Indian Journal of Chemical Technology
Vol. 6, March 1999, pp. 100-106

Residence time distribution of solids in a fluidised bed

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Received 21 November 1997; accepted 23 February 1999

The present work involves an experimental investigation on residence time distribution of solids in a continuous fluidised bed for uniform size and for binary solid mixture at different dilutions. The column was tested for improvement in performance with increase in dilution. The effect of gas flow rate, solids flow rate and dilution on the first, second and third moments and on F-curves have been determined. Fractional tank extension model fits the experimental data. High values of N as dilution increases, indicates reduced solids mixing, thus reducing spread of residence times, giving rise to more uniform quality of product. The work finds importance in that similar improved performance of the column using internals inside the bed can be obtained by using a mixture of solids rather than uniform size.

Fluidised beds find wide applications due to uniform temperature throughout the bed because of solids mixing. But this rapid solids mixing in the bed leads to non-uniform residence times of solids in the reactor. For continuous treatment of solids, this gives non-uniform product and lower conversions, especially at higher conversion levels. Despite its serious drawbacks, fluidised beds have been widely used by making modifications inside the bed. One such modification is to section the bed horizontally[3] or vertically[9], known as a multistage fluidised bed or using a spiral internal to make it a spiral fluidised bed[8]. These modifications have been made to reduce the gross irregularities and instability of the bed induced by the gas flow.

The present work is aimed at reducing the spread of residence times in a single stage flat fluidised bed, which is achieved by using a binary solid mixture. The uniform sized particles give rise to more non-uniform residence times for solids. Hence a binary mixture has been used, where the fine size formed the major portion and the coarser size formed the minor portion. In other words, the fine sized solids are diluted with the coarser sized particles and the percentage of dilution (same as the percentage of coarse size) is varied. Experiments were carried out to test the improved performance of the bed with increase in dilution. Similar observations of betterment in fluidisation phenomena were observed by Chen and Pei[2], where coarser particles were added to a bed of fine particles and an increase in fluid to particle heat transfer coefficient was observed.

Experimental Procedure

Fig. 1 shows the experimental set-up[10]. The unit consists of a fluidisation column and an air chamber both of identical dimensions and made of mild steel. The air chamber consists of two perforated plates of 3 mm perforations with 6 mm triangular pitch. The chamber is connected for air supply to a blower. The fluidisation column is provided with a perforated plate of 3 mm perforations and 6 mm triangular pitch with a stainless steel wire mesh of 40 mesh size fixed to it. The plate is provided with a downcomer tube which extends down through the air chamber to facilitate the exit of solids. The downcomer weir height is taken as the bed height which is kept constant at 25 mm for all the experiments. Solids were fed continuously through a hopper as shown in the figure.

Experiments were performed for the residence time distribution of solids at different gas flow rate, solids flow rate and dilution of the material. Experiments were performed using solids of uniform size as well as for different binary solid mixture, each of different dilution. Coloured material was used as the tracer during the experiments. Table 1 shows the different solid samples used in the present work and the experimental conditions. One sample of uniform particle size and five different samples of binary solid mixtures with dilution ranging from 10 to 50 % were

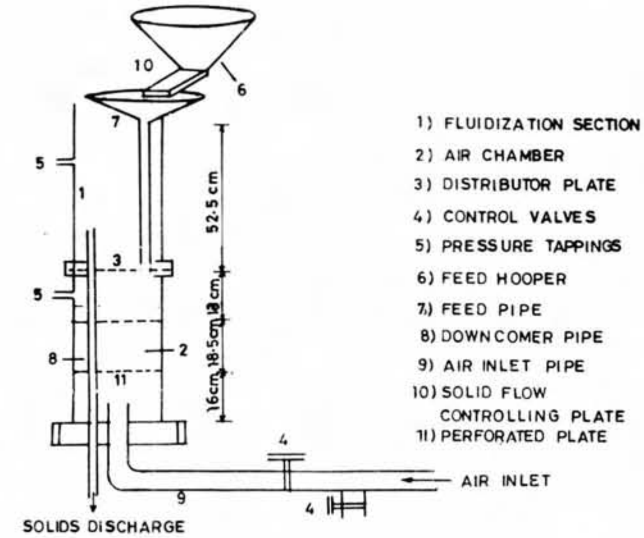

Fig. 1—Experimental set-up

Table 1—Experimental conditions of the present investigation

Column diameter , m :	0.1582
Column thickness , m :	0.0040
Downcomer tube diameter , m :	0.0120
Column length , m : (same as air-chamber length)	0.5250
Fluidised bed height , m	0.0250
Density of solids , kg / m^3	2620
Material Characteristics	
Sample	Type
A	Uniform Size (d_p=2.03 mm)
B	Uniform Size (d_p=1.44 mm)
C	10%
D	20%
E	30%
F	40%
G	50%
Solids Flow Rate, G_s = 0.4579 to 1.1700 kg / m^2 s	
Air Flow Rate , G_f = 1.1919 to 1.7879 kg / m^2 s	

used. The tracer was identical to that of the original material for the experiments using uniform sized particles. For the experiments using solid mixtures the tracer prepared was that corresponding to the major portion (fine size). Hence this experimental work gives information about effect of dilution on solids mixing of fine sized particles, when a bed of these particles are diluted by coarse sized particles. Tracer concentration analysis has been done by physical separation method by hand - picking and weighing the coloured material.

The mixture of sizes were made outside the column and again they were allowed to mix uniformly inside the column in the initial stages of fluidisation. After steady-state was obtained, a sample of mixture was analysed for the fractions and the analysis indicates no segregation of different sizes inside the bed. A mixture of 10% dilution contains 10% of coarse size (d_p=2.03) and 90% of fine size (d_p =1.44) . Same convention of percentage dilution is followed for all the mixtures.

Under steady state conditions at known gas and solids flow rate the tracer was admitted into the bed in the form of a pulse. Samples were collected at different time intervals and analysed for colour concentration by hand - picking.

Results and Discussion

The moments of RTD curves and the age distribution functions, $C(\theta)$ and $F(\theta)$ were found[4,6] as,

$$\bar{t} = \int_0^\infty ctdt \Big/ \int_0^\infty cdt \quad \ldots (1)$$

$$\sigma_t^2 = \left(\int_0^\infty ctdt \Big/ \int_0^\infty cdt \right) - (\bar{t})^2 \quad \ldots (2)$$

$$\sigma_\theta^2 = \sigma_t^2 / (\bar{t})^2 \quad \ldots (3)$$

$$\mu'_3 = \frac{\int_0^\infty ct^3dt}{\int_0^\infty ctdt} - 3\,\bar{t}\,\frac{\int_0^\infty ct^2dt}{\int_0^\infty cdt} + 2(\bar{t})^3 \quad \ldots (4)$$

$$\nu'_3 = \mu'_3 / (t)^3 \quad \ldots (5)$$

For each experimental $c(t)$ vs t curve, all the above moments have been found along with the normalized $c(\theta)$ values at different θ. The $F(\theta)$ vs θ data was obtained by integrating $c(\theta)$ over θ .

Effect of the following variables has been investigated: (i) Effect of gas flow rate (ii) Effect of solids flow rate (iii) Effect of dilution. Table 2 shows the values of moments corresponding to all the system variables.

It was observed that Mean residence time, $\bar{t}$ obtained from the RTD curve was found to decrease with increase in solids flow rate and was little effected with increase in gas flow rate. Mean residence time was found to decrease with increase in dilution rate. With increase in solids flow rate, solids concen-

Table 2—Experimental results and model parameter in the present work

Sample	G_S	G_f	$\bar{t}$	σ_θ^2	v'_3	ΔP_S	N	R.M.S Deviation
				Effect of gas flow rate				
B	1.1700	1.1919	40.56	0.488	4.81	2.5	2.15	0.0400
		1.3907	45.12	0.581	5.26	2.1	1.32	0.0148
		1.6149	49.02	0.642	5.26	2.1	1.24	0.0102
		1.7879	45.22	0.642	5.44	1.8	1.18	0.0142
C	0.6868	1.1919	49.72	0.217	3.68	2.1	4.64	0.0088
		1.3907	51.10	0.287	3.96	1.9	3.38	0.0107
		1.6149	49.19	0.411	4.51	1.6	2.27	0.0145
		1.7879	51.34	0.456	4.69	1.4	2.11	0.0125
				Effect of solids flow rate				
D	0.4579	1.1919	55.10	0.151	3.48	2.1	8.39	0.0148
	0.6868		48.90	0.159	3.47	2.1	6.48	0.0140
	0.8140		43.31	0.224	3.78	2.2	5.27	0.0274
	0.9666		38.97	0.337	4.25	2.3	3.36	0.0287
	1.1700		34.88	0.459	4.81	2.3	2.27	0.0310
E	0.4579	1.1919	53.68	0.173	3.60	2.2	8.27	0.0306
	0.6868		51.33	0.082	3.21	2.2	13.29	0.0130
	0.8140		41.26	0.188	3.63	2.2	7.38	0.0295
	0.9666		34.93	0.352	4.39	2.3	3.44	0.0290
	1.1700		34.51	0.304	4.16	2.4	4.34	0.0309
				Effect of dilution				
B	0.4579	1.1919	55.01	0.218	3.71	2.0	5.20	0.0136
C			54.40	0.165	3.51	2.0	6.85	0.0117
D			55.10	0.151	3.48	2.1	8.39	0.0148
E			53.68	0.173	3.60	2.2	8.27	0.0306
F			52.90	0.099	3.28	2.0	12.48	0.0182
G			50.52	0.069	3.19	1.9	18.68	0.0248
B	0.6868	1.1919	49.97	0.256	3.83	2.1	4.05	0.0073
C			49.72	0.217	3.68	2.1	4.64	0.0088
D			48.90	0.159	3.47	2.1	6.48	0.0140
E			51.33	0.082	3.21	2.2	13.29	0.0130
F			51.11	0.052	3.12	2.1	18.66	0.0212
G			45.84	0.063	3.14	2.1	18.62	0.0219
B	0.8140	1.1919	46.36	0.405	4.54	2.2	2.38	0.0201
C			44.39	0.285	4.00	2.2	3.55	0.0225
D			43.31	0.224	3.76	2.2	5.27	0.0274
E			41.26	0.186	3.63	2.2	7.38	0.0295
F			44.27	0.114	2.92	2.2	15.28	0.0285
G			40.06	0.089	3.25	2.1	17.28	0.0340

tration increases but it does not increase in proportion to solids flow rate. Increase in solids concentration is less as compared to increase in solids flow rate and hence $\bar{t}$ which is equal to W/AG_S decreases with increase in solids flow rate.

It was further observed that, at fixed solids flow rate, as the gas flow rate is increased, bubbling increases, thus increasing the solids mixing. Agitation of the bed increases increasing the random motion of particles. This is especially true when effect of gas flow rate at high solids flow rate was considered.

With increase in dilution from zero to 50%, $\bar{t}$ was found to decrease. It was found that with increase in dilution, solids mixing decreases i.e. the random motion and gross circulation pattern of particles decreases with increase in dilution and solids will be more and more diffusion oriented in motion. As dilution is increased, diffusion of particles is more, which reduces mean residence time.

It was also found in the present investigation that the dimensional second moment, σ_t^2 increases with increase in gas flow rate. With increase in solids flow rate, it was noted that σ_t^2 decreases to a certain extent and then increases. σ_t^2 vs G_S data shows a minimum. Abouzeid *et al.*[1] noted that the variance depends on particle collision frequency and the distance travelled

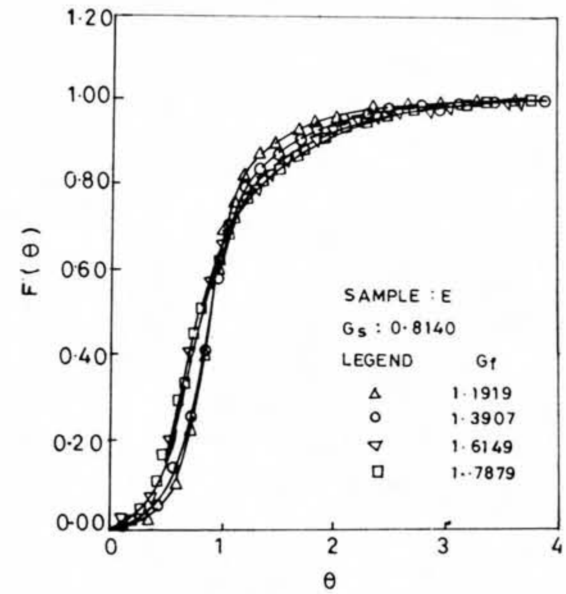

Fig. 2—Effect of gas rate on RTD of solids

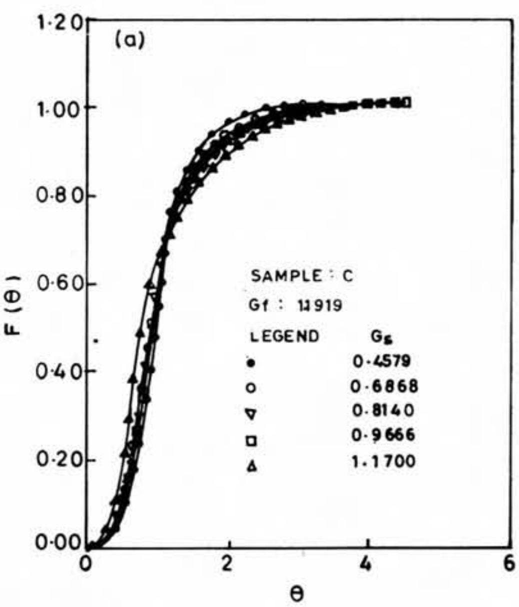

Fig. 3a—Effect of solids rate on RTD of solids at low dilution

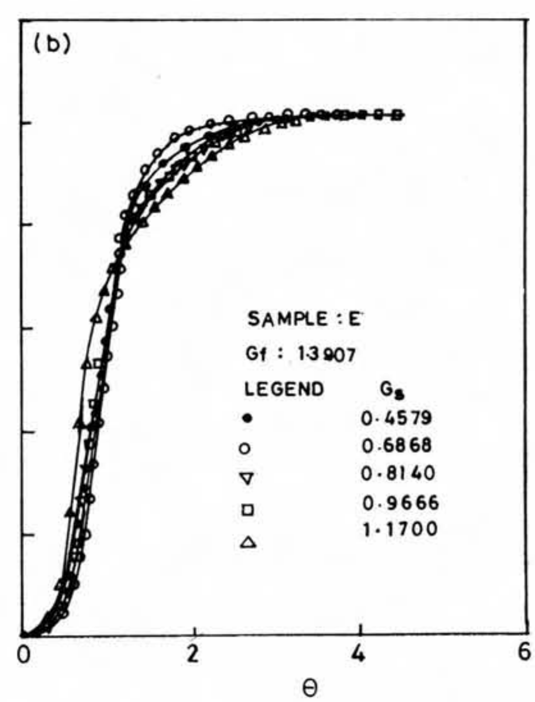

Fig. 3b—Effect of solids rate on RTD of solids at high dilution

due to collision. At low solids flow rates, the collision frequency will be less, while the distance due to collision will be more. Therefore the particles will be travelling to the exit rapidly and lesser travel path will be encountered. The phenomena will be reverse at high solids flow rate, where the collision frequency will be very high and the distance to the collision will be very less. Hence the travel path will be increased due to more hindrance for the particle to travel from the entrance to the exit.

The dimensionless variance, σ_θ^2 was found to increase with increase in solids flow rate at low dilution (up to 20%). At low dilution, the decrease in σ_t^2 is less compared to decrease in $\bar{t}$ with increase in solids flow rate. Hence σ_θ^2 increases. At high dilution and low solids flow rates reduction in σ_t^2 is more compared to reduction in $\bar{t}$ as solids flow increases. At high dilution and high solids flow rates, σ_θ^2 increases because σ_t^2 increases and $\bar{t}$ decreases. Pydi Setty *et al.*[8] reported a decrease in solids mixing with increase in solids flow rate in a spiral fluidised bed. Owing to the spiral geometry of the bed, the solids have more directional movement which leads to more diffusional movement of solids.

σ_θ^2 was found to increase with increase in gas flow rate which is in good agreement with earlier work [8]. Increase in mixing with increase in gas flow rate is due to increased heterogeneity because of more bubble phase, which increases spread in residence time.

With increase in dilution, spread of residence time was found to decrease. Chen and Pei[2] worked on a fluidised bed using a binary solid mixture where a fraction of coarse particles were added to a bed of fine particles. It was noted that such addition improves the performance of the bed and with increase in dilution, heat trasnfer coefficient increases. Im-

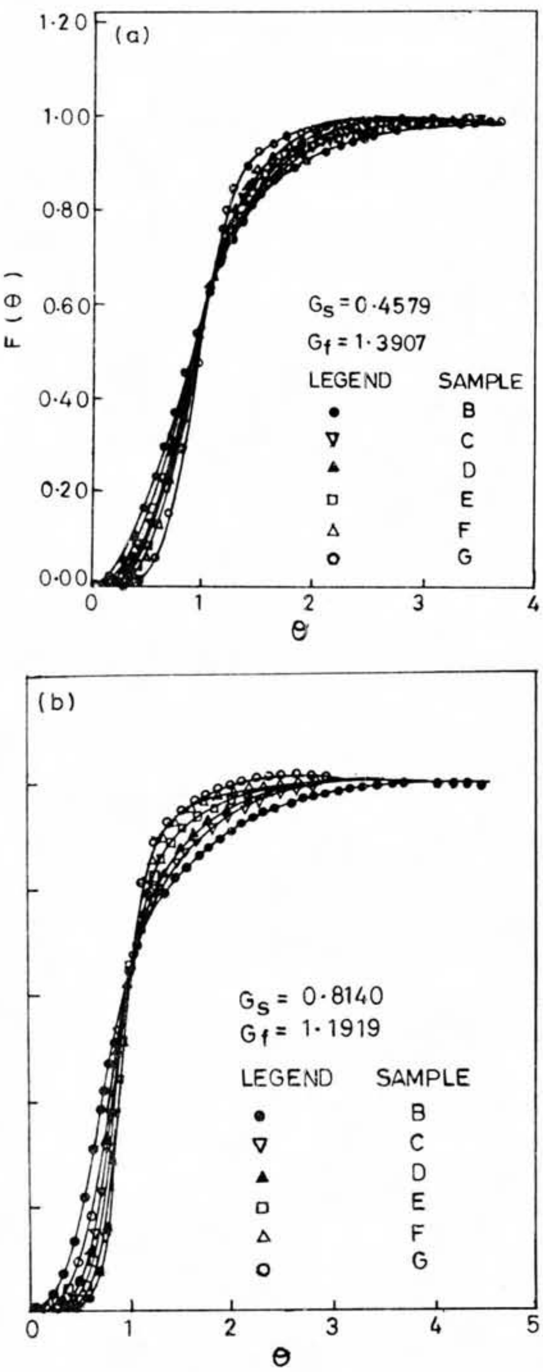

Fig. 4—Effect of dilution on RTD of solids

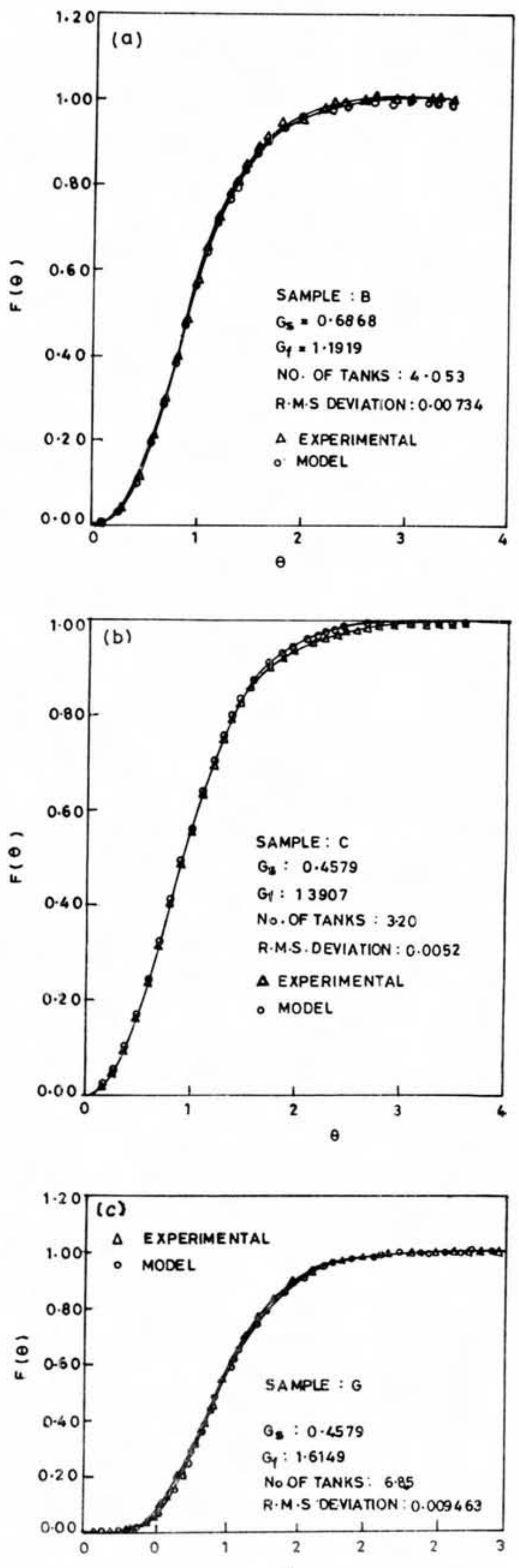

Fig. 5—Comparison of the experimental data with the Model

provement was also observed in the study[10] where solids mixing reduces with increase in dilution thus reducing the spread in solids residence time in the complete range of dilution up to 50 %.

The RTD curves at various experimental conditions were also compared for dimensionless third central moment. It was found that the curves get more skewed as gas flow rate increases for the complete range of experimentation. With increase in solids flow rate, there is no effect on the skewness of RTD curves at low solids flow rate, but it increases at high solids flow rate due to increased randomness of solids movement.

The third central moment, skewness decreases with increase in dilution. This is also due to reduced solids mixing as dilution increases. This indicates that the gross circulation pattern and random movement of particles decreases and flow becomes more and more diffusion oriented as dilution increases.

Modelling of RTD curves

The fractional tank extension model[11] has been fitted to the present experimental data. The model parameter, N, the number of tanks for different experimental conditions has been determined. The parameter, N was evaluated for each experiment by minimizing the root mean square deviation between the experimental and model $F(\theta)$ values at each interval of time for each experimental run. RMS deviation is given by:

$$\sigma = [(1/M)\sum_{k=1}^{M}\{(F_k)_{\mathrm{exptl}} - (F_k)_{\mathrm{model}}\}^2]^{1/2} \quad \ldots (6)$$

The deviation is minimized with respect to the parameter using the Fibonacci search method. The number of tanks is found to decrease with increase in gas flow rate. This is due to increased solids mixing which reduces number of tanks.

At low dilution, N decreases with increase in G_S, while at high dilution, N shows a maximum. It increases up to 20%. Above 30% dilution N increases at low G_S and decreases at high G_S indicating diffusional movement at low solids flow rates and random movement at high solids flow rate, which was also observed from the values of σ_θ^2 for higher dilution of fine size.

Number of tanks, N, increase with increase in dilution at any solids flow rate or gas flow rate, an observation of importance to reduce the spread of residence times without using any internal in a single stage fluidised bed. Increasing dilution increases plugflow tendency for the bed material.

Conclusion

In the present work, it was found that, solids mixing increases with increase in gas flow rate. At low dilutions, solids mixing increases with increase in solids flow rate but at higher dilution, it decreases initially and then increases with solids flow rate.

Since, in practice, the actual material will be a mixture rather than a material of uniform size, the present work finds importance practically.

Nomenclature

A = cross-sectional area of the column, m^2
c = concentration of the tracer, kg tracer/kg material
C = residence time density function
d_p = particle diameter, mm
F_E = residence time distribution function from the experiment
F_M = residence time distribution function from the model
G_S = mass velocity of solids, kg/m^2 - s
G_f = mass velocity of air, kg/m^2 - s
h = downcomer weir height, m
k = index of summation
M = number of intervals
N = equivalent number of ideal stages
ΔP_S = pressure drop due to solids, mm
t = time, s
$\bar{t}$ = mean residence time, s
t_K = time corresponding to 'K' th time interval, s
T = ambient temperature, °C
w = holdup of solids, kg
θ = dimensionless time ($= t/\bar{t}$)
μ'_3 = dimensional third central moment of the RTD curve, s^3
ν_3 = dimensionless third central moment of the RTD curve ($= \mu'_3/\bar{t}^3$)
ρ_S = density of solids, kg / m^3
σ_t^2 = dimensional variance of the RTD curve, s^2
σ_θ^2 = dimensionless variance of the RTD curve ($= \sigma_t^2/\bar{t}^2$)
$FTEM$ = fractional tank extension model
RMS = root mean square deviation
RTD = residence time distribution

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