Korean J. of Chem. Eng., 2(1) (1985) *87 – 92*

A STUDY ON MIXING MECHANISM IN AIR SPOUTED BEDS

Woong-Ki Kang and Se-Young Mo*

Department of Chemical Engineering, College of Engineering,

Korea University, Seoul, Korea

(Received 21 June 1984 • accepted 28 January 1985)

Abstract — The mixing mechanism of solid particles in the air spouted bed was studied by employing an impulse response technique. The particles, german millet and barley, were spouted by air in columns of diameter of 8.4 cm and 12.6 cm.

In the proposed theory, it was assumed that the mixing of the particles in the spouted bed occurs when they circulate through spout, fountain and annulus. Also a theoretical model was derived by assuming that the particle flow in the annulus is a combination of many annular plug flows while the flow in the spout as well as in the fountain is a mixed flow

The residence time distribution of the particles in the bed was measured by injecting a portion of colored particles into the feed line and analyzing the concentration of the colored particles in the discharge line. The experimental results and the proposed theory were most satisfactorily agreed when the null residence time in the spout and in the fountain was assumed in the theoretical model.

INTRODUCTION

After K.B. Mathur [1] reported that the spouted bed could improve the drying of a lot of wheat which could not be fluidized in the conventional fluidized bed, a considerable amount of researches to confirm its characteristics and to apply this technique to many fields such as granulation [2], coating of nuclear fuel particles [3], gas cleaning [4], low-temperature coal carbonization [5], thermal cracking of petroleum [6, 7], etc. have been carried out.

The mechanism of the solid mixing in the spouted bed is one of the fields on which many groups of investigators focused their interests. For example, Kugo et al. [8] proposed a cumulative residence time distribution from their experimental information of gross mixing behavior of solid particles in the spouted bed and Barton et al. [9] had derived the equation for an internal age distribution from which Quinlan and Ratcliffe [10] interpreted that 90% of spouted bed volume is in perfect mixing. Also Chatterjee [11], Mann et al. [12, 13] and Van Velzen [14] derived the equation for calculating the circulation rate in the spouted bed from their mixing model.

In this study, however, a theoretical model, based on the assumption that the solid flow in the annulus is a combination of many plug flows, was proposed and a tracer experiment was carried out to confirm the model [15].

* To whom correspondence should be addressed.

THEORETICAL MODEL

A spouted bed can be divided into three zones. Those are the spout which is the channel of the fluid and particles at the center of the bed, the annulus at which particles flow toward the spout wall and the fountain at which particles change their flow directions to the bed level afrer gushing out through the spout as shown in Fig. 1.

After several observations with a half cut spouted bed, it could be assumed that the particle flows in the annulus are the combination of many annular plug flows having different residence time, $\tau_p(j)$, while the flows in the fountain and the spout are mixed flows, presumably complete mixing. Also the distribution of the solid particles at the bed level after gushing out from the fountain is assumed to be uniform. With this assumptions, a theoretical model for mixing mechanism can be proposed as shown in Fig. 2 for a continuous flow spouted bed. In this system, solids are fed into the fountain and taken out from the top of the spout.

From Fig. 2, the overall material balance in the spout and the fountain at the time t, after a tracer injection, can be expressed as

$$M_s \frac{dC_s(t)}{dt} = \Sigma \left[\alpha(j) \ (1+R) \ v \ C_f(t-\tau_p(j)) \right] - (1+R) \ v \ C_s(t) \tag{1}$$

and

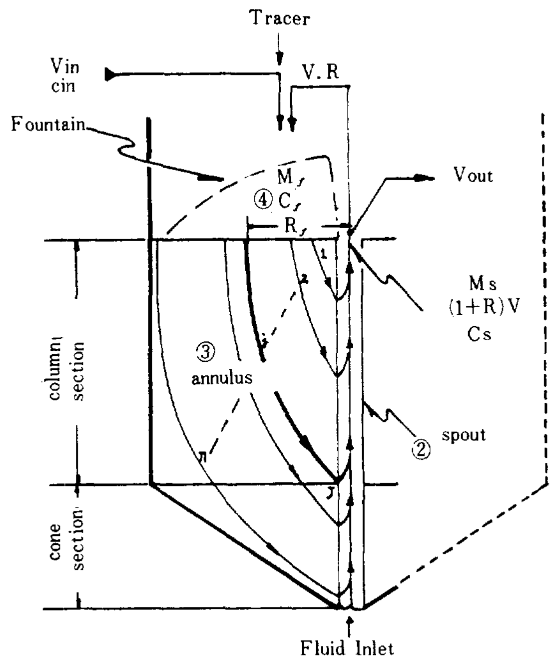

Fig. 1. Schematic explanation of the spouted bed.

C_f, C_s : tracer concentration in the fountain and in the spout,

M_f, M_s : particle hold-up in the fountain and in the spout,

V : particle mass flow rate,

R : particle recycle ratio,

R_f : distance from the column center.

$$M_f \frac{dC_f(t)}{dt} = R\ v\ C_s(t) + v\ C_{in}(t) - (1+R)\ v\ C_f(t) \qquad (2)$$

Where

$\tau_p(j)$: residence time of the particles in the j th streamline of the annulus.

$\alpha(j)$: fraction of the cross sectional area that occupied by the j th streamline on the bed level.

R : particle recycle ratio.

V : particle feed or discharge rate.

C(t) : tracer concentration at time t.

$C_f(t-\tau_p(j))$: tracer concentration of the j th streamline at the spout wall. It means that the tracer concentration at the spout wall at time t is equal to those of the fountain before time $\tau_p(j)$.

and subscript

s : spout.

f : fountain.

in : inlet.

out : outlet.

In this study, $\tau_p(j)$ was experimentally correlated with the variables such as radial distance from the center of the bed level to the column wall, superficial fluid velocity, density and viscosity of fluid, size and specific gravity of particles, column diamerer and packing height, elsewhere [15]. The correlated equation was

$$\frac{\tau_p(j)\ U_f}{d_p} = 449 \left(\frac{\mu_f}{d_p \rho_s U_f}\right)^{0.654} \cdot \left(\frac{D_c}{d_p}\right)^{-2.231} \cdot \left(\frac{rt}{d_p}\right)^{1.441} \cdot \left(\frac{H}{d_p}\right)^{1.012} \left(\frac{\rho_f}{\rho_s}\right)^{-1.337} \qquad (3)$$

where

D_c : column diameter

d_p : particle diameter

H : packing height

rt : radial distance from the center of the bed

U_f : superficial fluid velocity in the bed

μ_f : fluid viscosity

ρ_f : fluid density

ρ_s : particle density

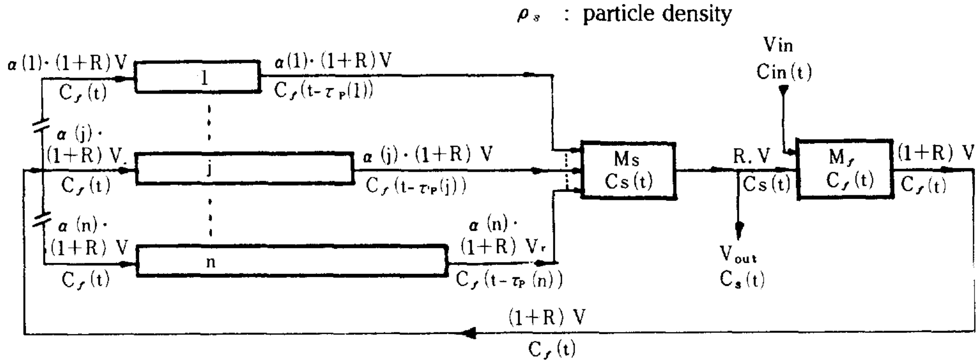

Fig. 2. A theoretical model for mixing mechanism in the spouted bed.

α : area fraction, 1∼n : number of fractionated area, $\tau_p(j)$: residence time of j th flow, others are same as in the Fig. 1.

Furthermore, the particle hold-up in the spout could be assumed negligible compared to those in the fountain and the annulus. This was confirmed through the visual observation that the retention of the colored particles in the spout was negligibly short compared to those in the annulus.
Thence, Eq.(1) becomes,

$$C_s(t) = \sum_{j=1}^{n} [\alpha(j)\ C_f(t-\tau_P(j))] \qquad (4)$$

and when Cin(t) = Cin δ(t) and Cf(0) = Cs(0) = 0, Eq.(2) can be solved with Eq.(4) as

$$C_f(t) = \frac{s(t)}{q} - e^{-q\Delta t}\left[\frac{s(t)}{q} - C_f(t-\Delta t)\right] \qquad (5)$$

where

$$q = \frac{(1+R)V}{M_f} \qquad (6)$$

$$s(t) = \frac{R \cdot V}{1+R} \cdot \left\{\sum_{j=1}^{n} [\alpha(j)\ C_f(t-\tau_p(j))]\right\} \qquad (7)$$

All the theoretical calculations are carried out with the logic shown in Fig. 3.

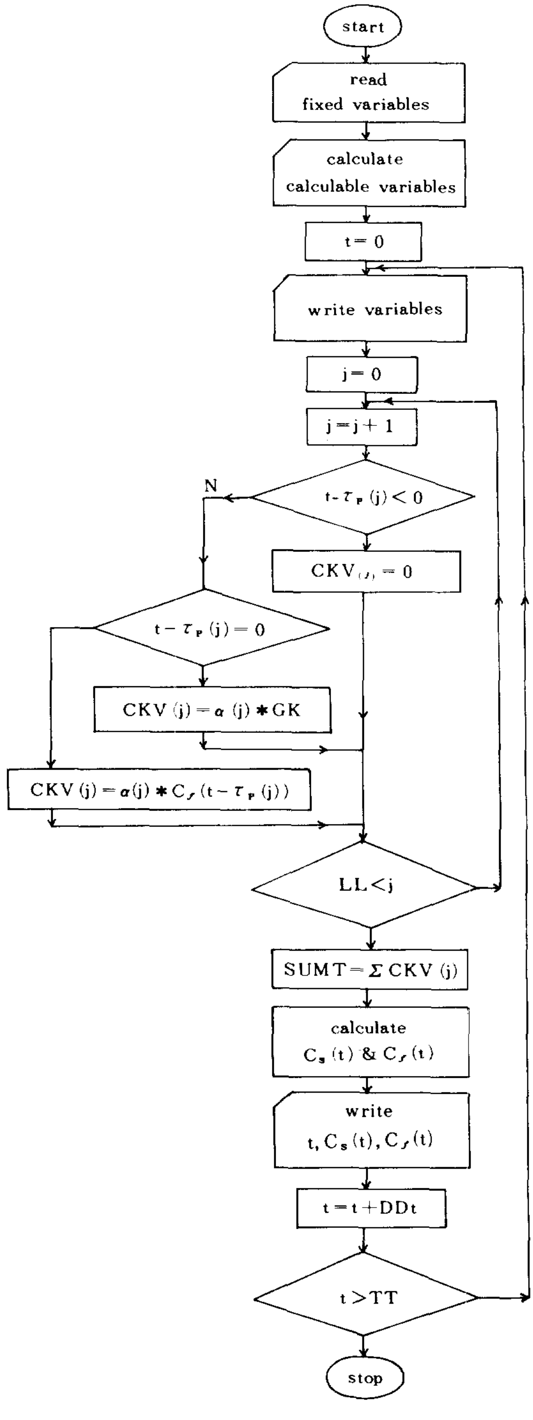

Fig. 3. Flow chart for the calculation of the tracer concentration.

EXPERIMENTAL

The particles used in this study were german millet and barley of which physical properties are shown in Table 1. The columns used were semicircular shape of 8.4 cm in diameter for the barley and 12.6 cm in diameter for the german millet with transparent acrylplate front. The cone angle and the size of fluid inlet nozzle were fixed as 60° and 0.66 cm in diameter, respectively.
The packing height of the solid particles in each column was set as 10 cm for the barley and 20 cm for the german millet from the bottom of the column section and the superficial velocities in the bed were 71.0 cm/sec. and 31.8 cm/sec., respectively.

The tracer used in this investigation was prepared by coloring the same particles as those in the spouted bed with direct dyes. After tracer particles were injected into the fountain of a steady state spouting bed, the outcoming particles through a hole placed at the top of the spout were sampled as a function of time and the concentration of the tracer particles could be measured by separating the colored from the noncolored. The air flow rate for the tracer run was ranged from 1.15 to 1.20 times of the minimum spoutable flow rate [1, 17].

The schematic diagram of the experimental apparatus is shown in Fig. 4.

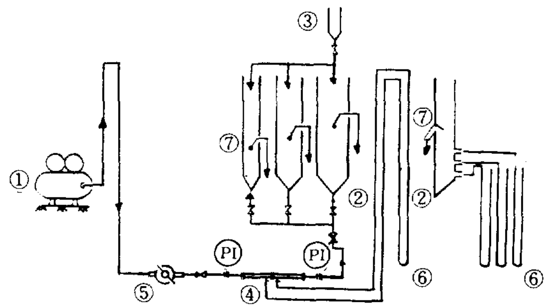

Fig. 4. Schematic diagram of the experimental apparatus.
1; compressor, 2; spouted bed, 3; hopper, 4; orifice, 5; regulator, 6; manometer, 7; outlet nozzle.

Table 1. Physical properties of the particles.

Particles / Phsical Properties		German Millet	Barley
Size (dia. cm)		0.145	0.317
Sphericity		0.980	–
Sp · Gr	absolute	1.320	1.404
(g/cm^3)	bulk	0.830	0.815

RESULTS AND DISCUSSION

Fig. 5 and Fig. 6 are to compare the theoretical residence time distribution with the experimental one for the barley spouted in the column of 8.4 cm in diameter and for the german millet spouted in the column of 12.6 cm in diameter, respectively. The theoretical values in the figures were the integrated ones over the corresponding experimental sampling times though the raw theoretical data calculated from Eq. (4) and Eq. (5) were pulses. This is because the experimental datum was the average value over a certain sampling time.

Also the theoretical lines presented in this figure are for the recycle ratios, mass of solid particles returned to the fountain per mass of solid particles leaving the bed, of 10 and 18 and the particle hold-up in the fountain, Mf, are used as a parameter in the plot. The tail part of the curves were treated by the method used by Edward and Richardson [16].

According to these figures, the closer to the zero Mf is and the higher the recycle ratio is, the better agreement between the theoretical and the experimental holds.From this fact, it could be said that the fountain simply acts as a distributor of particles from the spout.

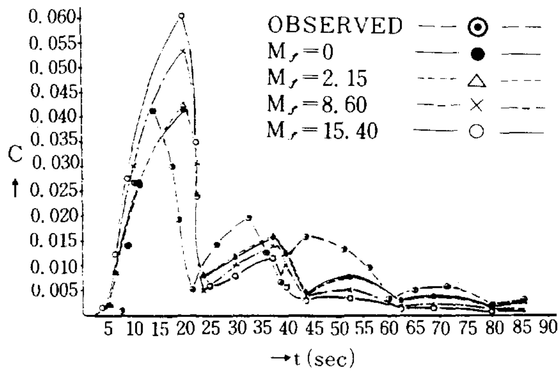

Fig. 5. a. C-curves in the air spouted bed for the M_f values of the german millet when R=10.

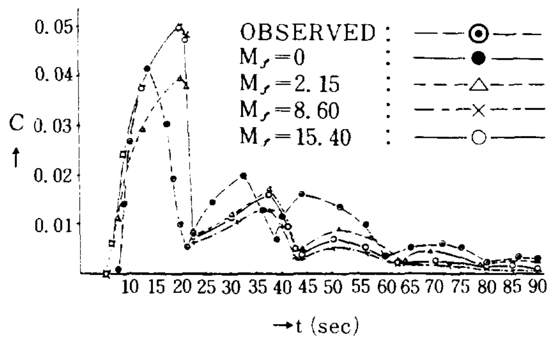

Fig. 5. b. C-curves in the air spouted bed for the M_f values of the german millet when R=18.

The peak values appeared at the every circulation of each streamline of the german millet appear earlier than the values of the theoretical ones while the experimental peak values of the barley appear later than that of theoretical ones. For the barley runs, the deviations of the peak values between the theoretical and the experimental are considerable. These deviations may be attributed to the assumption in the derivation of the theoretical equation that the particles are uniformly distributed at the same bed level. In the present investigation, however, the german millet requires less air velocity for being spouted than the barley and the former tends to be collected on the near side of the column center while the latter be collected around the column wall.

Barton et al. [9] proposed the equation for an internal age distribution from their experimental data for the information of gross mixing behavior in the spouted bed and Quinlan and Ratcliffe [10] interpreted this equation as 90% of total spouted bed volume is in perfect mixing. With this present theory proposed, the particles reside mostly in the annulus in which the flow of particles can

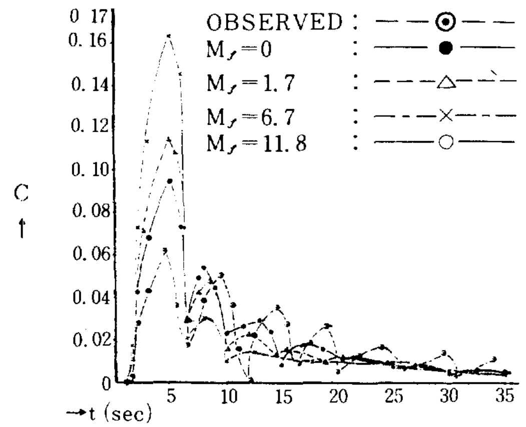

Fig. 6. a. C-curves in the air spouted bed for the M_f values of the Barley when R=10.

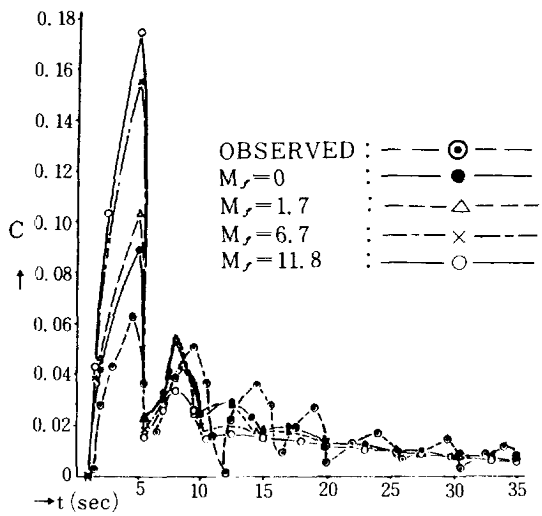

Fig. 6. b. C-curves in the air spouted bed for the M_f values of the Barley when R=18.

be expressed as a combination of plug flow paths of difference residence times. The difference of the two theories may comes from the fact that the residence time distribution of a combination of plug flows may be similar to that from a complete mixing.

With the theory presently proposed, the recycle ratio, R, could be estimated by many trial calculations from Eq.(4) and Eq. (5). This method differs from the Chatterjee's theory [11] which assumed only a single plug flow path. The estimated recycle ratio in this study are close to 18.

CONCLUSION

Through the present investigation, the following conclusions could be drawn;

(1) With the assumption that the annulus is a combination of many plug flows, a theory is proposed to calculate the residence time distribution of solids in the spouted bed.

(2) The theory is most successfully aggreed wigh experiment when the particle hold-up in the fountain as well as in the spout is assumed to be negligible.

(3) The assumption that the particles are uniformly distributed at the bed level of the annulus would not holds in practice.

(4) The particle recycle ratio could be calculated as about 18 with the present theory.

NOMENCLATURE

$C_f(t)$	:	tracer concentration in the fountain at time t	g/cm^3
$C_s(t)$	:	tracer concentration in the spout at time t	g/cm^3
$C_{in}(t)$	:	tracer concentration of feed at time t	g/cm^3
D_c	:	column diameter	cm
d_P	:	particle diameter	cm
D_s	:	spout diameter	cm
G	:	fluid mass flow rate	g/sec
H	:	packing height	cm
M_f	:	particle hold-up in the fountain	g
M_s	:	particle hold-up in the spout	g
R	:	particle recycle ratio	-
r_t	:	radial distance from the center of the bed	cm
R_f	:	distance from the column center (see Fig. 1)	cm
SUMT	:	summation of the tracer concentration in the spout at time t	g/cm^3
U_f	:	superficial fluid velocity in the bed	cm/sec
v	:	particle feed or discharge rate	g/sec

Greek Letters

α(j)	:	fraction of the cross sectional area occupied by the j th streamline on the bed level	-
$\bar{\varepsilon}_s$	:	average voidage of the particles in the spout	-
ε_s(Z)	:	particle voidage at the height Z in the spout	-
θ	:	dimensionless time	-
μ_f	:	fluid viscosity	g/cm-sec
ρ_b	:	particle bulk density in the bed	g/cm^3
ρ_f	:	fluid density	g/cm^3
ρ_s	:	particle density	g/cm^3
τ_p(j)	:	residence time of the particles in the j th streamline of the annulus	sec

REFERENCES

1. Mathur, K.B., and Gishler, P.E.: *AIChE J.*, **1**, 157 (1955).
2. Romankov, P.G., and Rashkovskaya, N.B.: "Drying

in a suspended state", 2nd ed., in Russion Chem. Publ, House, Leningrad Branch (1968).
3. Abdelrazek, I.D.: ph. D. Thesis, Univ. of Tennessee (1969).
4. Nemeth, J., Palli, I., and Baticz, S.: *Proc. Conf. Some Aspects phys. Chem., Budapest,* 259 (1966).
5. Ratcliffe, J.S., and Rigby, G.R.: *Mech. Chem. Eng. Trans.,* **5,** 1 (1969).
6. Uemaki, O., Fugikawa, M., and Kugo, M.: *Kogyo Kagaru Zassi,* **73,** 453 (1970).
7. Uemaki, O., Fugikawa, M., and Kugo, M.: *Kogyo Kagaru Zassi,* **74,** 933 (1971).
8. Kugo, M., Watanabe, N., Uemaki, O., and Shibata, T.: Bull. Hokkaido Univ., Sapporo, Jap., **39,** 95 (1965).
9. Barton, R.K., Rigby, G.R., and Ratcliffe, J.S.: *Mech. Chem. Eng. Trans.,* **4,** 105 (1968).
10. Quinlan, M.J., and Ratcliffe, J.S.: *Mech. Chem. Eng. Trans.,* **6,** 19 (1970).
11. Chatterjee, A.: *Ind. Eng. Chem. Process Des. Develop.,* **9,** 531 (1970).
12. Mann. U., and Crosby, E.J.: *Ind. Eng. Chem. Process Des., Develop.,* **11,** 314 (1972).
13. Mann. U., and Crosby, E.J.: *Chem. Eng. Sci.,* **28,** 623 (1973).
14. Velzen, D. Van, Flamm. H.J., Langenkamp, H. and Casile, A.: *Can. J. Chem. Eng.,* **52,** Apr., 156 (1974).
15. Mo, S.Y.: ph. D. Thesis, Korea Univ., Seoul Korea (1984).
16. Edwards, M.F. and Richardson, J.F.: *Chem. Eng. Sci.,* **2,** 1 (1957).
17. Smith, J.W. and Reddy, K.V.S.: *The Can. J. Chem. Eng.* Oct. 206 (1964).