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Hiroshi YAMAZAKI*, Kakuji TOJO** and Kei MIYANAMI**

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The solid concentration profiles in a slurry mixing tank with mechanical agitation have been measured by using a photo-electric method. The sedimentation-dispersion model which divides the reactor into two compartments, the upflow region and the downflow region, is found to be applicable for describing the concentration profiles in the slurry mixing tank with a marine propeller or a flat-disk turbine. The model parameters, modified Peclet numbers, have been markedly influenced by the amount of solid particles charged in the tank, and the trend of relationship between the model parameters and the average solid concentration implies that the flow pattern of the dense slurry of about 20 % by weight or more may be different from the lean slurry of less than about 20 % by weight.

Introduction

Slurry operation has been widely utilized in chemical and pharmaceutical industries. Use of slurries would appear to offer many advantages; uniform temperature distribution throughout the tank for eliminating the hot spot which may be occured in fixed beds, high reaction rate due to large interfacial area and vigorous turbulence between the phases, and so on. Typical industrial applications are hydrogenation with a suspended catalyst, leaching, coal liquefaction and gasification, crystallization, etc..

In these slurry operations, "Complete Suspension" conditons under which all solids are suspending in the reactor[1), 2), 3)] is generally preferable for attaining the maximum interfacial area and for avoiding clog of the feeding lines caused by solid accumulation on the tank bottom. A limiting condition of complete suspension, Homogeneous Suspension, which provides a uniform solid concentration distribution throughout the tank, may be required for some operations, especially a continuous slurry-flow system with relatively large solid size distribution. However, it is often unpractical to operate the slurry reactor under homogeneous conditions because enormous mixing energy is usually necessary to achieve the homogeneous suspension in commercial equipments.

In slurry reactors, the state of solid suspension is closely related to the operating variables: the agitator speed, the agitator type, the tank geometry, the rates of flows involved, and so on. Furthermore, the rate process which occurs in the slurry tank largely depends on the solid suspension phenomena, and therefore it is of great importance to investigate the flow characteristics of both the continuous and the dispersed phases. Especially, the state of solid suspension should be carefully examined because the solid phase is hardly mixed perfectly while the liquid phase can be easily mixed completely in conventional slurry reactors.

* Research Fellow of Chemical Engineering Department, Fujisawa Pharmaceutical Company, Osaka, Japan.

** Department of Chemical Engineering, College of Engineering.

In the present work, the solid concentration profiles in the slurry mixing tank with a conventional rotary agitation have been measured by using a photo-electric method, and analysed by a sedimentation-dispersion model.[4), 5)] Two types of impellers, a marine propeller and a flat-disk turbine are tested, and the effects of impeller speed, the amount of solids charged, and the type of impeller used on the solid concentration profiles have been shown and discussed.

Model of this study

In slurry reactors, three phases are generally present; these are the liquid medium, solid phase and gas phase. Mixing in the slurry reactor would be enchanced by both the liquid and gas phases. However, the gas flow will not play a significant role to improve solid suspension in the slurry reactor with mechanical agitation such as studied in the present work although the mixing due to the gas phase may be important to enhance the slurry suspension in the reactor without mechanical agitation such as fluidized beds and bubble bed reactors. It is of great importance to elucidate the flow behavior of the suspended solid particles following the vigorous flow of the liquid phase generated by the impeller.

In the present study, therefore, we consider only two phases of liquid and solid, and a flow model with respect to these two phases has been developed. In developing this model, liquid is assumed to flow through the two regions in the slurry reactor as shown in Fig. 1; these are upflow and downflow regions. The direction of flow depends largely on the reactor design, especially the type of impeller; the marine propeller is an axial flow impeller while the flat-disk turbine is a radial flow impeller.

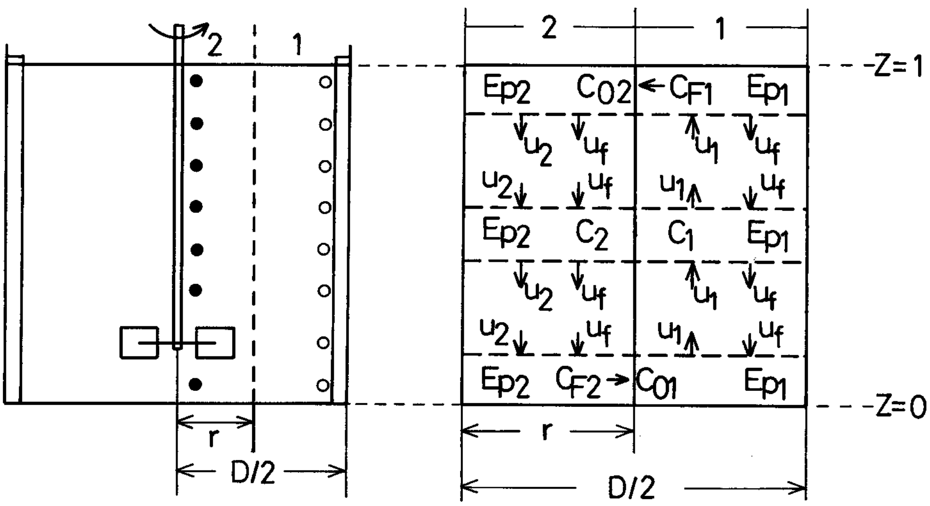

Fig. 1 Schematic diagram of the sedimentation-dispersion model
1: upflow region, 2: downflow region
○, ● : sampling positions of solid concentrations.

The material balance in a differential volume element of each region of the reactor with respect to the solid concentration leads to

$$\frac{\partial C_1}{\partial t} = -u_1 \frac{\partial C_1}{\partial h} + u_f \frac{\partial C_1}{\partial h} + \frac{\partial}{\partial h}\left(E_{p1} \frac{\partial C_1}{\partial h}\right) \tag{1}$$

in the upflow region, and

$$\frac{\partial C_2}{\partial t} = u_2 \frac{\partial C_2}{\partial h} + u_f \frac{\partial C_2}{\partial h} + \frac{\partial}{\partial h}\left(E_{p2} \frac{\partial C_2}{\partial h}\right) \tag{2}$$

in the downflow region, where u is the liquid superficial velocity, E_p is the solid dispersion coefficient, and u_f is the solid falling velocity which is assumed to be constant.

The appropriate boundary conditions are expressed by

$$E_{p1} \frac{dC_1}{dh} = -u_1 (C_{01} - C_1) - u_f C_1 \qquad \text{at} \quad h = 0 \tag{3}$$

$$E_{p1} \frac{dC_1}{dh} = -u_f C_{F1} \qquad \text{at} \quad h = H \tag{4}$$

for the upflow region, and

$$E_{p2} \frac{dC_2}{dh} = -u_f C_{F2} \qquad \text{at} \quad h = 0 \tag{5}$$

$$E_{p2} \frac{dC_2}{dh} = -u_2 (C_2 - C_{02}) - u_f C_2 \qquad \text{at} \quad h = H \tag{6}$$

for the downflow region, where C_{F1} and C_{F2} are the solid concentrations at the reactor top and the reactor bottom, respectively.

The dimensionless forms of Eqs. (1), (2), (3), (4), (5) and (6) are given, respectively, by

$$\frac{\partial X}{\partial \tau_1} = -(1 - 1/Q_1) \frac{\partial X}{\partial Z} + \frac{\partial}{\partial Z}\left(\frac{1}{Pe_{p1}} \frac{\partial X}{\partial Z}\right) \tag{7}$$

$$\frac{\partial Y}{\partial \tau_2} = (1 + 1/Q_2) \frac{\partial Y}{\partial Z} + \frac{\partial}{\partial Z}\left(\frac{1}{Pe_{p2}} \frac{\partial Y}{\partial Z}\right) \tag{8}$$

$$\frac{dX}{dZ} = (Pe_{p1} - Pe_{f1}) X - Pe_{p1} \qquad \text{at} \quad Z = 0 \tag{9}$$

$$\frac{dX}{dZ} = -Pe_{f1} \qquad \text{at} \quad Z = 1 \tag{10}$$

$$\frac{dY}{dZ} = -Pe_{f2} \qquad \text{at} \quad Z = 0 \tag{11}$$

$$\frac{dY}{dZ} = -(Pe_{p2} + Pe_{f2}) Y + Pe_{p2} \qquad \text{at} \quad Z = 1 \tag{12}$$

where $X = C_1/C_{F1}$, $Y = C_2/C_{F2}$, $Z = h/H$, $Pe_{f1} = u_f H/E_{p1}$, $Pe_{f2} = u_f H/E_{p2}$,

$Pe_{p1} = u_1 H/E_{p1}$, $Pe_{p2} = u_2 H/E_{p2}$, $Q_1 = u_1/u_f$, $Q_2 = u_2/u_f$, $\tau_1 = t/(H/u_1)$, $\tau_2 = t/(H/u_2)$.

Under steady state conditions, Eqs. (7) and (8) subject to the boundary conditions, Eqs. (9) to (12), can be solved analytically as

$$X = \frac{1}{Q_1 - 1} \left[Q_1 - \exp\{ Pe_{f1} \, (Q_1 - 1)(Z - 1) \} \right] \tag{13}$$

$$Y = \frac{1}{Q_2 + 1} \left[Q_2 + \exp\{ -Pe_{f2} \, (Q_2 + 1) Z \} \right] \tag{14}$$

As can be expected from the above equations, the concentration profiles in the upflow region and in the downflow region are convex and concave, respectively.

Experimental

The schematic diagram of experimental setup is shown in Fig. 2. A flat-bottomed cylindrical tank of 0.2 m (inside diameter) X 0.3 m (height), was employed. Two types of impellers, a 4-blade marine propeller and a 6-blade flat-disk turbine were tested to make complete suspension throughout the tank. Prior to measurement, known mass of solids and water were fed into the tank, and then the content was mixed under complete suspension conditions which were verified by careful observation. After reaching steady state, the solid concentrations at several positions in the tank in both radial and vertical directions were measured by using a light reflection method developed in the present work. The principle of measurement is described in our previous paper.[6] The details of the probe for measuring the solid concentration are shown in Fig. 2. The experimental conditions are listed in Table 1.

Table 1 Experimental Conditions

Inside diameter of tank	D	20	(cm)
Diameter of impeller			
4-blade marine propeller	d	6.6	(cm)
6-blade flat-disk turbine	d	6.9	(cm)
Impeller speed	N	850-1350	(rpm)
Impeller height	h_i	3.5	(cm)
Liquid depth	H=D	20	(cm)
Solid concentration	C	11.8-45.4	(wt%)

Solid particles	Mean particle size	Density	Settling velocity
	d_p (μm)	ρ_p (g/cm^3)	u_s (cm/sec)
Glass beads	135	2.47	1.85

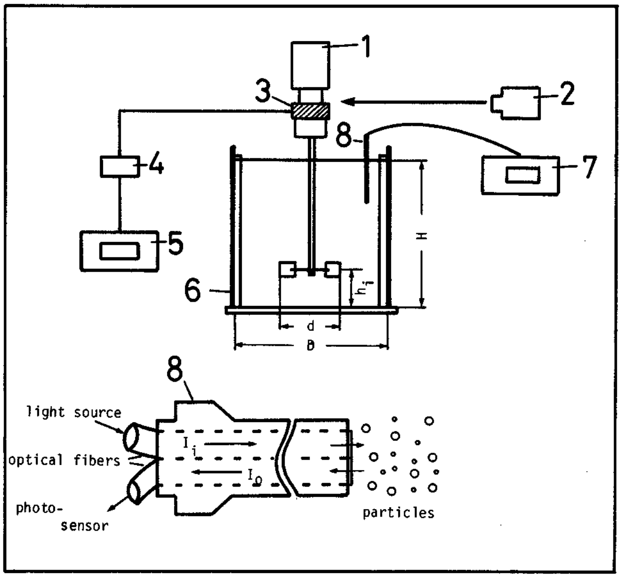

Fig. 2 Schematic diagram of experimental apparatus;
1: motor 2: tachometer 3: torquemeter 4: amplifier
5: recorder 6: tank 7: photometer 8: optic fiber probe

Results and discussion

The concentration profiles of solids suspended in the stirred tank with a marine propeller and a flat-disk turbine are plotted in Figs. 3 and 4, respectively. For both propeller and turbine agitation, the solid concentration profile approaches uniform suspension with increasing the speed of agitation. It is also interesting to find that the concentration near the surface decreases markedly as the amount of solids suspended increases. This is mainly attributed to the phenomenon of turbulence dumping in the liquid phase caused by an increased interference between solid particles, since the energy for solid suspension generated by the impeller rotation, is almost dissipated around the impeller in a dense slurry. The energy is hardly transfered to the place far from the impeller position. In Figs. 3 and 4, the concentration profiles calculated from the present model are also plotted for comparison. As can be seen, the calculated profiles agree well with the experimental data; the concentration profiles both in the upflow region and the downflow region of the turbine mixer can be excellently described by the present sedimentation-dispersion model, while some of the concentration profiles in the downflow region for the propeller agitation deviate from the calculated profiles. The reason of this finding is not clear at the present stage. The discrepancy is probably due to the oversimplification of the flow pattern; the flow pattern in the stirred tank is extremely complex, and a rigorous mathematical model for fluid flow is probably extremely difficult to develop even for the liquid single phase involved. The more sophisticated model for explaining the solid concentration near the surface will be included in our future work. However, suffice it to say at this stage of our research that the solid concentration profiles in the slurry reactor depend largely on

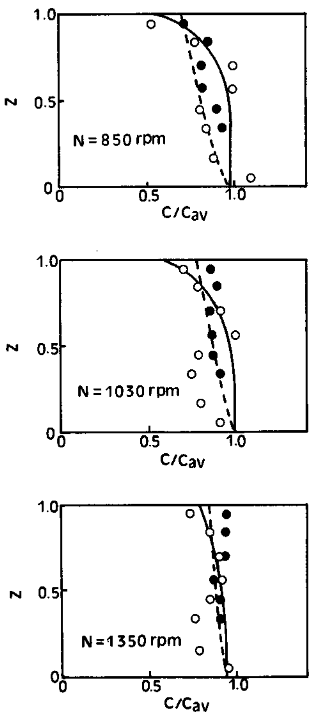

Fig. 3 (a) Axial concentration profiles of solid particles in the stirred tank with a marine propeller; C_{av} = 11.8 wt%, ○, ● : experimental data, –, ---: calculated concentration profiles.

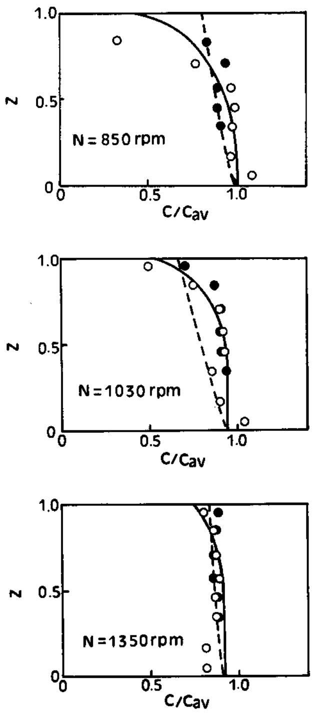

Fig. 3 (b) Axial concentration profiles of solid particles in the stirred tank with a marine propeller; C_{av} = 14.5 wt%, ○, ● : experimental data, –, ---: calculated concentration profiles.

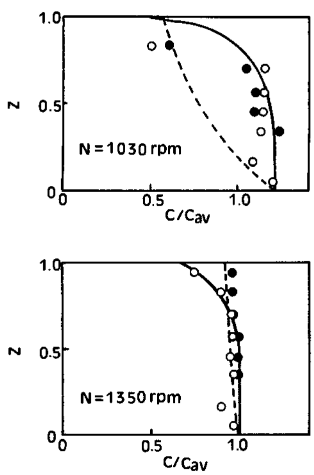

Fig. 3 (c) Axial concentration profiles of solid particles in the stirred tank with a marine propeller; C_{av} = 26.5 wt%, ○, ● : experimental data, –, --- : calculated concentration profiles.

both the operating variables and the reactor design, and the effect of these variables on the concentration profiles can be interpreted approximately by the present sedimentation-dispersion model. The effects of solid concentration on the model parameters, Pe_p and Pe_f, in the upflow region for the propeller and the turbine impellers are shown in Figs. 5 and 6, respectively. As can be seen, the Peclet number Pe_f increases linearly with increasing the solid concentration. It can be also seen that the ratio of parameters, Pe_p/Pe_f decreases as the solid concentration increases and then approaches a constant value. This is mainly due to the reduced upflow velocity in the liquid phase caused by the strong interference of the solid particles. The trend of the Pe_p/Pe_f versus concentration curves as seen in Figs. 5 and 6, implies that the flow pattern of the fluid in the slurry tank may change at the average concentration of about 20 % by weight. We can not draw the definite explanation of this experimental findings in the present

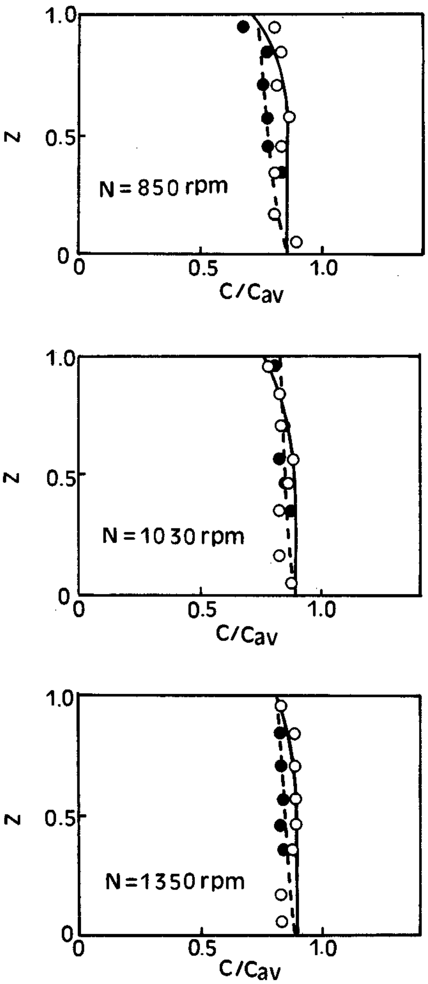

Fig. 4 (a) Axial concentration profiles of solid particles in the stirred tank with a flat-disk turbine; C_{av} = 14.5 wt%,
o, • : experimental data,
–, ---: calculated concentration profiles.

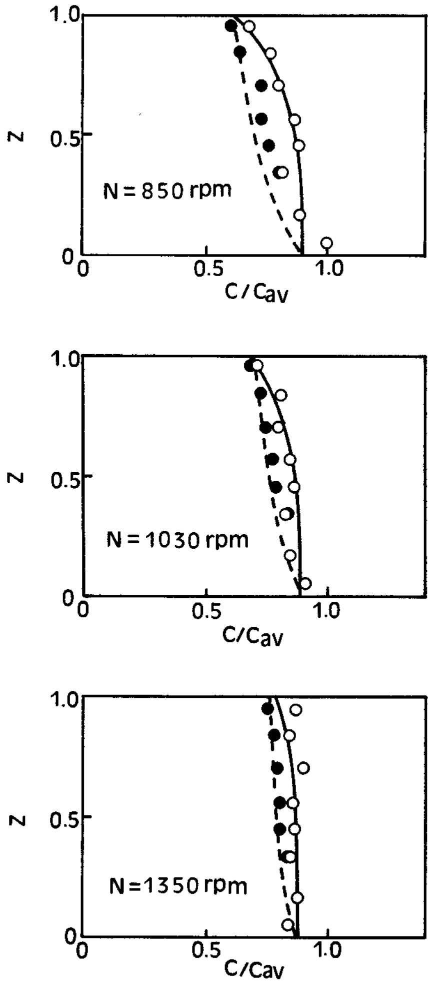

Fig. 4 (b) Axial concentration profiles of solid particles in the stirred tank with a flat-disk turbine; C_{av} = 20.9 wt%,
o, • : experimental data,
–, ---: calculated concentration profiles.

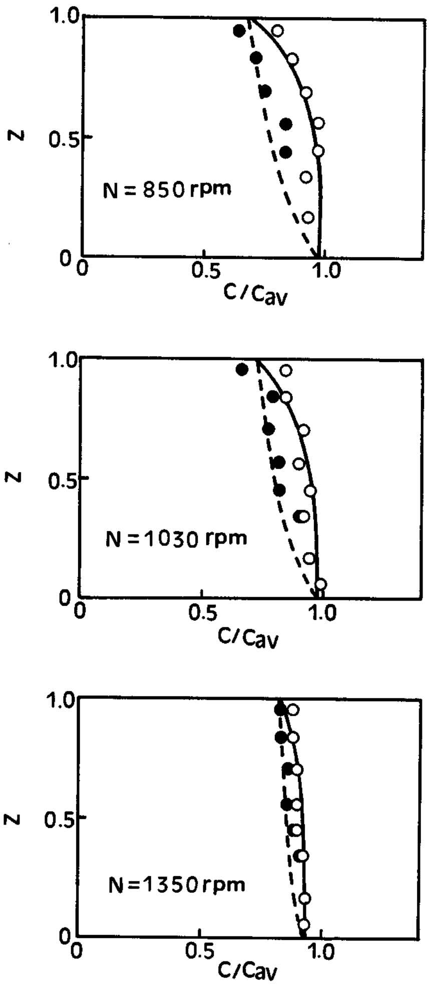

Fig. 4 (c) Axial concentration profiles of solid particles in the stirred tank with a flat-disk turbine; C_{av} = 26.5 wt%, ○, ● : experimental data, –, --- : calculated concentration profiles.

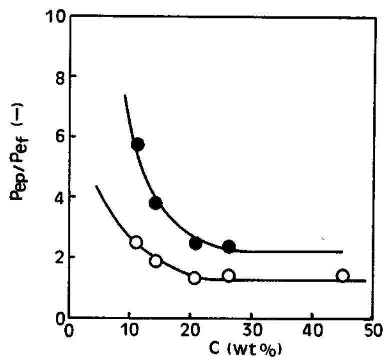

Fig. 5.1 Effect of solid concentrations on the ratio of model parameters, Pe_p/Pe_f in the stirred tank with a marine propeller :
○ ; 1030 rpm, ● ; 1350 rpm

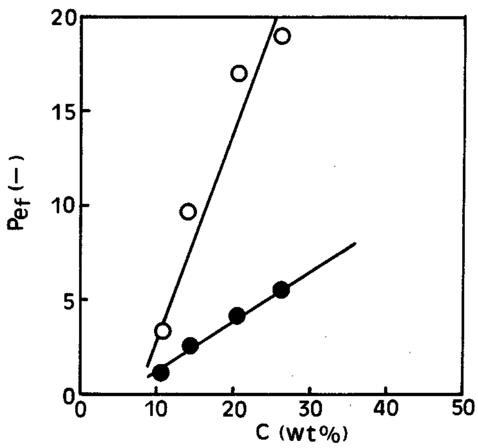

Fig. 5.2 Effect of solid concentrations on the model parameter, Pe_f in the stirred tank with a marine propeller : ○ ; 1030 rpm, ● ; 1350 rpm

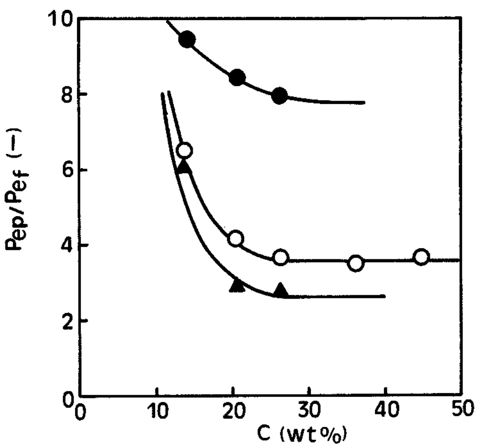

Fig. 6.1 Effect of solid concentrations on the ratio of model parameters, Pe_p/Pe_f in the stirred tank with a flat-disk turbine : ▲; 850 rpm, ○; 1030 rpm, ●; 1350 rpm

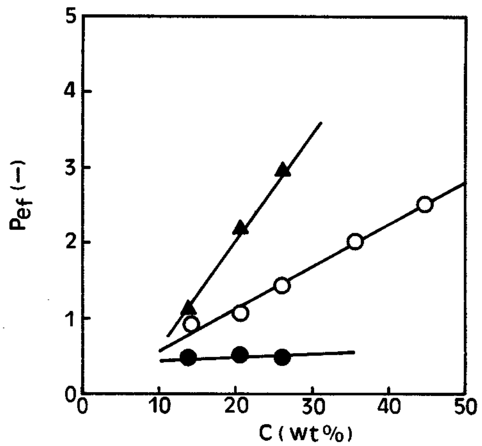

Fig. 6.2 Effect of solid concentrations on the model parameter, Pe_f in the stirred tank with a flat-disk turbine : ▲; 850 rpm, ○; 1030 rpm, ●; 1350 rpm

study. As concerns the correlation of the model parameters, we will discuss more detail in our future work.

Conclusion

The solid concentration profiles in the slurry mixing tank with mechanical agitation have been successfully measured by using a photo-electric method. The sedimentation-dispersion model which divides the tank into two flow regions, upflow and downflow regions, is found to be applicable for describing the experimental solid concentrations for both types of impeller, a marine propeller and a flat-disk turbine; specifically the calculated profiles for the turbine agitation agreed excellently with the experimental ones. The model parameters have been highly influenced by the amount of the solids charged, and the trend of their correlation curves in terms of the average solid concentration implies that the flow pattern of the dense slurry, the concentration of which is about 20 % by weight or more, may be different from that of the lean slurry.

Nomenclature

C	= solid concentration in the tank [wt%]
C_1	= solid concentration in the upflow region [wt%]
C_2	= solid concentration in the downflow region [wt%]
C_{01}	= solid concentration at the bottom ($Z = 0$) in the upflow region [wt%]
C_{02}	= solid concentration at the top ($Z = 1$) in the down flow region [wt%]
C_{av}	= average solid concentration in the tank [wt%]
C_{F1}	= solid concentration at the tank-top [wt%]
C_{F2}	= solid concentration at the tank-bottom [wt%]
d	= impeller diameter [cm]
D	= inside diameter of the tank [cm]
d_p	= particle diameter [μm]
E_{p1}	= solid phase dispersion coefficient in the upflow region [cm^2/sec]
E_{p2}	= solid phase dispersion coefficient in the downflow region [cm^2/sec]
H	= liquid depth in the tank [cm]
h	= height [cm]
h_i	= impeller height [cm]
I	= intensity of illumination [cd]
N	= impeller speed [1/min]
Pe_{p1}	= Peclet number for solid phase ($= u_1 H/E_{p1}$) [–]
Pe_{p2}	= Peclet number for solid phase ($= u_2 H/E_{p2}$) [–]
Pe_{f1}	= Peclet number for solid phase ($= u_f H/E_{p1}$) [–]
Pe_{f2}	= Peclet number for solid phase ($= u_f H/E_{p2}$) [–]
Q_1	= u_1/u_f [–]
Q_2	= u_2/u_f [–]
t	= time [sec]
u_1	= superficial upward velocity of liquid phase [cm/sec]
u_2	= superficial downward velocity of liquid phase [cm/sec]
u_f	= falling velocity of the solid particles [cm/sec]
X	= dimensionless solid concentration in the upflow region [–]
Y	= dimensionless solid concentration in the downflow region [–]
Z	= dimensionless height ($= h/H$) [–]
ρ_p	= density of the solid [g/cm^3]
τ_1	= dimensionless time defined by $t/(H/u_1)$ [–]
τ_2	= dimensionless time defined by $t/(H/u_2)$ [–]

References

1) T. H. Zwietering, Chem. Eng. Sci., 8, 244 (1958).
2) A. W. Nienow, Chem. Eng. Sci., 23, 1453 (1968).
3) K. Tojo, K. Miyanami and H. Mitsui, Chem. Eng. Sci., 36, 279 (1981).
4) W. B. Argo and D. R. Cova, Ind. Eng. Chem. Process Des. Dev., 4, 352 (1965).
5) D. R. Cova, Ind. Eng. Chem. Process Des. Dev., 5, 21 (1966).
6) K. Tojo and K. Miyanami, Ind. Eng. Chem. Fundam., 21, 214 (1982).