

CONCENTRATION DISTRIBUTION OF SUSPENSION IN A MIXED VESSEL

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A theoretical model is proposed enabling numerical solution of the distribution of concentration in a mixed vessel based on the knowledge of the velocity field and physical properties of the system. The model has been tested by measuring concentration distribution in a cylindrical vessel with baffles mixed by a paddle impeller. The data on the velocity field in the liquid were taken over from literature.

In the majority of papers¹ dealing with the suspension of solids in liquids the state of the suspension is being described in terms of the values averaged over the whole volume of the batch. However, the design of some reactions of solids with a liquid in suspension necessitates the knowledge of spatial concentration distribution in dependence on the frequency of revolution of the impeller. Description of the concentration field in the suspension is necessary, for instance, for the design of polymerization reactors or a variety of fermentors. The data existing in the literature on the distribution of concentration of solid particles in mixed vessels are relatively rare and mostly of only qualitative character. In this paper an attempt is made to describe the time-averaged concentration field of a monodispersed suspension in a cylindrical vessel with baffles under conditions when all particles are suspended. The description is based on the continuity equation and utilizes the knowledge of the distribution of liquid velocities and characteristics of the solids given in terms of their terminal velocity.

THEORETICAL

Since we are dealing with time-averaged concentrations in a system consisting of a large number of particles, the solid phase may be regarded as a continuum. The continuity equation then gives

$$\frac{\partial c}{\partial t} + \nabla(\bar{c}\mathbf{v}) = 0. \quad (1)$$

Substituting the sum of the mean value and the fluctuation component of concentra-

tion and velocity the following equation results

$$\partial(\bar{c} + c')/\partial t + \nabla(\bar{c} + c')(\bar{\mathbf{v}} + \mathbf{v}') = 0. \quad (2)$$

Averaging the last equation with respect to time over a sufficiently long time interval compared to the turbulent fluctuations, yet short enough compared to the time variations of the mean values, there results

$$\partial\bar{c}/\partial t + \nabla(\bar{c}\bar{\mathbf{v}}) + \nabla(\bar{c}'\bar{\mathbf{v}}') = 0. \quad (3)$$

The last term in Eq. (3) represents the time variation of concentration due to the turbulence. Solution of Eq. (3) requires the knowledge of the spatial distribution of solid particle velocity and the flux of particles induced by turbulence.

The Field of Solid Particle Velocity

The calculation of the velocity field of solid particles was based on the knowledge of the field of liquid velocity and the terminal velocity of solid particles in a turbulent medium. Neglecting inertia forces acting on the particle, the velocity of the particle was taken as a vector sum of the velocity of liquid and the terminal velocity of the particle in a turbulent medium

$$\bar{\mathbf{v}} = \bar{\mathbf{u}} + \mathbf{w}. \quad (4)$$

In cylindrical coordinates and neglecting tangential component of the velocity, Eq. (4) changes into

$$\bar{v}_r = \bar{u}_r, \quad \bar{v}_z = \bar{u}_z - w. \quad (5), (6)$$

The terminal velocity is taken with a positive sign owing to the selected frame of reference.

The velocity field in the liquid was expressed from the dimensionless stream function published by Fořt². The velocity of liquid and the stream function are related by an equation that in cylindrical coordinates takes the form

$$\bar{u}_R = D_m N (D_m/D_n)^2 (1/R) (\partial F/\partial Z), \quad (7)$$

$$\bar{u}_Z = -D_m N (D_m/D_n)^2 (1/R) (\partial F/\partial R). \quad (8)$$

Functional values of the stream function, F , for the given geometry of vessel and the

type of impeller, according to Fořt, are independent of the frequency of revolution and the relative size of impeller (D_m/D_n). Fořt estimated the values of the stream function, F , in mixed vessels graphically from velocity distribution in the liquid. The velocity field had been computed from pressures measured by a directional Pitot tube. The tabulated values of the dimensionless stream function determined by Fořt³ were used to compute the components of liquid velocity from Eqs (7) and (8).

The Terminal Velocity of Particles in the Turbulent Medium

The velocity of a particle falling in a turbulent medium varies with the intensity and the scale of turbulence which alter the coefficient of resistance and hence the terminal velocity of the particle. Literature data on terminal velocities of particles in a turbulent medium are rather incomplete. Schwartzberg and Treybal⁴ measured local velocities of solid particles in a vessel equipped with baffles and mixed by a turbine impeller. They found the terminal velocity of particles in a turbulent fluid within the vessel always smaller than that of particles in a quiescent fluid. The effect of turbulence on the terminal velocity of particles can be expressed formally by

$$w = k_w w_0, \quad (9)$$

where the value of the correction factor of the terminal velocity, k_w , is always less than unity. Local values of the factor k_w in region of the turbine impeller found by Schwartzberg and Treybal ranged between 0.3 and 0.6. The correction factor in this work was that averaged over the whole volume of the batch evaluated as a parameter of the proposed model. The terminal velocity of the particles is further affected by the concentration of the suspended particles. For highly diluted suspensions (<3% by volume) this effect may be neglected.

Turbulent Diffusivity

The flux of particles due to the turbulence may be expressed in analogy to molecular diffusion by the following equation

$$\bar{c}'\nabla = -E_t \nabla^2 \bar{c}, \quad (10)$$

defining the turbulent diffusivity E_t . Direct data on turbulent diffusivity in mixed vessels are not available in the literature. For this reason its mean value was assessed from a simplified concept of isotropic turbulence within the mixed vessel.

For turbulent diffusivity of liquid Friedlander⁵ recommends the expression

$$E_k = \bar{u}'^2 \int_0^{t \rightarrow \infty} K_k(t) dt. \quad (11)$$

A similar expression may be written also for the turbulent diffusivity of solid particles

$$E_s = \bar{v}'^2 \int_0^{t \rightarrow \infty} K \cdot(t) dt. \quad (12)$$

From the theoretical solution of Friedlander⁵ as well as from experimental measurements (Kalinske and Pien⁶, Rouse⁷) it follows that the integrals in Eqs (11) and (12) are approximately equal. From measurements of fluctuation velocities of liquid and solid particles Schwartzberg and Treybal⁴ found that turbulent diffusivity of solid particles affected primarily by the intensity of turbulence and, approximately, one may write that

$$\bar{v}'/\bar{u}' \approx 0.95. \quad (13)$$

Combining Eqs (11)–(13) and assuming equality of the integrals in Eqs (11) and (12) the following equation for the turbulent diffusivity is obtained

$$E_s = 0.95^2 E_k. \quad (14)$$

Turbulent diffusivity of liquid, E_k , may be expressed by means of the power input characteristics of the impeller. Namely, as a product of the mean fluctuation velocity and the mixing length

$$E_k = \bar{u}' l_M. \quad (15)$$

From analogy with the turbulent flow of gases there follows an approximate relation between the mixing length, l_M , and the size of the vortices, l_e

$$l_M = 1.5 l_e. \quad (16)$$

Cutter¹ proposed the following correlation for the size of the vortices in a vessel mixed by a turbine impeller

$$l_e = 0.08 D_m. \quad (17)$$

Schwartzberg and Treybal⁸ recommend the following relationship for the calculation of \bar{u}' assuming isotropic turbulence in the vessel mixed by a turbine

$$\bar{u}' = 0.73 N D_m. \quad (18)$$

A combination of Eqs (15)–(18) yields the following equation for the turbulent

diffusivity

$$E_k = 0.1ND_m^3/D_n \quad (19)$$

Finally, substitution of Eq. (19) into (14) gives the expression for the calculation of the turbulent diffusivity of solid particles

$$E_s = 0.09ND_m^3/D_n \quad (20)$$

Using the conclusions of Kuboi, Komazawa and Otake⁹, who measured the fluctuation component of solid particle velocity in mixed vessels, and the power input characteristics of the impeller a similar procedure yields the expression

$$E_s = 0.05ND_m^3/D_n \quad (21)$$

Both Eqs (20) and (21) suggest linear dependence of turbulent diffusivity on the frequency of revolution of the impeller. Even though in the derivation of Eqs (20) and (21) a number of simplifying assumptions had been made and data from system exhibiting different geometry had been used, it was assumed that the linear dependence of turbulent diffusivity of solid particles on rpm holds for vessel mixed by a paddle impeller as well. Because Eq. (20) is based on data obtained valid for a system with properties close to those of our apparatus, the same equation was used to express turbulent diffusivity of solid particles in this work.

Theoretical Model

Transforming the equation of continuity (3) into cylindrical coordinates, substituting Eqs (5) and (6) for the calculation of the velocity of solid particles, and Eqs (10) and (20) for the calculation of the flux of particles due to the turbulence, and introducing new dimensionless variables

$$R = 2r/D_n, \quad U_R = (\bar{u}_r/ND_m), \quad U_Z = (\bar{u}_z/ND_m) \quad (22)-(24)$$

$$W = (k_w w_0/ND_m), \quad B = (E_s/ND_m D_n), \quad C = (\bar{c}/c_v), \quad (25)-(27)$$

the following differential equation for the steady state is obtained

$$U_R(\partial C/\partial R) + (U_Z - W) \partial C/\partial Z - B[(1/R)(\partial C/\partial R) + \partial^2 C/\partial R^2 + \partial^2 C/\partial Z^2] = 0 \quad (28)$$

Solution of Eq. (28) in region $0 < R < 1; 0 < Z < 1$ with the boundary conditions

$$R = 0^+ ; \quad \partial C / \partial R = 0 \quad (29)$$

$$R = 1^- ; \quad \partial C / \partial R = 0 \quad (30)$$

$$Z = 0^+ ; \quad WC + B \partial C / \partial Z = 0 \quad (31)$$

$$Z = 1^- ; \quad WC + B \partial C / \partial Z = 0 \quad (32)$$

yields the appropriate concentration distribution of the suspension. The solution though necessitates the knowledge of the velocity

$$\int_0^1 \int_0^1 CR \, dR \, dZ = 1 \quad (33)$$

field in the liquid, *i.e.* functional values of $U_R(R, Z)$, $U_Z(R, Z)$, the parameter of the terminal velocity, W , and the parameter of diffusional mixing, B .

EXPERIMENTAL

Concentration distribution of the solid phase in liquid was measured in a cylindrical vessel 447 mm in diameter with flat bottom equipped with four vertical baffles. The geometry of the vessel was identical with that used by Fořt². The batch was mixed by a three-paddle impeller with flat blades inclined at 45°. The ratio of the height of the impeller over the bottom to the height of the liquid batch was 1 : 4; the impeller-to-vessel diameter ratio was adjusted successively to the following values: 1 : 3; 1 : 4 and 1 : 5. The measurements were carried out in the range of frequency of revolution of the impeller between 4 and 13 s⁻¹. The solid phase was glass ballotini of four different diameters with corresponding terminal velocity varying between 0.02 and 0.14 m s⁻¹.

Concentration of the solid phase did not exceed 3% by vol. Liquid phase was distilled water with 0.1 kg/m³ of sodium chloride added in order to increase sensitivity of the measuring method. The measurements of concentration of the suspension were carried out by the conductivity method in the instrumentation proposed by Rosenbaum and Čermák¹⁰. The used conductivity cell was essentially a set of platinum wires of similar construction as that used by Kudrna and Vlček¹¹. The scheme is shown in Fig. 1. The probe was connected into one branch of the measuring bridge fed by AC current. The output signal of the bridge was amplified and filtered. The produced DC signal was further amplified and, after conversion to a frequency signal, recorded on a tape recorder. The convertor permitted also reverse modification of the frequency signal to the voltage signal to be processed by a data logger and punched on a paper tape. Punched tapes were processed on a TESLA 200 computer. The scheme of electronic data processing is shown in Fig. 2. Because the measured system is axially symmetric the concentrations measured were those in only one vertical section delimited by the shaft of the impeller and the wall of the vessel located half-way between two neighbouring baffles. 22 measuring points were selected in this section, their locations being shown in Fig. 3. In horizontal direction the measuring points were evenly spaced and shifted toward the wall of the vessel because the region near the wall represents larger fraction of vessel's volume. In vertical direction the selected grid of measuring

points was denser near the bottom of the vessel as the profile in the upper parts of the batch had been anticipated to be more uniform.

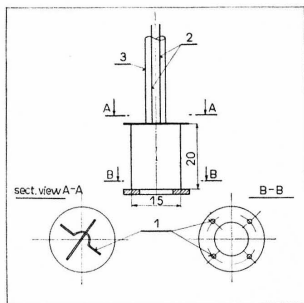


FIG. 1

Sketch of Conductivity Probe

1 platinum wires, 2 electric leads, 3 PVC tubes.

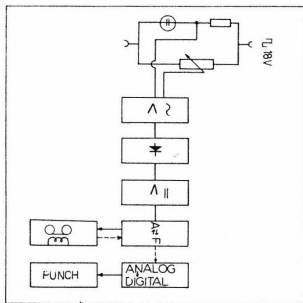


FIG. 2

Scheme of Electronic Signal Processing

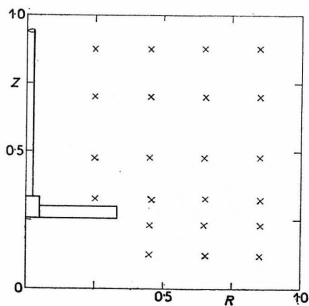


FIG. 3

Scheme of Locations of Measuring Points

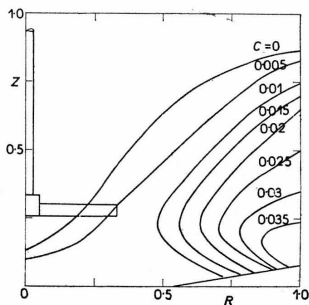


FIG. 4

Contours of Constant Concentration from Experimental Data for Subcritical Frequency of Revolution

$N = 10 \text{ s}^{-1}$, $w_0 = 0.0383 \text{ ms}^{-1}$, $D_m/D_n = 1 : 3$.

RESULTS AND DISCUSSION

The experimental results were presented earlier in detail in the form of tables in the thesis¹². The effect of intensity of mixing on the distribution of the solid phase may be apparent from Figs 4 and 5 showing the contours of constant concentration. For the speed of revolution below the critical limit, *i.e.* when a part of the solids remains unsuspended on the bottom of the vessel, the solid particles, owing to the character of the flow pattern, were swept along the bottom toward the walls and from here on upwards (suspended). In the part of the batch just above the impeller the particles moved by the action of radial component of velocity toward the center of the vessel up to a point where the terminal velocity exceeded the axial component of liquid velocity. Past this point sedimentation of particles occurred. For this reason the suspended solid phase was at low frequency of revolution (compared to the critical value) concentrated primarily at the wall while in the vicinity of vessel's axis the concentration was either low or zero (Fig. 4).

The contours of constant concentration for the frequency of revolution exceeding the critical value (Fig. 5) suggest that the assumption of negligible tangential liquid velocity component is not fully met primarily in the neighbourhood of the impeller (see the concentration maxima near the walls.) Further it may be apparent that under the given geometrical arrangement of the system it is impossible to achieve a perfectly uniform suspension. The speed of revolution of the impeller is limited by the

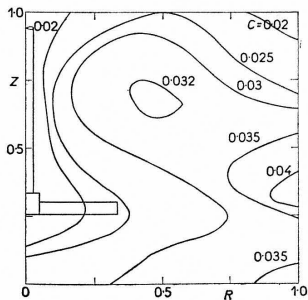


FIG. 5

Contours of Constant Concentration for Supercritical Frequency of Revolution

$$N = 13.3 \text{ s}^{-1}, w_0 = 0.0383 \text{ ms}^{-1}, D_m/D_n = 1:3.$$

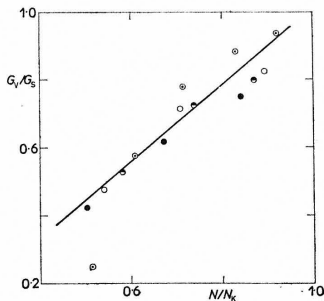


FIG. 6

Fraction of Suspended Solids as a Function of Relative Frequency of Revolution

entrainment of air at the freeboard. The tangential component of liquid velocity, causing entrainment of particles from the axis toward the wall, prevents the particles from sedimentation and, consequently, in systems exhibiting low terminal velocity the average concentration in the upper half of the vessel is higher than the average at the bottom.

The contours of constant concentration in Figs 4 and 5 pertain to particles of terminal velocity $3.83 \cdot 10^{-2} \text{ ms}^{-1}$ and the impeller whose diameter is in ratio 1 : 3 to vessel diameter. For this impeller and concentration of solids in the batch equalling 3% by volume the experiments involved also determination of the critical speed of revolution of the impeller. These data were evaluated by graphical extrapolation of the dependence of the average concentration of suspended solids on the frequency of revolution and verified by visual observation. The dependence of critical frequency of revolution on the size of the particles for the measured system was expressed by

$$N_k = \text{const. } d^{0.21} . \quad (34)$$

This correlation is in good agreement with ref.¹³⁻¹⁶ even though the investigated systems differed by the geometrical arrangement.

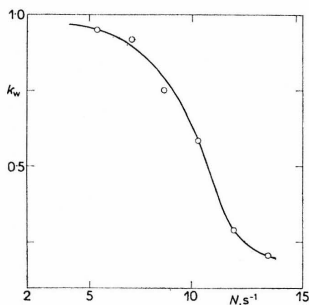


FIG. 7

Mean Correction Factor of Terminal Velocity of Suspension as a Function of Frequency of Revolution

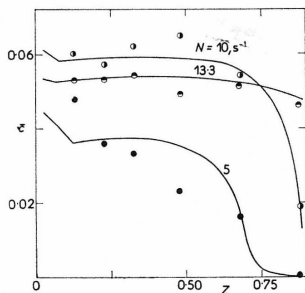


FIG. 8

Computed and Experimental Mean Concentration in a Horizontal Section as a Function of the Distance from Bottom

Curve — theoretical model, point — experimental values $w_0 = 0.0383 \text{ ms}^{-1}$, \bullet $N = 5 \text{ s}^{-1}$, $\bullet\cdot$ $N = 10 \text{ s}^{-1}$, \circ $N = 13.3 \text{ s}^{-1}$, $D_m/D_n = 1 : 3$.

Substantially more important than the dependence of the critical frequency of revolution on particle size is the dependence of the fractional amount of solids suspended on the relative frequency of revolution related to the critical frequency. From this dependence, depicted in Fig. 6, it may be apparent that for the given system the fraction of the solids suspended is a linear function of the frequency of revolution over a wide range.

Comparison of the calculated and measured distribution of concentration of the suspension called for solution of the differential equation (28) under the conditions of the experiment. The solution was performed numerically on a TESLA 200 computer using a computer program worked out by Trnka¹⁷.

The model was found rather insensitive to the variations of E_s . The evaluation of the parameter B from Eq. (26) was thus performed with a mean value of turbulent diffusivity for the whole volume of the batch, computed from Eq. (20). During evaluation of the parameter W from Eq. (25) the used terminal velocities were those found experimentally. The value U_z and U_R were obtained from the values of the stream function tabulated by Fořt³. Numerical differentiation of the stream function and the values of the velocity components in individual points of the grid have been described earlier¹². The correction coefficient, k_w , was estimated as a model parameter from experimental data so as to minimize the sum of square deviations of the measured and computed concentrations. Statistical analysis of the effect of particle size on the value of the correction factor k_w showed this effect to be insignificant in view of the experimental error involved. Accordingly, the data on the concentration distribution, obtained for individual fractions of the solids, were processed together. The values of the correction factor of the terminal velocity, corresponding to the minimum sum of square deviations of measured and computed concentrations are shown in Fig. 7.

A comparison of the measured and computed concentrations is furnished in Figs 8–10, where the calculated values are shown by curves; the experimental data by points. Fig. 8 shows the measured and calculated average concentrations of the suspension in a radial section for various speeds of revolution of the impeller in dependence on the distance from the bottom. Expected deviation of the measured and computed average concentration amounts (for the average concentration of 3% by volume) to 0–33% by volume. These dependences take a similar course also for particles exhibiting different terminal velocities. Fig. 9 shows experimental and computed local concentrations of suspension at the points corresponding to the radial coordinate $R = 0.65$ plotted *versus* the distance from the bottom for various frequencies of revolution of the impeller. For this figure it may be apparent that larger differences between the experimental and computed values occur only in region of subcritical frequencies of revolution where in spite of the same trend the experimental values are lower along the whole height than the theoretical ones. This dif-

ference appears as a consequence of incomplete suspension of the solid particles which at low frequencies of revolution are concentrated on the bottom of the vessel. Fig. 10 shows the experimental and computed local concentrations of the suspension at the points corresponding to the vertical coordinate $Z = 0.675$ in dependence on the radial distance from the center of the impeller. Maximum deviations of the experimental and computed values appear at high speed of revolution of the impeller. These deviations are attributed to the simplifying assumptions made. The model neglects the tangential component of liquid velocity and the effect of inertial forces on the solid particle. Owing to the higher density of the solid particles compared to the liquid, the effect of the inertia forces becomes manifest during tangential motion of liquid through the centrifugation of particles. Thus a region appears between the axis and the wall where the measured concentration exceeds that predicted by the model. The theoretical model utilizes the mean value of the correction factor of the terminal velocity and mean turbulent viscosity for the whole volume of the batch. In reality, the intensity of turbulence in the whole batch is not the same. Particularly not so in regions adhering to the wall where the intensity of turbulence is substantially lower than the computed mean. As a consequence, the model

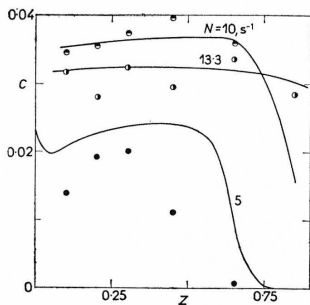


FIG. 9

Computed and Experimental Local Concentrations at Points of Radial Coordinate $R = 0.65$ as a Function of Distance from Bottom

Curve — theoretical model, points — experimental values $w_0 = 0.0383 \text{ ms}^{-1}$, ● $N = 5 \text{ s}^{-1}$, ● $N = 10 \text{ s}^{-1}$, ● $N = 13.3 \text{ s}^{-1}$, $D_m/D_n = 1 : 3$.

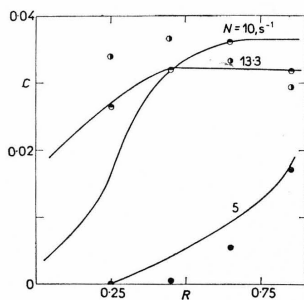


FIG. 10

Computed and Experimental Local Concentrations at Points of Vertical Coordinate $Z = 0.675$ as a Function of Radial Distance from Impeller

Curve — theoretical model, points — experimental values $w_0 = 0.0383 \text{ ms}^{-1}$, ● $N = 5 \text{ s}^{-1}$, ● $N = 10 \text{ s}^{-1}$, ● $N = 13.3 \text{ s}^{-1}$, $D_m/D_n = 1 : 3$.

in this region predicts higher concentration of the suspension, especially for particles with large terminal velocity.

As we had at our disposal only the data on the velocity field in water at 25°C the model could not be tested for nonaqueous systems. Though it may be assumed that the correction factor of the terminal velocity is generally a function of the Reynolds number, the character of this dependence cannot be safely predicted in the absence of experiments.

CONCLUSION

A theoretical model has been proposed based on the description of the velocity field in liquid enabling calculation of the distribution of the solid phase in liquid in region of low mean concentration of the suspension. The model has been tested using data on the concentration distribution of suspension in a cylindrical vessel mixed by a paddle impeller. A comparison of experimental and computed data has revealed that the proposed model predicts well the concentration distribution of the suspension both in the region of complete suspension as well as for the speed of revolution of the impeller below the critical limit. The calculation of the concentration distribution according to the proposed model requires the knowledge of mean concentration of the suspended solids, the terminal velocity of the particles and the velocity field in the liquid. At the frequency of revolution below the critical limit the mean concentration of the suspended particles can be estimated from the graphical dependence shown in Fig. 6 and from the knowledge of the critical frequency of revolution. The fractional amount of the solids suspended depends approximately linearly on the frequency of revolution of the impeller. In accord with the findings of other authors⁴, it has been established that the terminal velocity of particles in a turbulent medium significantly differs from that in a quiescent liquid. The dependence of the terminal velocity in a turbulent medium on the frequency of revolution has been expressed by the correction factor of terminal velocity whose value diminished with increasing speed of revolution. The calculation of the concentration distribution of the suspension has shown that maximum deviations of the experimental and computed concentrations occur on radial profiles in region of the plane of the impeller and in the vicinity of the liquid level. These deviations are result of the simplifying assumptions made in the derivation.

LIST OF SYMBOLS

B	dimensionless coefficient of turbulent diffusivity
c	volume concentration of solids
\bar{c}	time-averaged volume concentration of solids
c'	fluctuation component of volume concentration of solids
c_v	mean concentration in suspension

C	relative volume concentration
\bar{C}	mean relative volume concentration
d	particle diameter
D_{in}	impeller diameter
D_n	vessel diameter
E_k, E_s	coefficient of turbulent diffusivity for liquid and solids
F	dimensionless stream function
G_v	weight of suspended solids
G_s	weight of solids in system
K_k, K_s	correlation coefficient of velocity for liquid and solids
k_w	correction factor of terminal velocity
l_c	size of vortices
l_M	mixing length
N	frequency of revolution of impeller
N_k	critical frequency of revolution of impeller
r	radial coordinate
R	dimensionless radial coordinate
t	time
u	liquid velocity
\bar{u}	time-averaged liquid velocity
u'	fluctuation component of liquid velocity
\bar{u}'	mean fluctuation component of liquid velocity
\bar{u}_r, \bar{u}_z	radial and axial liquid velocity component
U_R, U_Z	dimensionless radial and axial liquid velocity component
v	velocity of solids
\bar{v}	time-averaged velocity of solids
v'	fluctuation component of velocity of solids
\bar{v}'	mean fluctuation component of velocity of solids
\bar{v}_r, \bar{v}_z	radial and axial component of velocity of solids
w	terminal velocity of a particle in turbulent medium
w_0	terminal velocity in quiescent liquid
W	dimensionless parameter of terminal velocity
z	axial coordinate
Z	dimensionless axial coordinate

REFERENCES

1. Cutter L. A.: *Thesis*. Columbia University, New York 1960.
2. Fořt O.: *This Journal* 37, 2371 (1972).
3. Fořt I.: Private communication.
4. Schwartzberg H. G., Treybal R. E.: *Ind. Eng. Chem. Fundam.* 7, 6 (1968).
5. Friedlander S. K.: *AIChE J.* 3, 381 (1957).
6. Kalinske A. A., Pien C. L.: *Amer. Geophys. Union* 24, 530 (1943).
7. Rouse H.: *Proceedings of the Fifth Intern. Congress of Applied Mechanics*. Wiley, New York 1939.
8. Schwartzberg H. G., Treybal R. E.: *Ind. Eng. Chem. Fundam.* 7, 1 (1968).
9. Kuboi R., Komazawa I., Otake T.: *Chem. Eng. Jap.* 5, 349 (1972).
10. Rosenbaum M., Čermák J.: *ÚTZCHT Research Report 34/73*, Prague 1973 (in Czech).

11. Kudrna V., Vlček J.: *Chem. Listy* 64, 263 (1970).
12. Peňáz F.: *Thesis*. Czechoslovak Academy of Sciences, Prague 1975.
13. Zwietering T. N.: *Chem. Eng. Sci.* 8, 244 (1968).
14. Nienow A. W.: *Chem. Eng. Sci.* 23, 1453 (1968).
15. Hobler T., Zablocki J.: *Chem. Tech. (Leipzig)* 18, 650 (1968).
16. Rushton J. H.: *AIChE J. Chem. Eng. Joint Meeting*, London 1965.
17. Trnka O.: Unpublished results.

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