ΔH = enthalpy change, cal./g.-mole
p_{SO_2} = partial pressure of sulfur dioxide, atm.
p_{O_2} = partial pressure of oxygen, atm.
R = universal gas constant, 1.98 cal./(g.-mole) (°K.)
r_0 = initial reaction rate, lb.-moles sulfur dioxide/(hr.) (lb. catalyst)
ΔS = entropy change, cal./(g.-mole) (°K.)
T = absolute temperature, °K.
π = total pressure, atm.

LITERATURE CITED

1. Mathur, G. P., and George Thodos, "Initial Rate Approach to the Kinetics of Heterogeneous Catalytic Reactions—an Experimental Investigation on the Sulfur Dioxide Oxidation Reaction," paper presented at the 58th Annual AIChE Meeting (Preprint 45c), Philadelphia, Pennsylvania, December 5-9, 1965.
2. Hougen, O. A., and K. M. Watson, *Ind. Eng. Chem.*, **35**, 529 (1943).
3. ——————, "Chemical Process Principles, Part III," Wiley, New York (1947).
4. Yang, K. H., and O. A. Hougen, *Chem. Eng. Progr.*, **46**, No. 3, 146 (1950).
5. Kittrell, J. R., W. G. Hunter, and C. C. Watson, *A.I.Ch.E. J.*, **11**, 1051 (1965).
6. Mears, D. E., and Michel Boudart, *ibid.*, **12**, 313 (1966).
7. Franckaerts, J. F., and G. F. Froment, *Chem. Eng. Sci.*, **19**, 807 (1964).
8. Kittrell, J. R., Reiji Mezaki, and C. C. Watson, *Brit. Chem. Eng.*, **11**, No. 1, 15 (1966).

Power Consumption in the Agitation of Solid-Liquid Suspensions

R. H. KOHLER and JOSEPH ESTRIN

Clarkson College of Technology, Potsdam, New York

This paper discusses experiments carried out to provide data describing power consumption characteristics in agitated vessels containing solid-liquid, two-phase systems. These experiments involved several slurry systems, and the data were treated by modifying the properties density and viscosity which appear in the Reynolds and Power numbers. Liquid-liquid and vapor-liquid experiments yielding power consumption data have been reported (*7, 2, 5, 8*); the data for single-phase liquids have been recently thoroughly summarized by Bates et al. (*1*).

When the suspension of solids is reasonably stable, powerful methods for power requirement determinations have been suggested based on concepts of non-Newtonian fluid systems (*6*). When the suspension of solids is not stable, that is, the solids settle freely, the work of Weisman and Efferding and others cited there (*12*) discuss criteria for obtaining complete suspension of the solids. This work is summarized by Perry (*10*).

The following discussion describes work carried out in which power measurements were made for agitated vessels in which the solids suspended do not generally form stable suspensions. In all runs the suspension was such that no particles remained stationary on the tank bottom. This is the criterion for complete suspension used by Hirsekorn and Miller (*3*), and Weisman and Efferding agreed with this criterion, at least to the level of the slurry-liquid interface. The interior of the vessel was completely submerged so that no air-liquid interface and no vortex problems were present. In all runs the slurry existed throughout the entire interior. Thus, the objective here is an investigation into the power consumption characteristics of uniformly distributed particles in an agitated vessel. In the practical situation, this occurs when the primary objective of the operation is some transport process such as solids dissolution, heat transfer in a particulate two-phase system, or crystallization.

APPARATUS

The agitation vessel used for most runs was a Pyrex battery-type jar, 21.4 cm. I.D., which was immersed partially in water contained in a larger diameter battery jar for temperature control. This entire assembly was placed on a Plexiglas sheet over an inclined mirror so that particles of the solids being suspended could be carefully observed at the bottom of the vessel. Four 0.1-diameter radial baffles were employed.

The volume of fluid agitated in this vessel was maintained constant by sealing a fixed plate 19.5 cm. from the bottom. Holes were cut into this plate to allow the agitator shaft to pass through, filling and draining of the system, and thermometer insertion. A small chimney about the center hole and shaft permitted air to escape before making a run and also provided for an extra head of liquid which helped avoid vortex formation due to the leakage of air about the shaft. The plate was sealed against the glass walls of the vessel and the baffles; the thermometer and solids feed holes were tightly stoppered. About 1 in. of distilled water was maintained above this horizontal partition to avoid air entrainment. Only insignificant amounts of solids of any size were found to permeate this upper region.

Table 1. Systems Studied

Liquids	Properties
Distilled water	
Distilled water-Karo syrup solutions	Viscosity range 9 to 5300 centipoise Density range 1.10 to 1.37 g./ml.
Solids	**Properties**
Spherical polystyrene beads	Over 80% through 40 and retained on 70 mesh; density = 1.0 g./ml.
20-30 mesh silica sand	Ottawa Silica Co., Ottawa, Ill. Density = 2.86 g./ml. by water displacement
Silica fine silica sand	Ottawa Silica Co., Ottawa, Ill. 99% through 100 mesh; ground. Density = 2.68 g./ml. by water displacement
Zinc dust	Fisher Scientific Co. through 400 mesh
Lead dust	E. H. Sargent Co. 80% through 200 mesh

The general power requirements for an enclosed system of this type for liquids is discussed by Laity and Treybal (5).

Use was made of a dynamometer obtained from the Mixing Equipment Company, Inc., which was constructed of a 1/3 hp. motor mounted on a 3/8 in. stainless base and equipped with two varidirectional pulleys so that measurements could be made either with clockwise or counterclockwise rotation. A Chatillon Dynamometer scale was connected to the pulleys. Rotational velocity was adjusted by a shifting brush control arrangement and by an externally located autotransformer. Rotational velocity was read from a voltmeter connected to a small generator attached to the shaft. Two six-flat blade turbine-type impellers were positioned upon a ½ in. shaft centrally located. These were 4 in. in diameter, obtained from the Mixing Equipment Company, Inc., and of standard geometry (4). The lower one was placed 5.1 cm. from the tank bottom and the upper impeller was 5.1 cm. above this. This arrangement was found to be efficient in effecting complete dispersion of the particles. This is not as efficient an arrangement as axial flow turbines for solids suspension (9), that is, impellers with flat blades set at an angle to the plane of the impeller; however, since the primary motive for the process visualized is not solids suspension but rather some other, such as solids dissolution or crystallization, the geometry used was considered representative. The systems employed in this apparatus are listed in Table 1.

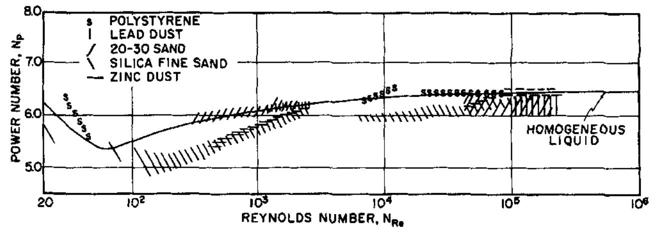

Fig. 1. Summary of data obtained in totally enclosed vessel.

RESULTS

The viscosity characteristics of liquid-solids systems, whose suspension stability characteristics are poor, are

Table 2. Operating Properties for Data Shown in Figure 1

System	Reynolds number range, modified (pure liquid)	Vol.-% Solids range	Settled density, g. solids/ml. settled volume
20-30 Sand:			
Water	6.8×10^4 to 2.0×10^5 (7.4×10^4 to 2.1×10^5)	5.4-38	1.66
Corn syrup solution (83.6 centipoise)	2.7×10^2 to 2.2×10^3 (1.5×10^3 to 2.4×10^3)	5.4-43	1.66
Silica fine sand:			
Water	7.9×10^3 to 2.0×10^5 (6.0×10^4 to 2.2×10^5)	5.4-43	1.50
Corn syrup solution (83.6 centipoise)	29 to 2.1×10^3 (614 to 2.4×10^3)	5.4-48	1.50
(83.6 centipoise)	3.5 to 15 (470 to 2,100)	54	1.50
Zinc dust:			
Water	3.8×10^4 to 1.7×10^5 (6.9×10^4 to 1.6×10^5)	4.0-28	3.40
Corn syrup solution (83.6 centipoise)	3.7×10^2 to 2.4×10^3 (7.9×10^2 to 2.4×10^3)	2.0-28	3.40
Lead dust:			
Water	9.0×10^4 to 2.1×10^5 (6.4×10^4 to 1.7×10^5)	2.5-18	6.01
Corn syrup solution (83.6 centipoise)	1.0×10^3 to 2.5×10^3 (8.7×10^2 to 2.3×10^3)	2.5-18	6.01
Polystyrene beads:			
Water	4.1×10^3 to 8.1×10^4 (8.0×10^4 to 2.3×10^5)	29-53	0.653
Corn syrup solution (200 centipoise)	26 to 54 (579 to 1,180)	53	0.653

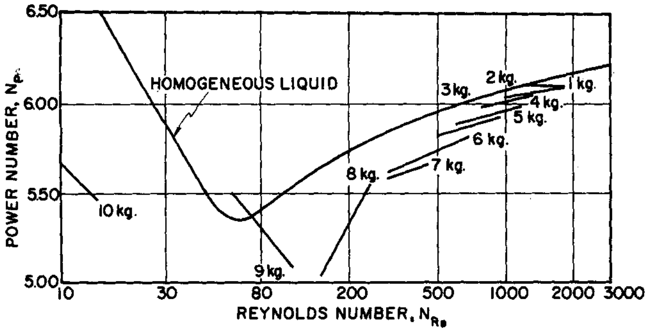

Fig. 2. Silica fine sand suspended in syrup solution (83.6 centipoise).

not readily evaluated in standard viscometers. The method of analysis of Orr and Dallavalle (*11*) was attempted in this work. They investigated the heat transfer characteristics of slurries in pipe flow by using the established dimensionless equations for pure fluids and carefully devised physical properties for the slurry system. Since momentum transfer characteristics properly considered are implied in their technique, the same viscosity and density expressions are used here. In particular, their expression for viscosity used in computing the Reynolds number was

$$\mu_s = \frac{\mu_L}{\left(\dfrac{1 - x_v}{x_{vb}}\right)^{1.8}} \quad (1)$$

and weighted average values for the density were used in both Reynolds and Power numbers. The x_{vb} values were computed from volume measurements made by placing a known mass of solids in liquid in a graduated cylinder, by thoroughly mixing and then allowing the solids to settle for a few days. The graduated cylinder was inverted when the polystyrene beads characteristics were investigated, since these were slightly less dense than the solution.

Figure 1 presents a graphical summary of the results of all runs made in the apparatus described above. Table 2 gives the appropriate ranges of solids concentrations and physical properties which are associated with Figure 1. Figures 2 and 3 show in more detail the results for silica fine sand in Karo solution (83.6 centipoise) and the results for polystyrene beads in water. This latter figure presents typical scatter of the data obtained in this apparatus. The kilogram values given in the figures are the masses of suspended solids.

Figure 4 gives data for pure solution and a suspension of silica fine sand (21 vol.-% solids) in the same solution in a larger vessel. Two 4-in., six-blade turbine impellers were used, 3.8 in. apart with the lower 2 in. from the bottom. The liquid height was 29.5 cm. (in a tank of diameter 39 cm.) and complete suspension was not entirely obtained, which may account for the scatter of these data. They show behavior similar to the other runs when a free interface is present and when the dimensionless variables are similarly modified.

These results show the applicability of the bulk density for concentrated slurry systems. They also suggest that

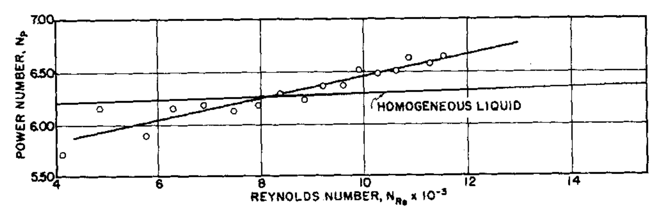

Fig. 3. Polystyrene beads suspended in water (3.7 kg.).

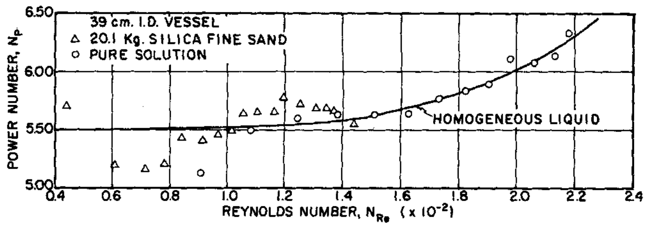

Fig. 4. Silica fine sand suspended in syrup solution (850 centipoise). Runs in 39 cm. I.D. vessel with air-liquid interface.

the viscosity computed by the method of Orr and Dallavalle is a readily convenient means for determining an apparent viscosity for use with $N_P - N_{Re}$ plots.

CONCLUSIONS

Experimental determinations of Power number–Reynolds number characteristics were made for various slurry systems by assuming the viscosity of Orr and Dallavalle (*11*) and average bulk density to be applicable. The slurries were not in stable suspension and this work would prove of use only for such systems. The results suggest that this approach is strictly empirical. It fails to account for the degree of pseudoplasticity which is suggested by the divergence of data in the transition region (cf. Figure 1) and is therefore useful only when techniques based on non-Newtonian behavior (6) are not readily applicable. In most instances, deviations from the homogeneous liquid curve were conservative as is desired for design considerations.

NOTATION

- D = impeller diameter, ft.
- N = rotational speed of impeller, rev./hr.
- N_{Re} = Reynolds number, dimensionless, $D^2N\rho_s/\mu_s$
- N_P = Power number, dimensionless, $Pg_c/D^5N^3\rho_s$
- P = power consumption, (ft.) (lb.$_f$)/hr.
- x_v = volume fraction suspended solids
- x_{vb} = volume fraction solids in sedimented bed
- ρ_s = density of slurry, total mass in vessel/total volume, lb.$_m$/cu.ft.
- μ_L = viscosity of homogeneous liquid, lb.$_m$/(ft.) (hr.)
- μ_s = viscosity of slurry as computed in Equation (1), lb.$_m$/(hr.) (ft.)

LITERATURE CITED

1. Bates, R. L., P. L. Fondy, and J. G. Fenic, in "Mixing: Theory and Practice," ed. by V. W. Uhl and J. B. Gray, ed., Chap. 3, Academic Press, New York (1966).
2. Flynn, A. W., and R. E. Treybal, *A.I.Ch.E. J.*, **1**, 324 (1955).
3. Hirsekorn, F. S., and S. B. Miller, *Chem. Eng. Progr.*, **49**, 459 (1953).
4. Holland, F. A., and F. S. Chapman, "Liquid Mixing and Processing," p. 6, Reinhold, New York (1966).
5. Laity, D. S., and R. E. Treybal, *A.I.Ch.E. J.*, **3**, 176 (1957).
6. Metzner, A. B., and R. E. Otto, *ibid.*, **3**, 3 (1957).
7. Michel, B. J., and S. A. Miller, *ibid.*, **8**, 262 (1962).
8. Miller S. A., and C. A. Mann, Trans. *Am. Inst. Chem. Engrs.*, **XL**, 709 (1944).
9. Correspondence, Mixing Equipment Co., Inc., Rochester, N. Y.
10. Perry, J. H., "Chemical Engineers' Handbook," 4 ed., pp. 19-12, 13, McGraw-Hill, New York (1963).
11. Orr, C., Jr., and J. M. Dallavalle, *Chem. Eng. Progr. Symp. Ser. No. 9*, **50**, 29 (1954).
12. Weisman, J., and L. E. Efferding, *A.I.Ch.E. J.*, **6**, 421 (1960).