R & D NOTES

Concentration Profiles for Solids Suspended in a Continuous Agitated Reactor

G. BALDI
R. CONTI
and
A. GIANETTO

Istituto di Chimica Industriale
Politecnico di Torino
10100 Torino, Italia

Processes involving the suspension of solid material in a liquid, such as crystallization, leaching, liquid-solid reactions, reactions with a solid catalyst, etc., are very often conducted in mechanically agitated reactors.

Agitation enables suspension to be maintained at the expense of energy dissipation, and facilitates liquid-solid mass transfer. Whereas discontinuous operations usually require nothing more than complete suspension of the particles (i.e., that particles should not be allowed to dwell for more than 1-2 seconds at the bottom of the reactor), continuous operations also necessitate quantitative evaluation of the total amount of solid in the reactor in relation to the concentration of solids in the inflow and/or outflow. If a uniform suspension were established, in fact, the solid concentration within the reactor would be equal to that in the outflow. However, since uniform suspensions are usually unobtainable unless a very high stirrer velocity is employed, concentration gradients are normally set up, with the result that a pseudo-homogeneous area, i.e., one in which the concentration is about equal to the average value, must be sought in which to site the outlet pipe.

We have previously proposed an experimental method for determining the mean residence time of a solid suspended in an agitated reactor (Baldi and Conti, 1978). This method has now been used to evaluate the vertical concentration profile of a suspension.

Pseudo-homogeneity was sought by examining a spectrum of operating conditions. Attention was primarily given to stirrer velocities greater than the minimum needed to ensure complete suspension, (N_m), to investigate the progress of the concentration profile towards greater uniformity.

In the second place, rotation speeds lower than this minimum were also studied to determine the amount of solid substance still suspended and its distribution in the reactor. This inquiry offers information on working possibility at stirrer velocities lower than N_m; in this way, there is a certain deposit of solid on the reactor bottom, but a decrease of dissipated power is obtained.

This operating way is, of course, only acceptable when there is no solid-liquid mass transfer control and the reaction does not give rise to too much heat.

EXPERIMENTAL PART

The apparatus is described in our previous paper (Baldi and Conti, 1978) and its layout can be seen in Figure 1.

The reactor geometry (Figure 2) is of a kind widely used in fundamental research.

A certain quantity of solid is poured into the reactor A, with the agitator set at a constant speed. Monomodal classes of sand particles are employed. When the suspension reaches a steady-state situation, a constant flow rate of pure liquid only is fed in and an equal suspension outflow is established through one of the outlets in the vessel wall.

The valve E is used to divert the outflow into the balloon flask C. This sample is then measured and its solid content is separated and weighed to determine the solid concentration in the outgoing flow at a given instant. The amount of liquid withdrawn is then replaced from a header container B. The entire operation repeated at predetermined intervals produces a concentration decay curve governed by an exponential law of the type:

$$c = c_o e^{-t/\tau} \tag{1}$$

where t = time elapsed since the start of the test, c_o = concentration at time O in the outflow pipe, and τ = the mean residence time of the solid.

Equation 1 was shown to be valid for each withdrawal point, solid initial concentration and stirred velocity. Both c_o and τ, on the other hand, are affected by these parameters.

Least squares interpolation of the experimental values for c in accordance with Eq. 1 leads to the simultaneous determination of c_o and τ. An example of this type of evaluation is illustrated in our earlier paper

Correspondence concerning this paper should be addressed to A. Gianetto.

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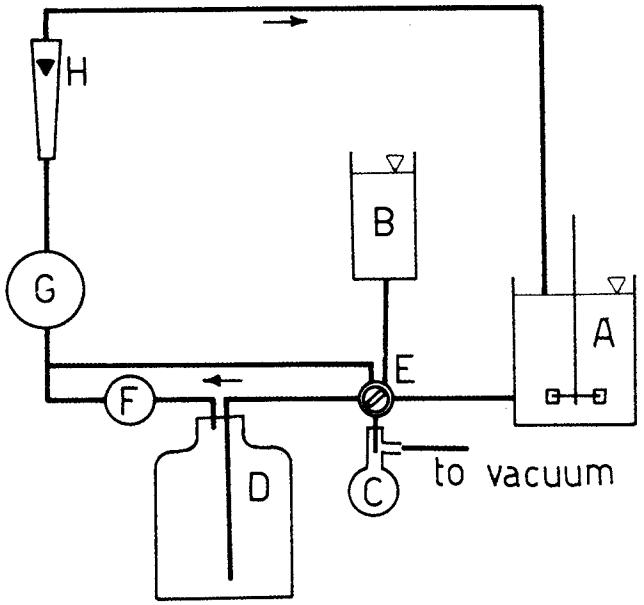

Figure 1. Experimental apparatus layout—*A* = stirred vessel; *B* = reservoir for replacement of liquid samples; *C* = sample bottle; *D* = sedimentation tank; *E* = four-way valve; *F* = filter; *G* = pump; *H* = flowmeter.

TABLE 1.

Symbol	D_p 10^{-3}m	$\bar{c}_o$ kg/m^3	N/N_m	c_{o1} kg/m^3	c_{o2} kg/m^3	c_{o3} kg/m^3	c_{o4} kg/m^3	c_{o5} kg/m^3	$\bar{c}_{os}/\bar{c}_o$
○	0.24	4.9	0.5	7.80	1.45	0.76	0.48	0.35	0.38
◐	0.24	4.9	0.75	16.00	2.88	2.75	2.83	0.74	0.51
⊖	0.24	4.9	0.875	18.90	5.34	4.78	2.72	9.97	0.97
⊙	0.24	4.9	1	14.00	6.80	5.50	4.95	3.00	1.06
⊕	0.24	4.9	1.5	12.50	6.70	6.50	5.80	3.80	1.15
⊗	0.24	4.9	1.8	9.46	6.96	5.27	5.07	4.03	1.04
◓	0.24	4.9	2	9.35	5.62	5.87	6.35	4.43	1.07
◒	0.24	4.9	2.1	8.87	5.17	5.50	5.07	4.59	1.04
□	0.24	20	0.5	42.48	8.56	7.32	6.25	4.19	0.38
◫	0.24	20	0.75	67.64	19.85	19.70	17.91	7.48	0.86
⊟	0.24	20	0.875	56.42	25.21	20.35	19.78	10.61	0.98
⊡	0.24	20	1	52.12	26.29	18.98	23.38	0.03	0.99
⊞	0.24	20	1.25	52.50	25.44	23.89	24.71	14.45	1.07
△	0.24	30	0.5	38.70	23.43	23.38	21.60	12.17	0.62
◭	0.24	30	0.75	78.57	33.82	30.83	25.96	11.19	0.84
◬	0.24	30	0.875	73.49	43.51	33.33	33.71	10.82	1.11
△	0.24	30	1	64.07	36.91	34.34	32.92	16.17	1.02
⧋	0.24	30	1.54	56.05	34.27	33.08	26.18	23.20	0.93
▽	0.385	20	1	87.03	28.12	24.90	23.71	12.03	1.11
▼	0.385	20	1.33	56.06	28.87	24.16	24.00	9.58	1.07
▽	0.385	20	1.60	52.50	23.34	21.93	20.16	11.16	0.91
◈	0.089	4.9	0.75	6.56	5.02	5.23	3.71	4.83	0.90
◇	0.089	4.9	1	6.30	5.05	4.57	4.89	4.09	0.88
◈	0.089	4.9	1.5	6.13	4.71	5.41	5.20	3.95	0.90
⊙	0.089	20	1	24.80	20.24	20.82	20.13	17.20	0.91
⊙	See Baldi and Conti, 1978								

(Baldi and Conti, 1978). The validity of the values obtained was checked by the mass balance between the outgoing solid and that initially placed in the reactor $V\bar{c}_o$:

$$F\int_0^\infty c\,dt = V\bar{c}_o \tag{2}$$

By substituting Eq. 1 to Eq. 2 and integrating, we obtain:

$$\frac{c_o}{\bar{c}_o} = \frac{1}{\tau}\frac{V}{F} \tag{3}$$

The two terms of Eq. 3 displayed a very close fit in every test (Baldi and Conti, 1978).

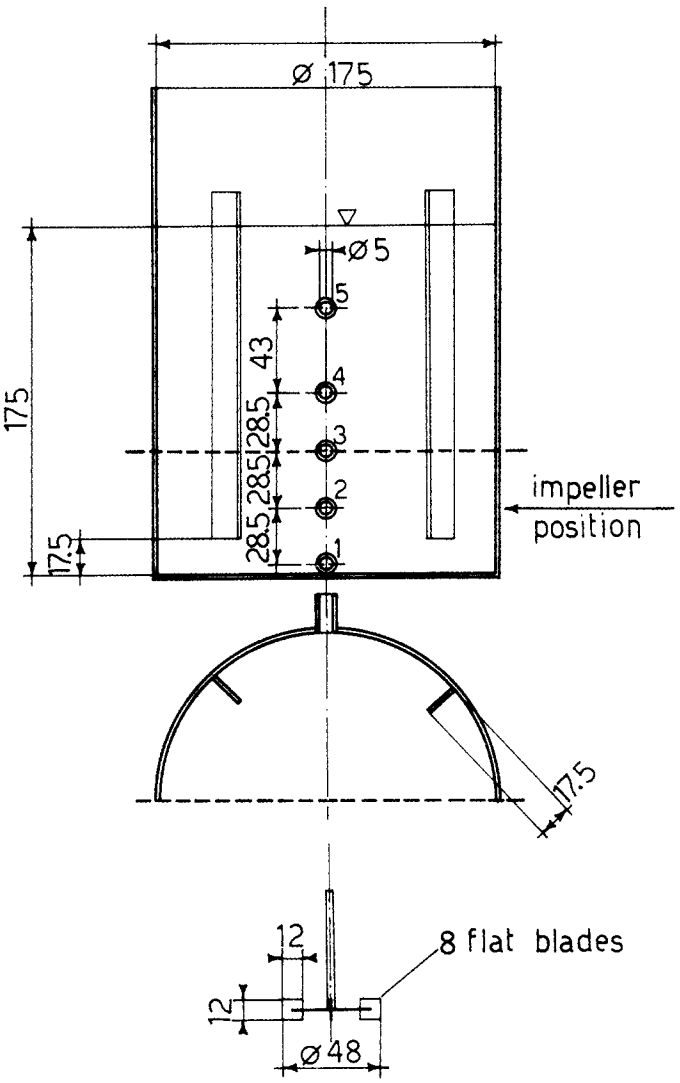

Figure 2. Stirred vessel with its major dimensions (in mm).

The results are set out in Table 1, in which D_p = particle diameter, $\bar{c}_o$ = mean initial concentration in the vessel, N/N_m = ratio between the stirrer speed and the minimum speed required for complete suspension, and c_{oi} (i = 1-5) = the concentration at time O at each of the five withdrawal points (Figure 2). The table also sets out the symbols used to indicate the results of each test in Figures 3-6.

The c_{oi} values for each test have been plotted as a function of the dimensionless distance Z from the bottom of the reactor. Direct observation showed that near the liquid surface the solid concentration was negligible. If, as a first approximation, it is assumed that the c_{oi} values are representative of the average concentration in the vessel for their respective cross-sections, the integral $\int_0^1 c_o dZ$ should represent the mean initial concentration of the actually suspended solid $\bar{c}_{os}$. When $N/N_m > 1$, this is very close to $\bar{c}_o$ (mean deviation ±7.8%; max ±15%), suggesting that the hypothesis put forward is valid and that the experimental method adopted to measure the vertical concentration profile is sound. When N/N_m is less than 1, $\bar{c}_{os}$ is less than $\bar{c}_o$.

The difference shows how much is deposited in the bottom. The value for $\bar{c}_{os}/\bar{c}_o$ are also included in the table.

The technique used to measure N_m for each particle size and concentration has already been reported (Baldi et al., 1978; Conti and Baldi, 1978).

CONCENTRATION PROFILES FOR $N/N_m > 1$

Figure 3 illustrates the dimensionless vertical concentration profiles for $N = N_m$ at various solid mean sizes and concentrations. Our present data offer further evidence of the fact that the dimensionless profiles at the minimum speed for complete suspension do not depend on the concentration in the $\bar{c}_o$ range

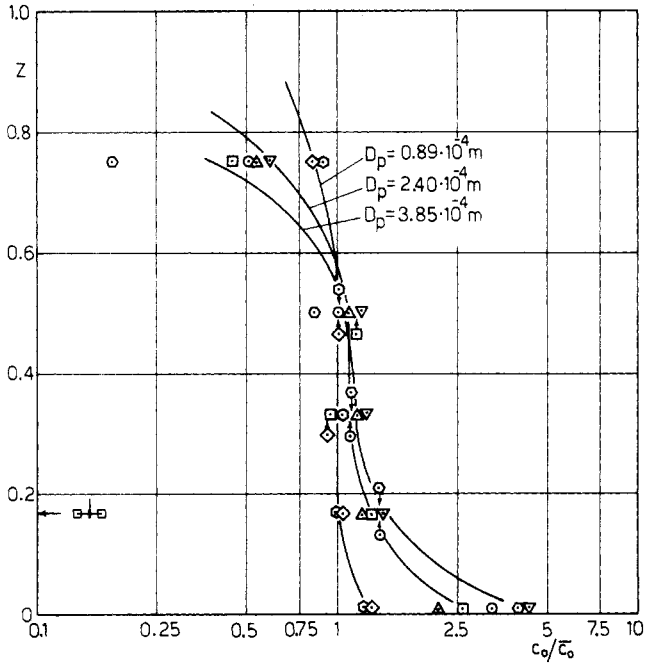

Figure 3. Solid concentration profiles for various particle sizes and mean concentrations.

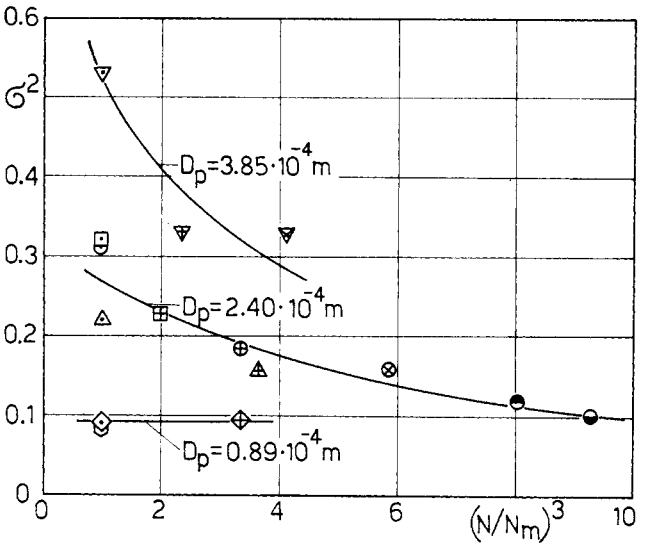

Figure 4. Variance of solid concentration as a function of N; the Keys of the figure are listed in table 1.

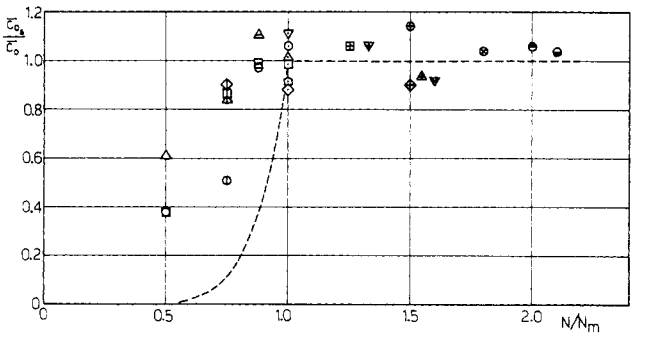

Figure 5. Suspended solid concentration vs. N/N_m; - - - = Eq. 7.

we investigated (Baldi and Conti, 1978). Their gradients do, on the other hand, increase with the diameter D_p.

It should be noted, however, that when $Z = 0.25 - 0.55$, $c/\bar{c}_o$ is more or less constant and very close to 1 (area of pseudo-homogeneity).

As N increases, the suspension becomes more uniform, and the c_o values at the fringe withdrawal points become close to the mean.

The homogeneity degree was evaluated by introducing the index σ^2:

$$\sigma^2 = \sum_{i=1}^{5} \left[\frac{c_{oim}}{\bar{c}_{os}} - 1 \right]^2 \cdot \Delta Z_i \qquad (4)$$

where

$$c_{oim} = \frac{c_{oi} + c_{oi+1}}{2} \qquad (5)$$

and ΔZ_i is the dimensionless distance between i and $i + 1$.

As already stated, the skin concentration was assumed to be negligible. σ^2 represents the concentration profile variance with respect to that of a homogeneous suspension.

The value $\bar{c}_{os}$ used in Eq. 4 is taken from the integration of the experimental profile to offset any measurement error.

Figure 4 shows σ^2 in function of $(N/N_m)^3$. The parameter on the x axis represents the ratio between the power dissipated at a certain number of revs and that dissipated at N_m.

As can be seen, σ^2 decreases (i.e., the system becomes more homogeneous) as the power rises and D_p becomes smaller, whereas it is virtually unaffected by the concentration.

With respect to the effect of N, it may be noted, for example, that a tenfold increase in power (by comparison with that required when suspension is complete) is needed to obtain the same degree of homogeneity with 2.4×10^{-4}m particles as that obtained with 8.9×10^{-5}m particles.

In practical terms, this means that it is inadvisable to aim at a greater degree of uniformity than that obtained with $N = N_m$ unless the process involved demands a particular degree of homogeneity, since this would lead to a heavy increase in cost due to dissipated power.

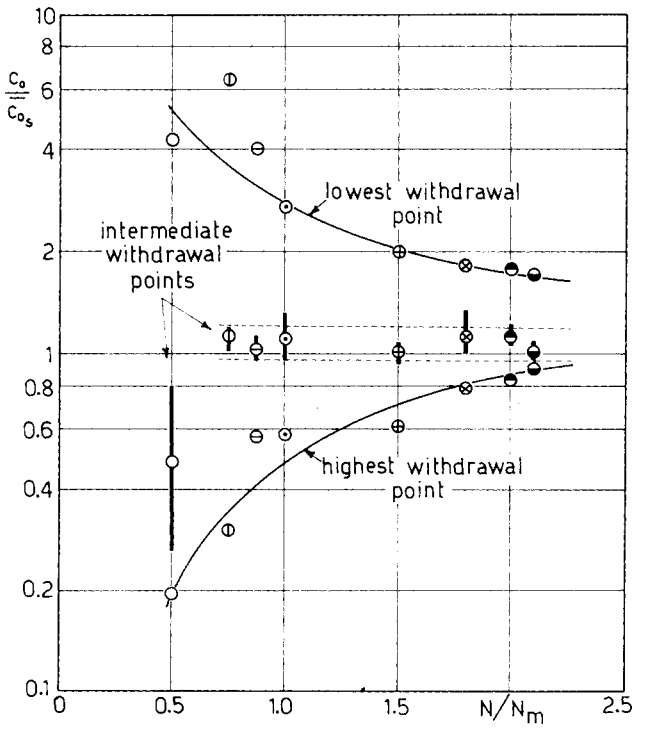

Figure 6. $\bar{c}_o/\bar{c}_{os}$ vs. N/N_m for $D_p = 2.4 \times 10^{-4}$m particles; the Keys of the figure are listed in table 1.

INFLUENCE OF N ON THE AMOUNT OF SOLID SUSPENDED

Fig. 5 plots the values for $\bar{c}_{os}/\bar{c}_o$ in function of N/N_m for 2.4×10^{-4}m particles. When N is greater than N_m, $\bar{c}_{os}$ is sufficiently equal to $\bar{c}_o$. When it is smaller, $\bar{c}_{os}$ is less than $\bar{c}_o$, because the energy supplied by the agitator is not enough to keep all the solid in suspension. Earlier work (Baldi et al., 1978; Conti and Baldi, 1978) has shown that, if all the other variables are equal, N_m depends on the solid concentration in accordance with

$$N_m \propto B^{0.134} \tag{6}$$

where B = solid concentration as solid weight per unit of liquid weight per cent. If Eq. 6 is used to determine the solid concentration that can be completely suspended for every $N < N_m$, one obtains

$$\frac{B_s}{B} = \frac{\bar{c}_{os}}{\bar{c}_o} = \left(\frac{N}{N_m}\right)^{\frac{1}{0.134}} \tag{7}$$

The curve calculated with Eq. 7 is shown as a broken line in Figure 5. According to this model, $\bar{c}_{os}/\bar{c}_o$ should fall rapidly as N/N_m decreases. By contrast, the experimental values display a slower fall that only begins when N/N_m is about equal to 0.9.

There is a degree of uncertainty in the experimental determination of $\bar{c}_{os}$ for $N < N_m$, due to the difficulty of obtaining a reliable value for the withdrawal point immediately above the bottom of the vessel. This is because the high concentration in this area means that the continuous extraction of particles rapidly leads to a transition from incomplete to complete suspension.

This can be responsible for over evaluation of c_o, especially at withdrawal point 1, and hence of $\bar{c}_{os}$ as well.

A part from this, the discrepancy between the theoretical and the experimental values is probably due to the inadequacy of the model as a description of the phenomenon. Equation 6, in fact, is only valid when there is complete suspension, i.e. when there are no more than a few, briefly resident (1-2 s) particles on the bottom, whereas when $N/N_m < 1$, there are heavy deposits, and it becomes easier to lift particles, if only on statistical grounds. The experimental pattern, at all events, suggests that an energy saving of nearly 50% could be obtained by operating at $N \simeq 0.8\ N_m$ and $\bar{c}_o = 1.2 - 1.3$ times the desired suspended solid concentration.

PSEUDOHOMOGENEITY CONDITIONS

We have already seen that complete suspension is associated with a pseudohomogeneity zone for $Z = 0.25 - 0.55$ (i.e., from a distance a little above withdrawal point 2 to point 4).

This zone persists (obviously) when $N > N_m$, and also when N is not much lower than N_m (up to $N/N_m = 0.75$), though here pseudohomogeneity is related to $\bar{c}_{os}$. By way of example, Figure 6 presents the experimental $c_o/\bar{c}_{os}$ values for 2.4×10^{-4}m particles at $\bar{c}_o = 4.9$ kg/m^3. The three intermediate withdrawal points (c_{o2}, c_{o3}, c_{o4}) were gathered into a single point to represent their mean value and integrated with the variation interval between them. The points above and below the pseudohomogeneity band obviously refer to the other two withdrawal points (point 1 and 5).

When $N/N_m = 0.5$, the pseudohomogeneous zone does not exist, but is obtained well enough starting from $N/N_m = 0.75$.

Vice versa, it may already begin to form for $N/N_m = 0.5$ when the concentration is higher (Table 1) though it will be marked by a certain degree of instability.

CONCLUSIONS

The first conclusion to be drawn from the results is that the experimental method adopted appears to be sufficiently reliable for the determination of the vertical concentration profiles of a suspended solid. There may, of course, be radial or tangential gradients in the reactor, especially when baffles are present. The finding obtained must thus be regarded as a mean value that is particularly meaningful for continuous reactors, since the experimental was conducted in a manner that was reasonably similar to their operating conditions. It will in any event be supplement by work on apparatus more closely modelled on the geometries used on the industrial scale.

For a given agitation system geometry and for constant physical properties and flow rate of the suspending liquid, the concentration profiles depend on the speed of the stirrer and the size of the particles. They are, however, independent of the mean concentration in the reactor (especially when $N > N_m$), if the profile is referred to N/N_m.

The minimum stirrer velocity for complete suspension seems to be a correlation parameter for the degree of the homogeneity of a suspension for a given particles size and density.

As N increases, the homogeneity increases, but the result obtained does not offset the higher cost incurred for the dissipated power. In this respect, the results show that one can even operate at slightly below N_m and thus save a considerable amount of energy, without causing a heavy deposit on the bottom.

As far as the problems peculiar to continuous reactors are concerned, it may be noted that the vessel employed has a rather extensive area of pseudohomogeneity from which the suspension may be continuously withdrawn, without thereby causing such an excessive accumulation of solid material as to bring the mean internal concentration to a value very different to that in the outflow.

NOTATION

B	=	concentration of suspended solid for $N = N_m$, wt. %.
B_s	=	concentration of suspended solid for $N < N_m$, wt. %.
c	=	solid concentration in the vessel, kg/m^3.
c_{oi}	=	solid concentration at time zero, near the i-th withdrawal point, kg/m^3
$\bar{c}_o$	=	mean concentration of solid in the vessel at time zero, kg/m^3
$\bar{c}_{os}$	=	mean suspended solid concentration for $N < N_m$, at time zero, kg/m^3
D_p	=	particles diameter, m
F	=	liquid flowrate, m^3/s
N	=	rotation speed of the stirrer, rps
N_m	=	minimum stirrer velocity for complete suspension, rps
t	=	time, s
V	=	liquid volume in the vessel, m^3
Z	=	distance from the vessel bottom, dim. less
τ	=	mean residence time of solid, s
σ^2	=	variance of the concentration profile, dim. less

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