Continuous Mixing of Fine Particles

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A series of experimental studies on continuous mixing of fine particles has been done by using a vertical cylinder mixer with a variety of impellers. It has been found that the principle of designing an effective impeller for continuous mixing is to give intensive radial mixing without increasing axial mixing, while keeping a large holdup of the particles to be mixed. It has also been shown that a well designed vibratory feeder with a proper feedback control system can be used to maintain the feed rate of fine and cohesive powders into the continuous mixer at a constant rate.

1. Introduction

An effective solution to satisfy a demand for mass production of particulate solid mixtures in a variety of industries is to take a continuous mixing process. Continuous solids mixing can reap the full advantages of; (1) a large throughput of materials for less plant space and less labor costs, (2) possible improvement of air pollution problems by taking a closed system, and (3) easiness of introducing a process control system into the process.

The most difficult problem in operating a continuous solids mixing process is to keep the feed rate of particulate materials into the mixer as constant as possible. Furthermore, if fine and cohesive powders are to be mixed, a careful attention should be paid to design of impellers of solids mixers.

This paper presents a continuous mixing system of fine and cohesive powders, which is provided with a specially designed impeller and feeder control systems.

2. Experimental

The schematic diagram of the experimental setup is shown in Fig. 1. The mixer consists of a vertical cylinder (1) (made of methylmetacrylate resin, inner diameter = 12 cm and height = 50 cm) and an impeller (2) (outer diameter = 11.8 cm). The electrical vibratory feeders, (3) and (4), and the discharger (5) are installed at the inlet and outlet of the mixer. A rotational motion of the impeller is provided by the electric motor with a reducer (8).

Fig. 2 shows the impellers used. Their dimensions are summarized in Table 1. The impeller RA consists of multi-divided double helical blades. The impellers X-I and X-II

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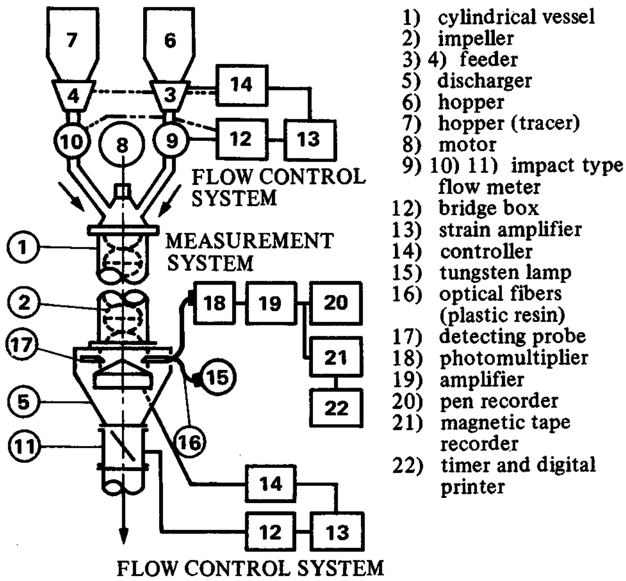


Fig. 1. Experimental setup

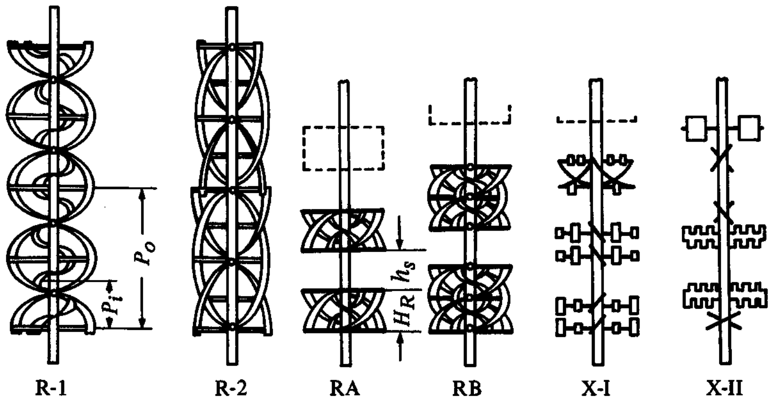


Fig. 2. Impellers employed in the present study

are made from small comblike blades of a simple structure.

The materials used are glass powders and the powders of calcite and red iron oxide. Their properties are summarized in Table 2.

The experiments were carried out in the following manner: The mixer was filled with the bulk powder (white glass particles or white calcite powder) and the inlet flow rate, F [gr/s], of the bulk powder was controlled to become equal to the flow rate at the outlet. After the powder holdup, V [gr], reached a steady state, a part (usually one

Table 1. Dimensions of impellers

Ribbon type	Outer ribbon			Inner ribbon			Ribbon Height
	Diameter D_o [cm]	Width of blade b_o [cm]	Pitch P_o [cm]	Diameter D_i [cm]	Width of blade b_i [cm]	Pitch P_i [cm]	H_R [cm]
R-1 (a)	11.8	0.7	6.0	7.9	1.0	2.0	36.0
R-1 (b)	11.8	0.95	18.0	7.9	1.24	6.0	36.0
R-1 (c)	11.8	1.5	18.0	7.9	1.70	6.0	36.0
R-1 (d)	11.8	0.7	18.0	7.9	1.0	6.0	36.0
R-2	11.8	1.0	36.0	9.8	1.0	36.0	36.0
R A	11.8	1.5	20.0	7.7	1.5	10.0	6.0
R B	11.8	1.5	16.0	7.7	1.5	8.0	9.0
X-I	11.8	1.0	–	–	0.7	–	4.0
X-II	11.8	0.6	–	–	0.6	–	6.0

Table 2. Physical properties of solid particles

Material	Range of diameter [μm]	Mean diameter [μm]	Density of particles			Angle of repose [deg]	Flow-ability
				Apparent			
			[gr/cm^3]	Loose	Pack		
Glass particles	177–350	260	2.50	1.42	1.46	40.0	good
Calcite	1–150	16.5	2.70	0.88	1.37	71.0	poor
Red iron oxide	0.1–1.0	0.3	3.50	0.55	1.03	70<	poor

tenth) of the bulk inlet particles was replaced stepwise by the tracer material (dyed glass particles or red iron oxide) without changing the total flow rate F. Then, the concentration of dyed glass particles or red iron oxide at the outlet of the mixer was measured by an optical method to check the degree of mixing.

2.1 Feeding system

It is very difficult to feed fine and cohesive powders, and especially small amounts of trace elements, at a constant rate. In the present study, a control system with electrical vibratory feeders has been developed as shown in Figs. 3 and 4. The feeder is a commercially available one (FLO-TRON of Hosokawa Iron Works) modified to improve its capability of handling fine and cohesive powders. A couple of combinations of the feed tubes and the troughs including the effect of the ring weir has been tested and the configuration as shown in Fig. 3 has been found to be best.

The flow rate is detected by measuring the impulsive force the powder particles exert to an impacting plate. The plate is supported by an elastic beam on which a pair of strain gauges is sticked (Fig. 4). The electrical signal from the strain amplifier is filtered and is compared with a reference which determines the flow rate. The difference bet-

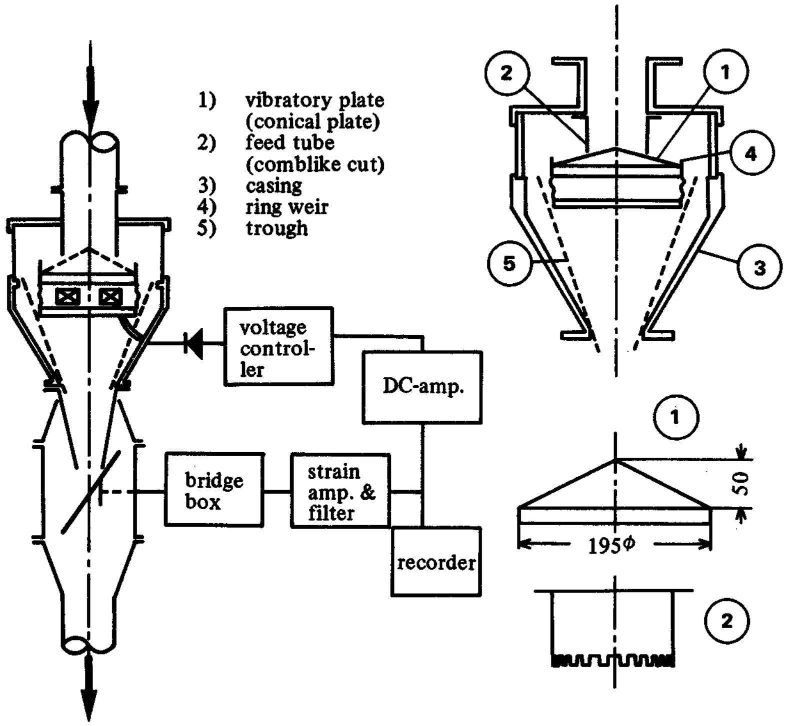
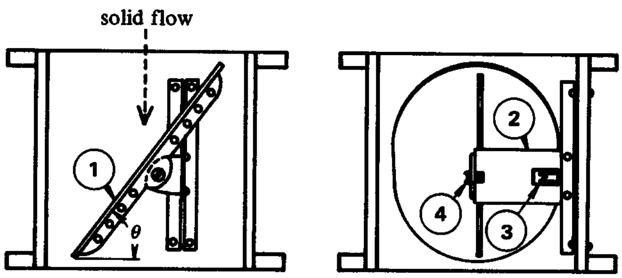


Fig. 3. Control system and electrical vibratory feeder



1. impacting plate
2. elastic beam
3. strain gauge
4. setting screw

Fig. 4. Impact line flow meter

ween the signal and the reference is fed to the servomechanism controlling the driving energy of the electrical vibratory feeder. The performance of this control system is illustrated in Fig. 5, where the flow rate under control is compared to that without control under identical experimental conditions.

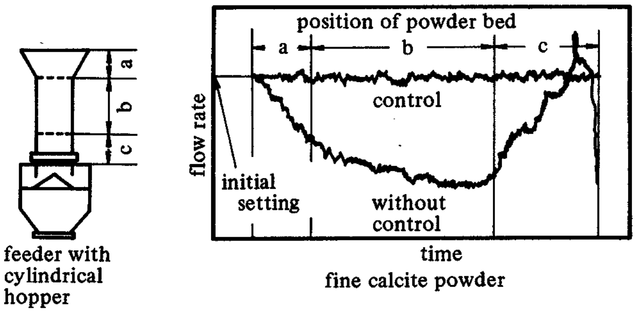


Fig. 5. Performance of feeder control system

2.2 Measurement of degree of mixing

The system for measuring the outlet tracer (dyed glass particles or red iron oxide) concentration consists of optical fibers (CROFON–plastic resin made) and six detecting spots at the outlet of the mixer as shown in Fig. 1. The light beam from a tungsten lamp is projected onto the powder mixture covering the detecting spots. The reflected light from the mixture is guided into the photomultiplier to measure its intensity. Reflection characteristics of powder particles are highly influenced by the tone of a color and the conditions of their contacting with the detectors. Therefore, for every experimental run, the relationship between the output voltage of the detector and the concentration of the tracer in mixture was calibrated by measuring a series of mixtures of known concentrations.

The step response of the tracer at the mixer outlet has been usually recorded as an S-shaped curve as shown in Fig. 6. The steady state performance of a continuous solids

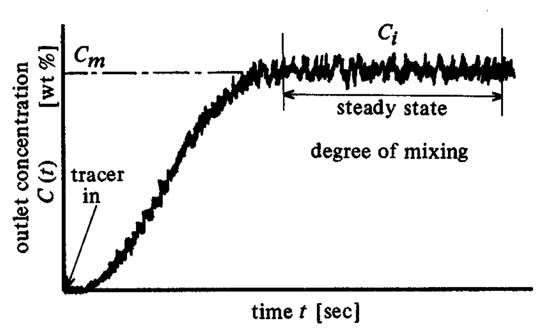


Fig. 6. Recording of tracer concentration at outlet of mixer

mixer can be evaluated from continuous recording of the steady state fluctuations in the outlet tracer concentration, $C(t)$. Then, the degree of mixing, M, may be defined by

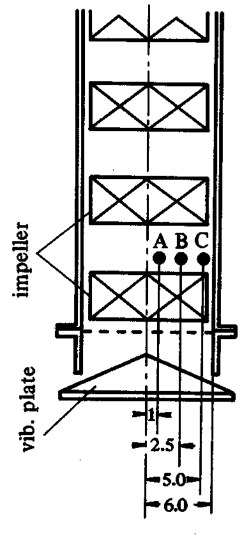
$$M = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{C_i}{C_m} - 1\right)^2\right]^{1/2}, \tag{1}$$

where

$$C_m = \frac{1}{n}\sum_{i=1}^{n} C_i \quad \text{(mean value of } C \text{ at steady state)} \tag{2}$$

and C_i is a randomly sampled value of C, n the number of the samples (usually $n \geq$ 100). The smaller the value of M, the better the degree of mixing is[1].

Generally speaking, however, the degree of mixing in continuous mixing should be assessed by the spatial distribution of tracer concentration as in the case of batch mixing, and equating the standard deviation of the spatial fluctuation to that of the time fluctuation needs the assumption that all the possible states of the tracer concentrations along with the spatial coordinates, especially along with the radial position in the mixer, should appear at the mixer outlet as time passes. Fig. 7 shows the averages, C_m, and the standard deviations, M, of the time series of tracer concentration at several radial positions in



X–I impellers 4 stages
Calcite Red iron oxide
9 : 1
$F = 10$ [gr/s]
sampling point between
3rd and 4th
A : 1.0 cm from center
B : 2.5
C : 5.0

	C_m [wt%]	σ^2	$M = \sigma$
A	9.83	1.82×10^{-4}	0.0135
B	9.79	1.90×10^{-4}	0.0138
C	9.86	1.74×10^{-4}	0.0132

Fig. 7. Degree of mixing at several radial positions in mixer.

the mixer. As can be seen, C_m's and M's, respectively, at the points A, B and C, agree well with each other. Then, if the probability distribution of the concentration fluctuation with time, $C(t)$, is normal or Gaussian, the identical stochastic phenomena can be expected to be observed at the points A, B and C. Fig. 8 gives the results of the test if the distribution is normal. When the degree of mixing is good, the distribution can be well approximated by the normal curve as shown in Fig. 8. When the degree of mixing is poor, however, the distribution is skewed and even periodic variations have been observed in some cases. Therefore, the distribution of the tracer concentration fluctuation at

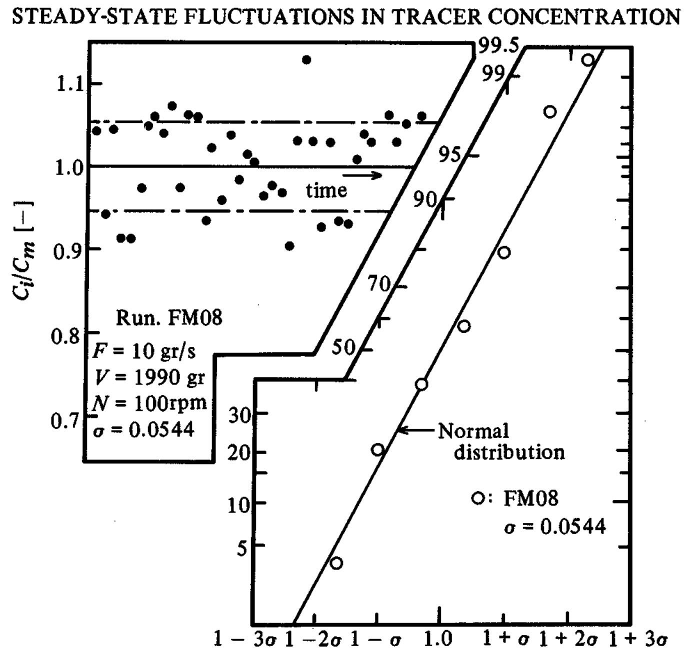


Fig. 8. Plots in normal probability paper of steady state fluctuations in tracer concentration

steady state has been checked for every experimental run. After these observations, it has been decided to utilize the standard deviation as defined in Eqs. (1) and (2) of the concentration fluctuation time series as the degree of mixing for evaluating the performance of the continuous mixer.

3. Results and discussion

In Table 3, the characteristics of mixing in the continuous mixer are compared with

Table 3. Characteristics of mixing in continuous and batch mixers

Ribbon type	Batch		Continuous	
	θ_∞ [sec]	M_∞ [–]	$(V/F)_\infty$ [sec]	$M_{c,\infty}$ [–]
R-1 (a)	108	0.044	110	0.052
R-1 (b)	120	0.031	95	0.034
R-1 (c)	90	0.043	95	0.030
R-1 (d)	210	0.035	225	0.032
R-2	36	0.033	45	0.042

those in the corresponding batch mixer for various impellers. In this table, the mean residence time in the continuous mixer, V/F, is regarded as identical with the time of mixing in the batch mixer, θ. M_∞ or $M_{c,\infty}$, respectively, denote the final degree of mixing which can be attained in the batch or continuous mixer with enough time of mixing (θ_∞) or mean residence time ($(V/F)_\infty$). As can be seen from this table, the impellers suitable for batch mixing are not always good for continuous mixing. In other words, the impellers capable of giving vigorous agitation in both axial and radial directions (the impellers R-1 and R-2) are effective to batch mixing. On the other hand, only radial mixing is desirable in continuous mixing, since axial mixing lowers the volume efficiency of a continuous mixer as in the case of continuous flow chemical reactors[2]. This is the reason why the impellers RA, RB, X-I and X-II have been devised for use in continuous mixers. Fig. 9 shows the effect of the number of stages (the number of the blades) on the degree of mixing of the glass powders in the continuous mixer with the impellers RA and RB (the multi-divided double helical ribbon blades[3]). In this figure, M_∞ is the final degree of mixing obtained by the corresponding batch mixer. As the number of stages increases, the degree of mixing approaches to M_∞ except in the case of $h_s = 3$ cm. This effect of the clearance between stages, h_s, on the degree of mixing, M, as shown in Fig. 9 also implies the importance of reducing axial mixing in continuous

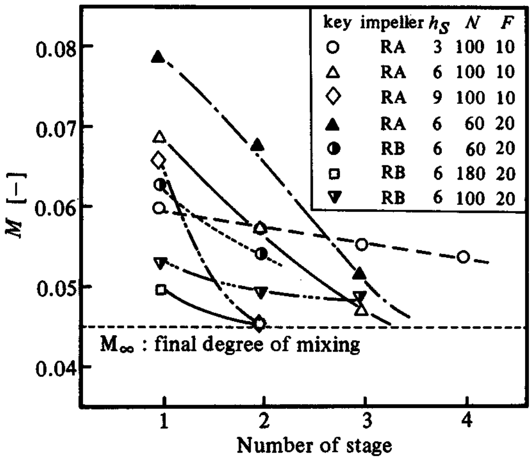


Fig. 9. Effect of number of stages on degree of mixing (glass powders)

mixers without reducing radial mixing.

On the other hand, in case of continuous mixing of the fine and cohesive powders containing the particles of less than 16 μm in diameter such as calcite and red iron oxide, it has been found that the impeller RA does not work well. Because of their poor flowability and tendency to agglomerate, the powders were trapped in the impeller structure and sticked to the mixer wall. A large number of dead zones were then easily formed around the impeller and at the vessel wall and almost no effective motion of the powders was observed.

On the contrary, the impellers X-I and X-II were able to generate a strong shear force field around the comblike blades and to mix the powders vigorously. It has also been noted that a simple structure of the impellers prevents the powders from being trapped by and sticking to the blades.

Fig. 10 shows the effect of the mean residence time, V/F, on the degree of mixing,

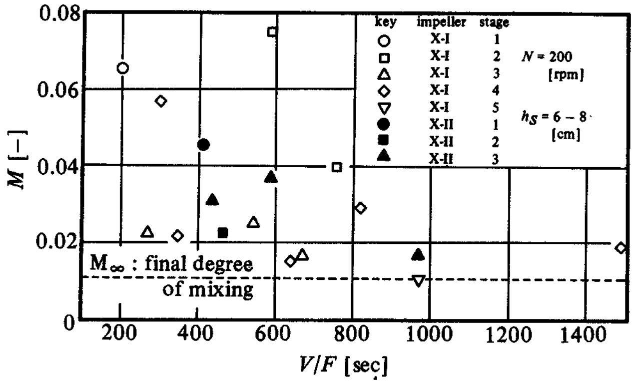


Fig. 10. Effect of mean residence time on degree of mixing (calcite and red iron oxide)

M. It can be seen from the figure that, M decreases toward M_∞ (the final degree of mixing attainable with the batch mixer) as V/F and/or the number of stages (blades) increases, and an impeller with three to four stages may be expected to give a satisfactory performance.

The effect of the rotational speed, N [r.p.m.], on M is illustrated in Fig. 11. The value of M decreased linearly at an early stage as N increased, and at $N = 150$ or

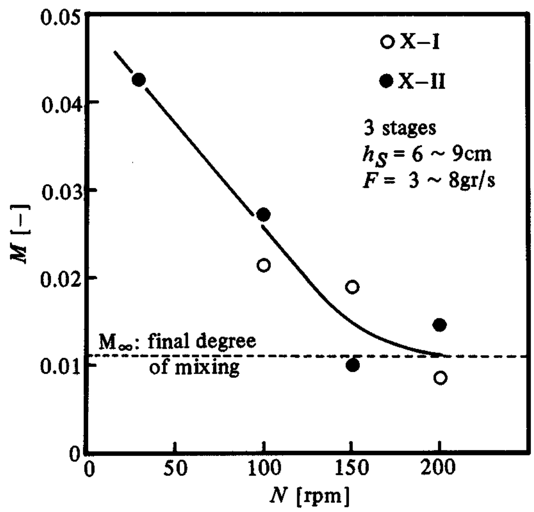


Fig. 11. Effect of rotational speed on degree of mixing (calcite and red iron oxide)

more, M became equal to M_∞. This results show that the impeller rotating at higher speed fluidizes the fine particles bed in the mixer to give a good mixing.

Fig. 12 shows the relations between the degree of mixing and the number of stages (separated blades) for the impellers X-I and X-II, in the case of N = 200 [r.p.m.]. The

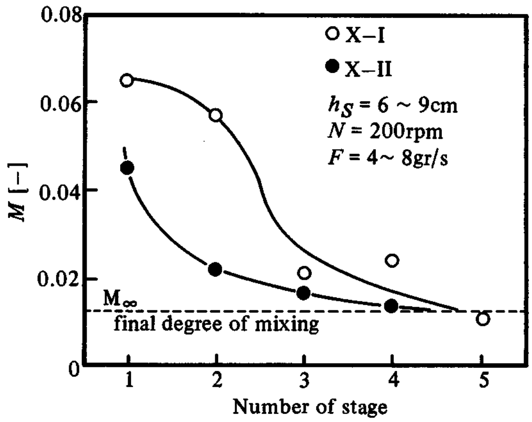


Fig. 12. Effect of number of stages on degree of mixing (calcite and red iron oxide)

dotted line in this figure gives the final degree of mixing attainable with the batch mixer.

4. Conclusion

The principle of designing an effective impeller for continuous mixing is to give intensive radial mixing (in the direction perpendicular to the direction of bulk powder flow) of solid particles without increasing axial mixing (in the direction of bulk powder flow), while keeping a large holdup of the solid particles.

On the basis of this principle, the new types of impellers suitable for continuous mixing of fine and cohesive powders have been developed and their performance has been evaluated by means of the tracer technique. The impeller with multistage comblike blades has proven effective. It has also been shown that, a properly designed vibratory feeder with a suitable feedback control system can be used to keep the feed rate of fine and cohesive powders into a continuous mixer at a constant value.

Notation

b_i	:	width of inner ribbon	[cm]
b_o	:	width of outer ribbon	[cm]
C_i	:	outlet concentration of tracer	[wt %]
C_m	:	mean concentration	[wt %]
D_i	:	diameter of inner ribbon	[cm]

D_o	:	diameter of outer ribbon	[cm]
F	:	flow rate	[gr/s]
H_R	:	height of ribbon	[cm]
h_s	:	clearance between stages (separated blades)	[cm]
M	:	degree of mixing	[–]
M_∞	:	final degree of mixing in batch mixing	[–]
$M_{c,\infty}$	:	final degree of mixing in continuous mixing	[–]
N	:	rotational speed	[r.p.m.]
n	:	number of samples	[–]
P_i	:	pitch of inner ribbon	[cm]
P_o	:	pitch of outer ribbon	[cm]
t	:	time	[s]
V	:	holdup of solids	[gr]
θ	:	time of mixing in batch mixer	[s]
σ	:	standard deviation of concentration fluctuation	[–]

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