Mass Transfer in the Flow of Gases Through Fluidized Beds

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Mass transfer studies were conducted for the flow of air through fluidized beds. These studies were concerned with the sublimation of *p*-dichlorobenzene spherical particles, approximately 0.04 to 0.08 in. in diameter, and with the evaporation of nitrobenzene and water from alumina spheres. 0.1168 in. in diameter.

Void volumes for these fluidized beds were calculated from pressure-drop measurements. The results of this investigation were used to establish mass transfer factors which were in agreement with values obtained for fixed beds for corresponding modified Reynolds numbers, $D_pG/\mu(1-\epsilon)$.

Mass transfer studies of fixed beds have been extended to fluidized systems and are reported by a number of investigators. Gamson (*6*) correlated the results for both types of beds to produce a single relationship. Studies on fluidized beds conducted by Chu, Kalil, and Wetteroth (*2*) and by McCune and Wilhelm (*16*) were found to be in agreement with most of the previous work reported for fixed beds (*5, 7, 9, 11, 15*).

For both fixed and fluidized beds the mass transfer factor is related to the modified Reynolds number $D_pG/\mu(1-\epsilon)$. For fluidized beds the void fraction is ordinarily established by direct observation and is thus difficult to determine accurately. Therefore it would be desirable to determine these values with properties of the system which can be dependably measured. In the present investigation an attempt has been made to determine void fractions in fluidized beds through pressure-drop measurements.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Preparation of Particles

After a careful review of substances which exist in the solid state at room temperature and which are also considerably volatile, *p*-dichlorobenzene was selected for study. For the preparation of spherical particles suitable for mass transfer studies of fluidized systems, crystalline *p*-dichlorobenzene was melted in an enclosure which was provided with a spray nozzle at the bottom and which was connected at the top to a pressurized nitrogen supply. The spray nozzle was constructed by drilling a hole 0.028 in. in diameter through a solid stainless steel plug. Resistance wire, wrapped around the unit, provided the necessary heat to melt the contents. Nitrogen at a pressure of 2 to 5 lb./sq. in. gauge was applied to the surface of the molten *p*-dichlorobenzene to produce a spray which was then solidified by liquid nitrogen. After the evaporation of the liquid nitrogen the solid particles were sized with standard screens.

Alumina spheres, 0.1168 in. in diameter, were soaked with nitrobenzene or water before these substances were subjected to mass transfer studies.

Equipment

A schematic diagram of the equipment is presented in Figure 1. The unit was constructed from transparent acrylic plastic and consisted of a permanent fixed section into which fitted a removable cylindrical column provided with a screen at the bottom. When inserted in place this column rested on a circular ledge provided with a rubber washer to prevent bypassing of air. The inner cylinder was 1-½-in. I.D. and 12 in. long. Pressure taps were provided at the inlet and outlet of the reactor. A short hollow rod attached to a threaded brass cap which fitted over the discharge end of of the unit properly sealed the rubber gasket by pressing against the inner cylinder.

Air was furnished from the building supply. Flow measurements were made with two flowmeters capable of delivering 6 and 27 cu. ft. of air/min., respectively. A vertical U-tube manometer was provided for measuring pressure drops. Liquids of 0.827, 1.000, and 2.95 specific gravities were used. The lower end of the inside cylinder was graduated to measure the height of the fluidized bed. Temperatures of the air were measured before and after the fluidized bed with thermometers, while the temperature of the fluidized bed was obtained with an iron-constantan thermocouple.

Procedure

A typical run was conducted by operating without any material in the unit until steady state conditions were established. A weighted sample of the particles was then placed inside the reactor. Periodic weighings of the bed contents were made by stopping the flow of air and removing and weighing the particles. At higher flow rates it became necessary to replenish the quantity of material lost in order to keep the bed at essentially the same volume.

For a typical run the following experimental data were taken: the air flow rate, air temperatures at the inlet and outlet of the reactor, the average temperature of the fluidized bed, pressure drop, and average height of the fluidized bed. Because of the brevity of the constant rate period for the nitrobenzene and water runs durations as short as 0.3 min. were frequently encountered.

INTERPRETATION OF EXPERIMENTAL DATA

The experimental data of this study have been interpreted with an approach similar to that used by Chu, Kalil, and Wetteroth (*2*) and Gamson (*6*) to establish k_g. In this approach rates of mass transfer were determined from the periodic weighings of the bed particles, and the transfer area

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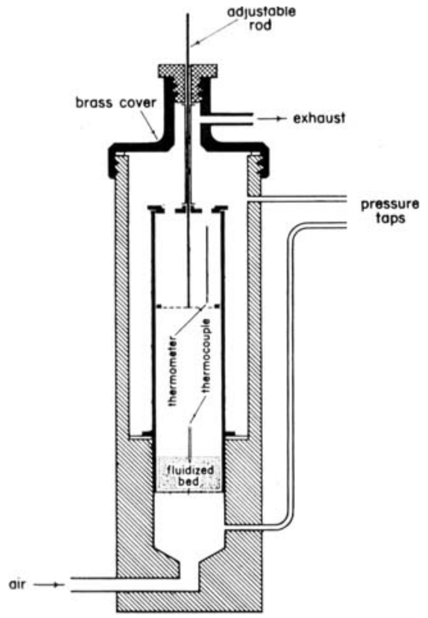

Fig. 1. Schematic diagram of experimental unit.

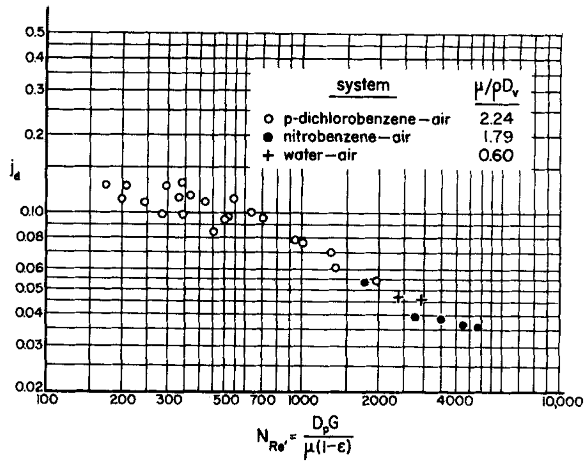

Fig. 2. Mass transfer factors and modified Reynolds numbers for fluidized beds.

was obtained from the average particle diameter and the number of particles present in the bed. The partial pressure of the transferable component in the effluent stream was calculated from the air flow rate and the loss of weight of the bed particles. The differences at the inlet and outlet of the bed between the partial pressure of the transferable component and its vapor pressure on the surface of the spheres gave the log-mean driving force $(\Delta p)_m$. For p-dichlorobenzene the following vapor pressure was used (*12*):

$$\log p_{mm} = 12.480 - \frac{3{,}771.9}{T,\ ^\circ\mathrm{K.}} \quad (1)$$

The equation proposed by Lynch and Wilke (*14*) was used for nitrobenzene:

$$\log p_{mm} = 7.545 - \frac{2{,}064}{t,\ ^\circ\mathrm{C.} + 230} \quad (2)$$

From all this information k_g was calculated directly. To determine the Schmidt number for the air-p-dichlorobenzene system the diffusion coefficient was calculated from the Chapman-Enskog equation, modified by Hirschfelder, Curtiss, and Bird (*8*), which can be expressed as

$$D_{AB} = 0.002628 \frac{\sqrt{T^3(M_A + M_B)/2M_AM_B}}{\pi\sigma_{AB}\,\Omega^{(1,1)}\left[T/\frac{\epsilon_{AB}}{\kappa}\right]} \quad (3)$$

For p-dichlorobenzene the Lennard-Jones force constants σ and ϵ/κ were calculated from the following approximate relationships suggested by Lee and Wilke (*13*):

$$\sigma = 0.833\, v_c^{1/3}$$

and

$$\frac{\epsilon}{\kappa} = 1.21\, T_b$$

The method of Lydersen, Greenkorn, and Hougen (*10*) permitted the estimation of a critical volume. For p-dichlorobenzene the following values were obtained: σ = 5.914Å. and ϵ/κ = 541.1°K. These constants were combined with the corresponding values for air to produce σ_{AB} = 4.765Å. and ϵ_{AB}/κ = 229°K. for the air—p-dichlorobenzene mixture. When these constants were substituted into Equation (3), a diffusion coefficient of 0.276 sq. ft./hr. resulted. This diffusion coefficient produced a Schmidt number N_{Sc} = 2.24 for the air—p-dichlorobenzene system.

The experimental value of the Schmidt number N_{Sc} = 1.79, reported by Lynch and Wilke (*15*), was used for the nitrobenzene-air system, while that for water was accepted to be N_{Sc} = 0.602. This information permitted the calculation of the mass-transfer

TABLE 1. EXPERIMENTAL AND CALCULATED RESULTS

Run	Fluidized bed Duration, min.	Temp., °C.	Height, in.	ΔP, in. of water	ϵ	D_p, in.	G, lb./hr. sq. ft.	$r \times 10^3$, lb.-mole/hr.	P_2, mm. Hg	aV, sq. ft.	k_g, lb.-moles/hr. sq. ft. atm.	j_d	$\frac{D_pG}{\mu(1-\epsilon)}$
	Air-p-dichlorobenzene (N_{Sc} = 2.24)												
2	11.0	27	1.20	0.745	0.750	0.0721	2,036	0.638	0.820	0.249	3.26	0.0781	925
3	10.0	27	1.00	0.94	0.666	0.0499	1,831	0.637	0.628	0.304	3.68	0.0958	508
12	10.0	30	0.60	0.58	0.580	0.0363	1,067	0.516	0.879	0.338	2.86	0.129	170
19	10.0	24	0.90	0.75	0.573	0.0515	1,469	0.455	0.561	0.285	4.04	0.132	331
28	2.8	28	1.50	0.92	0.765	0.0548	2,373	0.952	0.716	0.490	3.42	0.0700	1,274
32	3.6	27	2.30	2.18	0.782	0.0768	3,797	0.956	0.452	0.294	3.78	0.0477	2,482
33	3.6	27	2.60	2.30	0.811	0.0766	4,103	1.004	0.442	0.294	3.95	0.0461	3,085
	Air-water (N_{Sc}= 0.60)												
1	0.6	16.1	0.55	0.59	0.686	0.1168	3,340	16.72	8.85	0.189	7.86	0.0470	2,338
2	0.6	15.6	0.60	0.74	0.699	0.1168	3,818	18.11	8.43	0.189	8.78	0.0460	2,779
	Air-nitrobenzene (N_{Sc} = 1.79)												
1	0.76	29	0.40	0.65	0.623	0.1168	3,025	0.295	0.162	0.204	3.86	0.0538	1,733
3	0.27	29	0.50	0.88	0.670	0.1168	4,148	0.316	0.134	0.204	3.86	0.0392	2,714
4	0.30	29	0.60	1.18	0.726	0.1168	5,279	0.380	0.128	0.204	4.60	0.0367	4,161
5	0.32	29	0.65	1.33	0.740	0.1168	5,672	0.400	0.125	0.204	4.80	0.0357	4,711

factor proposed by Chilton and Colburn (1):

$$j_d = \frac{k_g\, p_{gf}}{G/M} \left(\frac{\mu}{\rho D_v} \right)_f^{2/3} \qquad (4)$$

A modified Reynolds number $D_pG/\mu(1-\epsilon)$ was used to correlate the j_d-values resulting from the three different systems of this investigation. For the alumina spheres the diameter was a constant value, as 0.1168 in. However for p-dichlorobenzene it became necessary to use the average particle diameter for each run.

The void volume of the fluidized bed was calculated from the pressure-drop measurements, the average bed height, and the air flow rate with the equation developed by Ergun (4):

$$g_c \frac{\Delta P}{L} = 150 \frac{\mu u^2}{D_p^2} \frac{(1-\epsilon)^2}{\epsilon^3} + 1.75 \frac{Gu}{D_p} \frac{1-\epsilon}{\epsilon^3} \qquad (5)$$

Because of the involved nature of this equation a trial-and-error procedure was necessary to determine the average void volume.

The mass transfer factors resulting for the three systems and the corresponding Reynolds numbers are presented graphically in Figure 2. The basic data of typical runs for each system are presented in Table 1.

RESULTS AND CONCLUSIONS

The mass transfer factors presented in Figure 2 for the three systems of this study are consistent with each other, despite the fact that their Schmidt numbers range from 0.602 to 2.24, their particle diameters from 0.0413 to 0.1168 in., and their mass velocities from 1,212 to 5,672 lb./hr. sq. ft. These factors are sufficient to establish a relationship with the modified Reynolds number; however such a relationship was not established until a comparison was made with other existing data. These j_d-values are again presented in Figure 3, along with representative data from the works of Gamson, Thodos, and Hougen (7), Lynch and Wilke (15), and De Acetis and Thodos (3) for fixed beds, and of Chu, Kalil, and Wetteroth (2) for fluidized beds. The results obtained from this study for the systems p-dichlorobenzene-, nitrobenzene, and water-air are consistent with the values reported by other investigators (2, 3, 7, 15). A curve representing the combined results of these studies was established and can be expressed analytically as

$$j_d = \frac{1}{N_{Re'}^{0.40} - 1.5} \qquad (6)$$

for modified Reynolds numbers ranging from 100 to 6,000. This relationship applies to both fixed and fluidized beds, provided that the fractional void volume is available. The consistency of the results of this investigation with the work previously reported indicates that void fractions can be dependably evaluated from pressure-drop measurements by Equation (5).

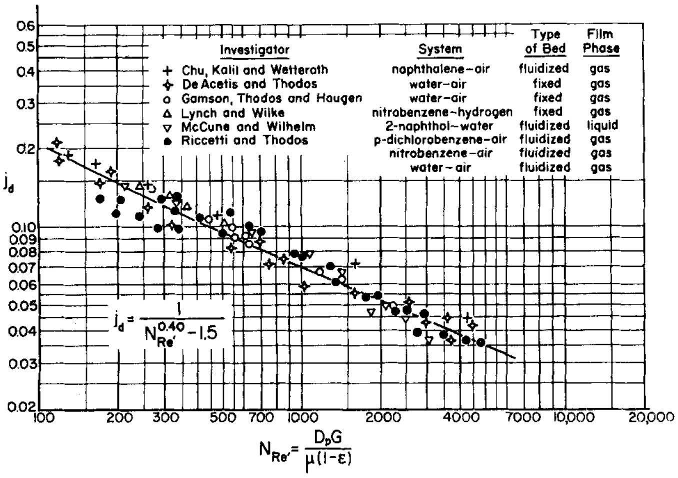

Fig. 3. Comparison of j_d factors and modified Reynolds numbers for both fixed and fluidized beds.

NOTATION

D_{AB} = binary diffusion coefficient, sq. ft./hr.
D_p = average particle diameter, ft.
g_c = gravitational conversion constant, 32.17 lb.-mass ft./lb.-force sec.^{2}
G = superficial mass velocity, lb.-mass/hr. sq. ft.
k_g = mass transfer coefficient, lb.-moles/hr. sq. ft. atm.
j_d = mass transfer factor, dimensionless
L = length, ft.
M = molecular weight
p_{gf} = partial pressure of nontransferable component, atm.
p_{mm} = vapor pressure, mm. of mercury
ΔP = pressure drop, lb.-force/sq. ft.
$N_{Re'}$ = modified Reynolds number, $D_pG/\mu(1-\epsilon)$
N_{Sc} = Schmidt number, $\mu/\rho D_v$
T = absolute temperature, °K.
T_b = normal boiling point, °K.
T_N = normalized temperature, $T/\epsilon/\kappa$
t = temperature, °C.
u = superficial velocity, ft./sec. or ft./hr.
v_c = critical volume, cc./g.-mole

Greek Letters

ϵ = fractional void volume, dimensionless
ϵ = maximum energy of attraction between a pair of molecules, erg./molecule
κ = Boltzmann constant, 1.3805 $\times$ 10^{-16} erg./°K. molecule
μ = viscosity, lb.-mass/ft. sec.
π = total pressume, atm.
ρ = density, cu. ft.
σ = collision diameter, Å.
$\Omega^{(1,1)}[T_N]$ = collision integral for Equation (3)

LITERATURE CITED

1. Chilton, T. H., and A. P. Colburn, *Ind. Eng. Chem.*, **26**, 1183 (1934).
2. Chu, J. C., James Kalil, and W. A. Wetteroth, *Chem. Eng. Progr.*, **49**, 141 (1953).
3. De Acetis, James, and George Thodos, *Ind. Eng. Chem.*, **52**, 1003 (1960).
4. Ergun, Sabri, *Chem. Eng. Progr.*, **48**, 89 (1952).
5. Gaffney, B. J., and T. B. Drew, *Ind. Eng. Chem.*, **42**, 1120 (1950).
6. Gamson, B. W., *Chem. Eng. Progr.*, **47**, 19 (1951).
7. Gamson, B. W., George Thodos, and O. A. Hougen, *Trans. Am. Inst. Chem. Engrs.*, **39**, 1 (1943).
8. Hirschfelder, J. O., C. F. Curtiss, and R. B. Bird, "Molecular Theory of Gases and Liquids," Wiley, New York (1954).
9. Hobson, Merk, and George Thodos, *Chem. Eng. Progr.*, **47**, 370 (1951).
10. Hougen, O. A., K. M. Watson, and R. A. Ragatz, "Chemical Process Principles," p. 87, Wiley, New York (1954).
11. Hurt, P. M., *Ind. Eng. Chem.*, **35**, 522 (1943).
12. "International Critical Tables," Vol. 3, p. 208, McGraw-Hill, New York (1928).
13. Lee, C. Y., and C. R. Wilke, *Ind. Eng. Chem.*, **47**, 1253 (1955).
14. Lynch, E. J., and Charles R. Wilke, *UCRL-8601*, University of California Radiation Laboratory (Jan. 14, 1959).
15. ———, *UCRL-8602* (Feb. 10, 1959).
16. McCune, L. K., and R. H. Wilhelm, *Ind. Eng. Chem.*, **41**, 1117 (1949).

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