères d'environ 0,30 m de diamétre; la gamme des nombres de Reynolds s'étend de 2 à 1,33 . 10^6. L'erreur d'estimation moyenne pour toutes les mesures était environ de 15 pour cent tandis que l'erreur d'estimation moyenne pour des mesures dans une gamme plus étroite de diamètres de sphères était approximativement de 4 pour cent.

Zusammenfassung—Wärme- und Stoffübertragung von Kugeln im turbulenten Luftstrom wurde auf analytische Ausdrücke zurückgeführt, wobei die Reynolds-Zahl, der Turbulenzgrad und der Kugeldurchmesser berücksichtigt wurden. Die Koeffizienten dieser Ausdrücke beruhen auf Versuchsegebnissen an Tropfen und Kugeln bis zu 30 cm Durchmesser im Reynolds-Bereich von 2 bis 1,33 · 10^6. Die Standardabweichung der Schätzung für alle experimentelle messungen war ungefähr 15 Prozent, während in einem wesentlich kleineren Bereich von Kugeldurchmessern die geschätzte Standardabweichung nur etwa 4 Prozent war.

Аннотация—Получены аналитические выражения, описывающие перенос тепла и вещества для шаров при обтекании турбулентным воздушным потоком с учетом числа Рейнольдса, степени турбулизации и диаметра шара. Выбор коэффициентов для этих выражений основан на экспериментах над частицами размером от капли до шара диаметром около 1 фт. Диапазон чисел Рейнольдса от 2 до 1,33 × 10^6. Обычная погрешность в оценке для всех экспериментальных измерений составляет 15 процентов, тогда как обычная погрешность в измерениях для гораздо меньшего диапазона диаметров шаров составляет примерно 4 процента.