Material Transfer in Turbulent Gas Streams

Effect of Turbulence on Local Transport from Spheres

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THE GROSS material transport from spheres has been studied in detail and there is no need to review the literature. Only limited data are available concerning local material transport. The data of Frössling (*10*), Hsu (*14*), and Garner (*12, 13*) are of particular interest in this regard. The studies of Cary (*4*), Lautman and Droege (*16*), Xenakis (*31*), Wadsworth (*30*), Hsu (*14*), and Short (*26*) on the local thermal transport from spheres are available.

The effect of level of turbulence upon macroscopic transport from spheres was investigated by Maisel and Sherwood (*20*), Brown (*3*), Sato (*23*), and Short (*26*). Sibulkin (*28*), Korobkin (*15*), and Frössling (*11*) made important theoretical analyses of thermal transport and thermal and material transport from spheres. Analyses based on approximations to the actual flow encountered in the forward hemisphere of of a blunt body are also available (*8, 9*).

The present investigation was directed to study of the local thermal and material transport from a porous sphere 0.5 inch in diameter. Measurements were made in an air stream at Reynolds numbers between 900 and 3700 and several levels of turbulence. Level of turbulence was defined for the purposes of this study as the ratio of the root-mean-square of the fluctuating longitudinal velocity to the average macroscopic velocity of the stream. The local thermal transport was obtained directly from the radial temperature gradient encountered within the boundary flow, whereas the local material transport was obtained from the local thermal transport and the energy balance at the liquid-gas interface. Conduction through the sphere was considered to be negligible.

METHODS AND EQUIPMENT

The temperature distribution in the boundary flow about the 0.5-inch porous sphere was measured in an air stream maintained at 100° F. Data were taken at gross velocities of 4, 8, and 16 feet per second, at levels of turbulence between 0.013 and 0.15 root-mean-square longitudinal fluctuation (*5, 6*).

The facilities for supplying air at a constant temperature and velocity and a low level of turbulence have been described (*23*). The temperature of the stream was determined within 0.1° F. relative to the international platinum scale. The velocity was established within 0.5% and remained constant within 0.2% throughout a given set of measurements (*23*).

The transverse level of turbulence of the undisturbed air stream at the working area was 0.013 (*25*). The level of turbulence was varied by inserting a steel plate, 0.187 inch thick with 0.875-inch holes located on 1.0-inch centers, at the exit of the jet (*23*). Davis (*5, 6*) made an extensive investigation of the turbulent characteristics in the wake of a grid of the same dimensions, and the reported longitudinal levels of turbulence are based on his measurements. It is possible that the levels of turbulence encountered in this study differed somewhat from those reported by Davis because of the smaller conduit used. To emphasize the possible uncertainty, the phrase "apparent level of turbulence" is employed, and the downstream position of the sphere relative to the grid is indicated on figures and tables.

The porous sphere was composed of diatomaceous earth and supported by a small glass tube used to introduce *n*-heptane. A nearly uniform supply of *n*-heptane could be maintained at all points on the sphere surface because of the high capillary pressure of the porous ceramic. The attainment of steady state between the rate of injection and the rate of evaporation of *n*-heptane was determined with a manometer of small diameter attached to the injection tube. A detailed description of the equipment is available (*3, 14*).

The temperature of the air in the boundary flow was determined with a 0.0003-inch platinum, platinum-rhodium thermocouple mounted upon a conventional probe (*14*). The position of the thermocouple relative to the surface of the sphere was established with traversing equipment and was known within approximately 0.001 inch. The temperature of the junction measured from the electromotive force, was known within 0.02° F. relative to the international platinum scale. Local fluctuations in air temperature outside the wake of the sphere were of the order of 0.05° F.

ANALYSIS

It is advantageous to use a number of normalized variables in describing local, associated thermal and material transport. The temperature in the boundary flow may be described with the following variables:

$$\Upsilon = \frac{t_\infty - t}{t_\infty - t_i} \tag{1}$$

The local thermal flux may be established from

$$\frac{q}{d\theta} = -k_i \left(\frac{\partial t}{\partial n}\right)_{i,\psi} \tag{2}$$

The total energy flux at the surface, exclusive of radiation, may be obtained from

$$\frac{q}{d\theta} = \int_0^A \frac{q}{d\theta}\, dA = -\int_0^A k_i \left(\frac{\partial t}{\partial n}\right)_{i,\psi} dA \tag{3}$$

If the thermal conduction within the body of the sphere is neglected, it follows that the local material flux is given by:

$$\frac{dm_k}{d\theta} = \frac{q/d\theta}{H_{k,g} - H_{k,l}} \tag{4}$$

Earlier work (*3*) indicated that the temperature variations about the surface of the porous sphere and the thermal conductivity of the porous material were both sufficiently small that the associated thermal transport by conduction within the sphere could be neglected without introducing added uncertainty. Equations 2 and 4 are the

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basic relations used in the analysis of the local thermal and material transport from the sphere.

The local thermal transport at the surface of the sphere is reported in terms of a local Nusselt number:

$$\mathrm{Nu}_i = \frac{hd}{k_i} = \frac{(q/d\theta)\,d}{(t_\infty - t_i)k_i} = \frac{(\partial t/\partial n)_{i,\psi}\,d}{t_\infty - t_i} \quad (5)$$

Similarly, the local Sherwood number (*3*) was defined as

$$\mathrm{Sh}_i = \frac{(dm_k/d\theta)\,b_k T dr}{D_{M,k} Z (f_k^\circ/P) \ln (n_{j,i}/n_{j,\infty})} \quad (6)$$

The properties shown in Equations 5 and 6 were evaluated for the conditions at the interface, and in Equation 6 it was assumed that fugacity is the driving force in the gas-phase diffusion.

In relating the properties at a point on the surface of the sphere to the macroscopic transport properties, it is desirable to determine average values of temperature, macroscopic Nusselt number, Nu_i^* and macroscopic Sherwood number, Sh_i^*.

Because the total evaporation rate $d\underline{m}_k/d\theta$ was available, the total energy flux for use in evaluating the average value of the macroscopic Nusselt number was obtained from:

$$\frac{q}{d\theta} = -\frac{dm_k}{d\theta}(H_{k,g,i} - H_{k,l,i}) - \frac{q_l}{d\theta} - \frac{q_r}{d\theta} \quad (7)$$

In Equation 7 the last two terms account for the non-convective thermal transfer to the sphere, denoting, respectively, the conductive transfer through the feed line which supported the sphere, and the radiant transfer from the surroundings. The use of an over-all energy balance to evaluate the macroscopic convective transport was described in detail by Brown (*3*). The directly measured total rate of material transfer, $d\underline{m}_k/d\theta$, was employed in all calculations to determine values of the macroscopic Sherwood and Nusselt numbers, Sh_i^* and Nu_i^*.

To illustrate more clearly the effect of changes in condition upon the local transport rates, a relative Nusselt number consisting of the ratio of the local Nusselt number to the macroscopic Nusselt number at the same Reynolds number and turbulence level was used:

$$\frac{\mathrm{Nu}_i}{\mathrm{Nu}_i^*} = \frac{(t_\infty - t_i^*)}{(t_\infty - t_i)}\frac{k_i^*}{k_i}\frac{(q/d\theta)\,A}{\oint_0^A (q/d\theta)\,dA}$$

$$= \frac{(\partial t/\partial n)_{i,\psi}\oint_0^A (t_\infty - t_i)dA}{(t_\infty - t_i)\oint_0^A (\partial t/\partial n)_{i,\psi} dA} \quad (8)$$

It was assumed that these relative values for thermal transport were identical with the corresponding relative values for material transport:

$$\frac{\mathrm{Sh}_i}{\mathrm{Sh}_i^*} = \frac{\mathrm{Nu}_i}{\mathrm{Nu}_i^*} \quad (9)$$

but not that the local or the macroscopic Nusselt and Sherwood numbers were equal.

Methods of treating the traverse data, taking into account the discrepancy between the measured wire temperature and the associated air temperature in the three dimensional boundary flows, have been described (*1, 26, 27*). In this case the thermal boundary layer thickness (*1, 26*) was used to make an appropriate correction to the wire temperature gradient in order to evaluate the temperature gradient in the air at the surface of the sphere. This gradient was established as a function of polar angle and conditions of flow.

MATERIALS

The values for the molecular properties of air employed in the calculations of this investigation were taken from a recent correlation (*21*); the vapor pressure, enthalpy change upon vaporization, and specific gas constant for *n*-heptane, from a critical review by Rossini (*22*); and the isobaric heat capacity of *n*-heptane, from Douglas (*7*). Chosen values of the properties of mixtures of *n*-heptane and air at dew point and a pressure of 14.696 p.s.i. are given in Table I. It was assumed that the mixtures of *n*-heptane and air were ideal solutions (*17*) and that local equilibrium existed at the interface. The thermal conductivity was evaluated by the method of Lindsay and Bromley (*18*), using the thermal conductivities of air and *n*-heptane vapor given by Page (*21*) and McAdams (*19*), respectively. Lindsay and Bromley's method (*18*) gives about a 7% smaller value than the method used in earlier computations (*3*). The Maxwell diffusion coefficient of *n*-heptane in air was obtained from Schlinger (*24*).

Table I. Properties of Air and *n*-Heptane Mixtures at Dew Point for a Pressure of 14.696 P.S.I.

Temp., °F.	*n*-Heptane, Mole Fraction	Specific Volume, Cu. Ft./Lb.	Thermal Conductivity, B.t.u./(Ft.)(Sec.)(°F.)	Maxwell Diffusion Coefficient, Lb./Sec.
50	0.03310	11.881	3.765×10^{-6}	0.14899
55	0.03864	11.848	3.758	0.15175
60	0.04441	11.810	3.751	0.15452
65	0.05105	11.751	3.740	0.15739
70	0.05756	11.697	3.730	0.16026
75	0.06583	11.600	3.710	0.16307
80	0.07546	11.475	3.683	0.16589

Table II. Experimental Conditions

	Air Stream					Porous Sphere			
Test No.	*P*., lb./sq. ft.	Air temp., °F.	Weight fraction water in air	Bulk velocity, ft./sec.	Apparent level of turbulence, fraction	Distance downstream from grid, in.	Total evaporation rate, lb./sec.	Temp. of entering fluid, °F.	Av. surface temp., °F.
165	2062.7	100.0	0.0076	4.06	0.013	No grid	2.528×10^{-6}	95.13	64.06
121	2063.7	100.1	0.0074	8.04	0.013	No grid	3.784	96.38	63.77
107	2066.3	100.1	0.0065	8.04	0.056	13.04	3.888	96.86	63.52
98	2060.2	100.1	0.0107	8.08	0.094	7.07	3.931	96.99	63.55
101	2065.8	100.1	0.0060	8.03	0.148	4.09	4.731	97.77	63.94
290	2052.4	100.2	0.0127	16.15	0.013	No grid	4.756	97.30	64.12
108	2060.4	100.1	0.0061	16.23	0.052	13.03	5.515	97.95	63.88
99	2059.9	100.1	0.0057	16.22	0.088	7.07	5.681	98.29	64.15
100	2076.0	100.1	0.0052	16.22	0.135	4.09	6.467	98.77	64.80

Table III. Macroscopic Transport from 0.5-Inch Porous Sphere

Test No.	Reynolds Number, Free Stream	Total Thermal Flux[a] B.t.u./Sec.		Nusselt Number[b] Nu[*]		Sherwood Number[b,c] Sh[*]
		Uncorrected[c]	Corrected[d]	Uncorrected[c]	Corrected[d]	
165	913	0.3544	0.3200	21.4	19.1	24.4
121	1809	0.5296	0.4979	29.5	27.5	33.2
107	1811	0.5448	0.5068	30.0	27.9	34.6
98	1815	0.5467	0.5137	30.9	28.6	36.1
101	1808	0.6577	0.6267	33.9	31.6	39.0
290	3613	0.6653	0.6315	41.1	38.9	45.8
108	3649	0.7669	0.7325	42.6	40.7	48.1
99	3642	0.7899	0.7552	44.8	42.9	50.3
100	3671	0.9000	0.8650	49.4	47.3	55.0

[a] Measured in present investigation.
[b] Smoothed values based both upon present and other data (*3*).
[c] Uncorrected for radiant transport.
[d] Corrected for radiant transport.

The *n*-heptane was purchased as research grade from the Phillips Petroleum Co. and yielded an index of refraction relative to the *D* lines of sodium of 1.3852 at 77° F., compared with 1.38511 reported by Rossini (*22*) for an air-saturated sample at the same temperature. The specific weight of the *n*-heptane utilized in this investigation was 42.429 pounds per cubic foot at 77° F., which compares with 42.420 reported by Rossini (*22*) for an air-saturated sample.

EXPERIMENTAL RESULTS

The experimental conditions associated with the investigation of the temperature distribution in the boundary flows around the porous sphere are set forth in Table II. Horizontal temperature traverse data for each set of experimental conditions are available in tabular form (*2*). The fluctuations of temperature in the wake of the porous sphere were similar to those encountered with a heated sphere (*26*). It did not prove feasible to measure in detail the temperature gradients adjacent to the porous sphere throughout the after hemisphere where separation of the boundary flow occurred, although limited data were obtained in this region.

Several macroscopic transport parameters for the experimental conditions recorded in Table II are set forth in Table III. The macroscopic Nusselt and Sherwood numbers were based upon present and earlier measurements (*3*) of macroscopic transport. Table III includes values of the Nusselt numbers corrected for the influence of radiant transport to the porous sphere from the surroundings of the laboratory. These corrected values were obtained using Equation 7 and indicate a smaller convective thermal transport. Thecorrection amounts to as much as 10% at the low Reynolds numbers and about 4% at Reynolds numbers of approximately 3600. Throughout the graphical presenta-

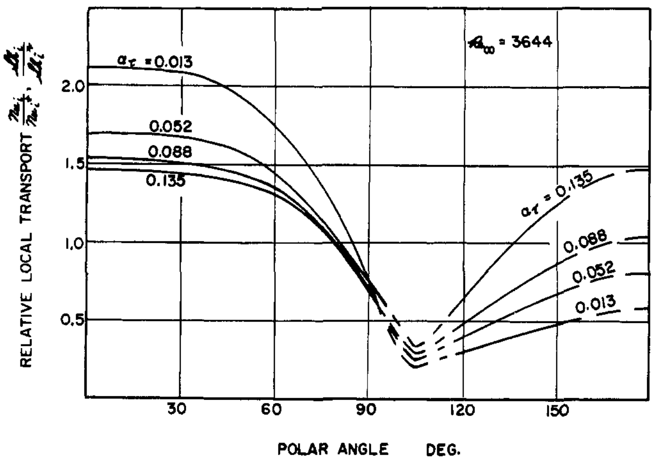

Figure 1. Relative local transport around porous sphere

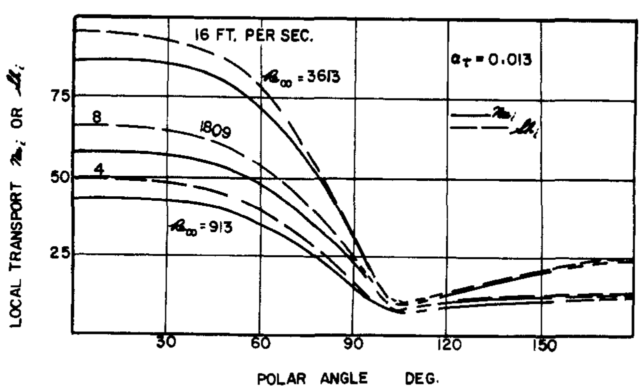

Figure 2. Local transport around porous sphere at an apparent level of turbulence of 0.013

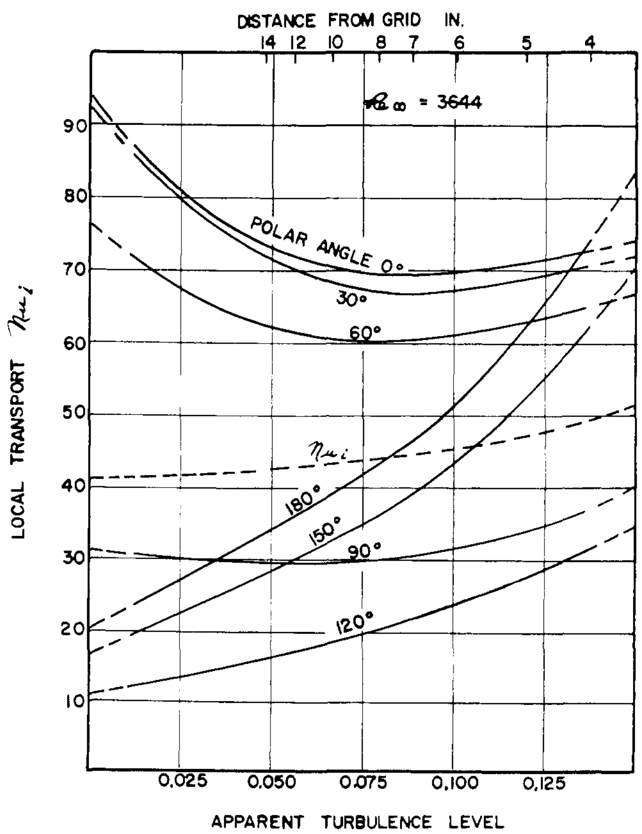

Figure 3. Effect of apparent level of turbulence upon local thermal transport

tion, values of the Nusselt numbers uncorrected for radiant transport were employed in order to make them comparable to the Sherwood numbers.

By use of Equation 8, values of the relative Nusselt number, Nu_i/Nu_i^* were obtained as a function of position for each set of conditions of flow. These values are presented in tabular form (*2*), along with the normalized wire temperatures for several polar angles, the ratio of the thermal boundary layer thickness to the diameter of the sphere (*1*), and the normalized surface temperature. A number of figures were prepared from this information. The points are omitted because they do not represent directly measured quantities, but quantities derived by graphical and algebraic manipulations based upon the smoothed curves of radial temperature distribution.

The standard error of estimate of the relative local transport Nu_i/Nu_i^* was 0.08, considering all the error to lie in the ratio and none in the independent variables. Figure 1 shows the variation with polar angle of the relative local transport. As is the case with thermal transfer alone (*26*), an increase in the level of turbulence decreases the relative transport in the forward hemisphere, but increases it materially in the after hemisphere. The relative local transport is assumed to be the same for the thermal and material transport. However, the local thermal transport and local material transport are not equal.

Table IV. Relative Local Transport Nu_i/Nu_i^* or Sh_i/Sh_i^*

Polar Angle, Deg.	Apparent Turbulence Level 0	0.05	0.10	0.15
	Gross Air Velocity, 8 Ft. per Sec., $Re_\infty = 1811$[a]			
0	2.02	1.84	1.70	1.59
30	1.98	1.81	1.67	1.55
60	1.66	1.52	1.40	1.30
90	0.81	0.79	0.77	0.76
120	0.26	0.37	0.48	0.64
150	0.35	0.56	0.83	1.27
	Gross Air Velocity, 16 Ft. per Sec., $Re_\infty = 3644$[a]			
0	2.33	1.70	1.50	1.31
30	2.28	1.67	1.47	1.44
60	1.90	1.45	1.33	1.42
90	0.77	0.73	0.70	0.80
120	0.25	0.39	0.52	0.69
150	0.40	0.66	0.95	1.36

[a] Average value of Reynolds number for experimental work.

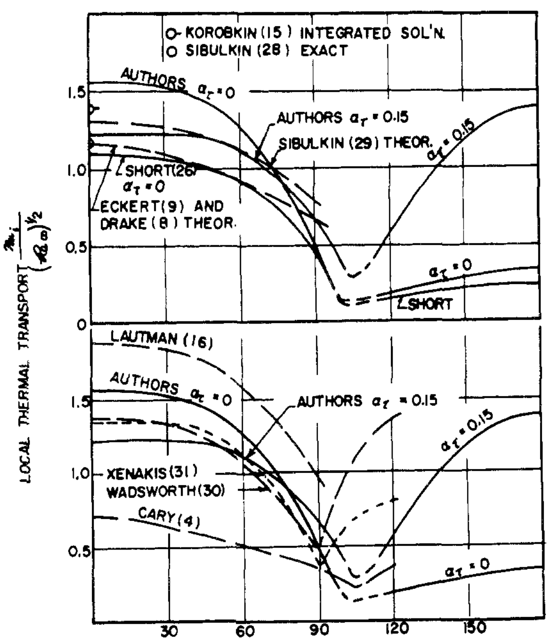

Figure 4. Comparison of local thermal transport with other experimental and calculated data

The actual local transport for a level of turbulence of 0.013 is shown in Figure 2. It is apparent that the local transport increases markedly with an increase in velocity. The local thermal transport, Nu_i, is depicted in Figure 3 as a function of apparent level of turbulence, with polar angle as a parameter. The apparent turbulence level exerts most pronounced influence in the after hemisphere. The trends are the same as those encountered in thermal transport from a silver sphere (*26*).

A comparison in Figure 4 of the experimentally determined local thermal transport with predicted transports shows wide variations. The recent experimental thermal transfer data of Wadsworth (*30*) near stagnation fall between the information obtained by the authors at two levels of turbulence. The local Nusselt number for a 0.5-inch porous sphere is greater than that for a 0.5-inch silver sphere, as indicated by a comparison of the present data and those of Short (*26*). However, the heat transfer coefficient, h, is smaller for the porous sphere than for the silver sphere. This reversal is associated with the difference in the molecular properties of the fluids at the surface between the porous and silver spheres. The theoretical values in Figure 4 are reported for the molecular properties of the fluid at the average of the temperature existing at the interface and in the free stream and differ from those reported in a discussion of the silver sphere (*26*) because the values of the molecular properties for average conditions were not the same for the porous and the silver sphere.

The relative local transport for the 0.5-inch porous sphere is recorded in Table IV as a function of polar angle and apparent level of turbulence. Figure 5 compares the relative local transport for the porous sphere with that for a 0.5-inch silver sphere (*26*) involving thermal transport alone. The data of Hsu (*14*) are also included. Material transport does

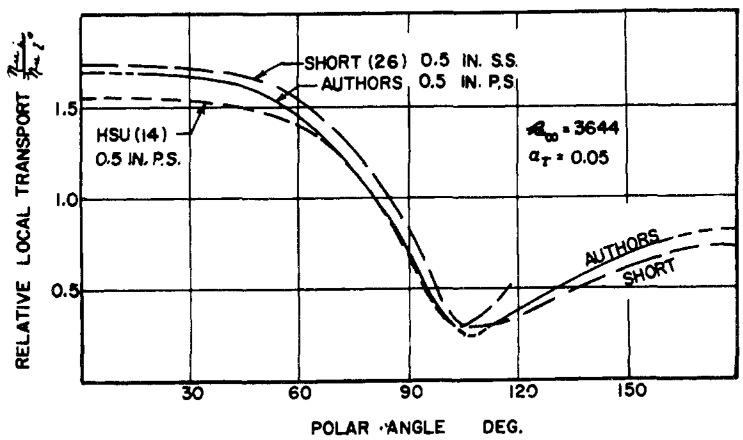

Figure 5. Relative local thermal transport with and without material transport

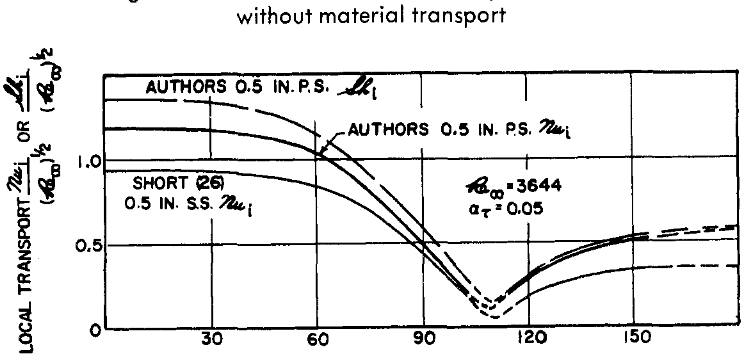

Figure 6. Local transport as a function of polar angle

not exert a pronounced influence upon the relative local thermal transport, Nu_i/Nu_i^* although it does on the actual value, as shown in Figure 4.

Figure 6 compares data of the authors and Short (26). The limited data reported by Hsu (*14*) are not included because they were based on individual measurements and not on statistical treatment of a large amount of data. Figure 6 indicates more clearly than Figure 4 the decidedly greater values of local Nusselt numbers in situations where thermal transport occurs with material transport than where it occurs alone. The values shown in Figure 6 for the 0.5-inch porous sphere are not corrected for radiant transport. Such a correction would decrease the Nusselt number about 4%. The radiant transport correction for the silver sphere is negligible.

It appears that the presence of material transport does not appreciably influence the relative local thermal transport, Nu_i/Nu_i^* about the sphere. However, it significantly increases the actual value of the local Nusselt number, as found earlier by Brown (*3*). This is particularly true in the forward hemisphere. Furthermore, as indicated in Figure 4, at the present status of theoretical knowledge concerning the boundary flows about spheres, experimental measurements are to be preferred to theoretical attempts to predict the effect of polar angle upon the thermal transport from spheres.

NOMENCLATURE

- A = area, sq. ft.
- b = specific gas constant, ft./° R.
- $D_{M,k}$ = Maxwell diffusion coefficient of component k, lb./sec.
- d = diameter of sphere, in. or ft.
- f_k^0 = fugacity of component k, pure state, lb./sq. ft.
- H = enthalpy, B.t.u./lb.
- h = heat transfer coefficient, B.t.u./(sec.)(sq. ft.)(° F.)
- k = thermal conductivity, B.t.u./(sec.)(sq. ft.)(° F./ft.)
- $dm/d\theta$ = evaporation rate, lb./(sec.)(sq. ft.)
- $d\underline{m}/d\theta$ = total evaporation rate, lb./sec.
- n = distance normal to surface of sphere, in. or ft.
- n = mole fraction
- Nu = Nusselt number
- P = pressure, lb./sq. ft.
- $q/d\theta$ = local thermal flux from the surface, B.t.u./(sec.)(sq. ft.)
- $\underline{q}/d\theta$ = total thermal flux from the surface, B.t.u./sec.
- $\underline{q}_r/d\theta$ = total radiant transport rate from the surface, B.t.u./sec.
- $\underline{q}_t/d\theta$ = total conductive flux from sphere through tube and its contents, B.t.u./sec.
- Re = Reynolds number
- Sh = Sherwood number
- T = thermodynamic temperature, ° R.
- t = temperature, ° F.
- Z = compressibility factor
- a_τ = apparent level of turbulence (fractional)
- Υ = normalized temperature ratio

Subscripts

- g = gas phase
- i = gas-liquid interface
- j = air
- k = n-heptane
- l = liquid phase
- t = supporting tube
- ∞ = free stream
- ψ = polar angle

Superscript

- $*$ = space-average

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