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The Effect of Vertical Internal Baffles on Fluidization Hydrodynamics and Grain Drying Characteristics

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Abstract The effect of vertical internal baffles on the particle mixing and grain drying characteristics in a batch fluidized bed column is investigated. Experimental work was carried out in a 3 m high rectangular fluidized bed dryer of cross sectional area of 0.15 m×0.61 m at different operating conditions using paddy, a group D particle, as the fluidizing material. The results of the study showed that the fluidized bed dryer system with vertical internal baffles gave better particle mixing effect in the bed of particles than that without vertical internal baffles. This is due to the fact that the vertical internal baffle act as gas bubble breakers by breaking up the large gas bubbles into smaller ones. The smaller bubbles cause a more vigorous mixing in the bed of particles before finally erupting at the bed surface. This improves the contacting efficiency and enhanced the heat and mass transfer of the fluidized bed system. Thus a higher drying rate was obtained in the falling rate period because the higher contacting efficiency increases the evaporation rate at the particle surface. However, the drying rate in the diffusion region shows little improvement because the moisture diffusivity does not depend on the contacting efficiency. The fluidized bed dryer with vertical internal baffles could therefore be used in the initial rapid drying stage in a two stage drying strategy for paddy. The insertion of vertical internal baffles into a fluidized bed system improves the processing of Group D particles in a fluidized bed system especially if the system is large in scale.
Keywords bubble characteristics, critical moisture content, drying curves, fluidization quality, fluidized bed dryer, group D particles, paddy

1 INTRODUCTION

Fluidization operation has the advantages of high intensity of heat and mass transfer as well as high thermal efficiency with uniform bed temperature. In addition, solid mixing is excellent for Group A and B particles, while the mixing effect of Group C and D particles could be enhanced by the aid of external means. This paper investigated fluidization hydrodynamic and drying characteristic of paddy (Group D) in a pilot scale fluidized bed dryer.

According to Geldart, group D particles exhibit poor fluidization quality[1]. The poor fluidization quality of Group D particles becomes even more significant if the process is operated in a large scale fluidized bed column with a deep bed. However the fluidization quality of Group D particles could be improved and further enhanced by using the spouting mode, or operating in a shallow bed, or using an expanded freeboard region, or combining both spouting and bubbling[2].

2 THEORETICAL BACKGROUND

2.1 Bubbles in unbaffled and baffled fluidized beds

In conventional fluidized bed systems without vertical internal baffles, large bubbles are formed when small bubbles coalesced as they move upwards. The formation of large bubbles in the fluidized bed system reduces the heat and mass transfer processes in the bed. It is proposed that the fluidization quality of Group D particles in a large scale fluidized bed could be increased by inserting several vertical internal baffles to divide the fluidized bed into several smaller fluidized bed sections, with each section serving as a separate fluidization unit operation (Fig. 1). As gas bubbles form at the distributor, coalesce as they rise through the bed of particles, and eventually erupt at the bed surface, the vertical baffles act as gas bubble breakers by breaking up large bubbles into smaller ones. These smaller bubbles affect a more vigorous mixing in each partitioned fluidized bed section. As a result, the contacting efficiency between the gas and particles is improved. Thus, with the insertion of vertical internal baffles, the formation of large bubbles in a large scale fluidized bed operation could be avoided while its mixing effect is enhanced.

2.2 Drying rate periods and critical moisture contents

A review of paddy drying would help the understanding of the effect of the baffles on the drying characteristics of the paddy. Many thin layer drying mod-

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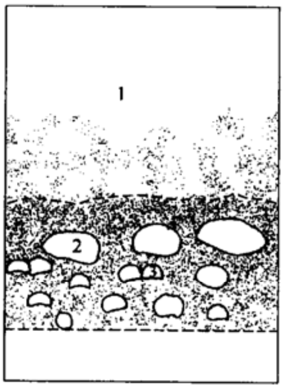
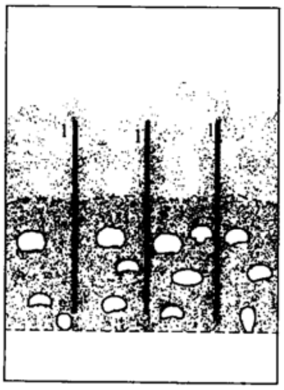
els have been used over the years to characterize the drying process of grains that are fully exposed to various drying conditions[3]. More recently Midilli *et al.*[4] listed 8 mathematical models that are generally used by researchers[5–11] to describe the drying curves of grains. These models could describe the drying kinetics fairly well because their regression coefficients are generally quite high[4].



(a) Without baffle
1—freeboard region;
2—formation of large bubles;
3—coalescence of bubbles



(b) With vertical internal baffles
1—vertical internal baffles

Figure 1 Comparison of bubble size in conventional fluidized bed system (without baffle) with baffled fluidized bed system (with vertical internal baffles)

However, these models are highly empirical in nature and are therefore not able to give a satisfactory theoretical explanation of the heat and mass transfer phenomena occurring during the drying process. The drying process rarely proceeds to completion in a uniform manner but undergoes different drying rate periods and each period has different limiting factors that affect and control its moisture removal[12,13].

Law *et al.*[14] studied the drying characteristics of paddy in a rapid bin dryer and found that the normalized drying rate of paddy was proportional to the normalized moisture content in the first falling rate period but the normalized drying rate of the material in the second falling rate period does not vary as a power function of the normalized moisture content but varies exponentially with the latter. Law *et al.* found that the first falling rate period is given by

$$\frac{\mathrm{d}X/\mathrm{d}t}{\mathrm{d}X/\mathrm{d}t\big|_{\mathrm{cr1}}} = a\frac{X - X_{\mathrm{cr2}}}{X_{\mathrm{cr1}} - X_{\mathrm{cr2}}} \tag{1}$$

where X is the dry basis moisture content, a is an empirical parameter and the subscripts cr1 and cr2 indicate the first and second critical points respectively. If equation (1) is integrated then

$$\frac{X - X_{\mathrm{cr2}}}{X_{\mathrm{cr1}} - X_{\mathrm{cr2}}} = \exp\left[\frac{a(\mathrm{d}X/\mathrm{d}t)_{\mathrm{cr1}}}{X_{\mathrm{cr1}} - X_{\mathrm{cr2}}}t\right] \tag{2}$$

They also found that the second falling rate period on the other hand does not follow power law as is assumed by Daud *et al.*[8] but is exponential instead and is given by a new exponential model

$$\frac{\mathrm{d}X/\mathrm{d}t}{\mathrm{d}X/\mathrm{d}t\big|_{\mathrm{rc2}}} = b\exp\left[c\left(\frac{X - X_{\mathrm{eq}}}{X_{\mathrm{cr2}} - X_{\mathrm{eq}}}\right)\right] \tag{3}$$

where the subscripts eq indicate the equilibrium point, and b and c are empirical parameters. If Eq. (3) is integrated then

$$\frac{(X - X_{\mathrm{eq}})}{X_{\mathrm{cr2}} - X_{\mathrm{eq}}} = 1 - \ln\left[1 - \frac{\exp[c]bc(\mathrm{d}X/\mathrm{d}t)_{\mathrm{cr2}}}{X_{\mathrm{cr2}} - X_{\mathrm{eq}}}t\right]^{1/c} \tag{4}$$

If the power model for the second falling rate period of paddy drying given by Daud *et al.* is used then

$$\frac{\mathrm{d}X/\mathrm{d}t}{\mathrm{d}X/\mathrm{d}t\big|_{\mathrm{cr2}}} = \mathrm{d}\left(\frac{X - X_{\mathrm{eq}}}{X_{\mathrm{cr2}} - X_{\mathrm{eq}}}\right)^n \tag{5}$$

where n is the power index. If Eq. (5) is integrated then

$$\frac{X - X_{\mathrm{eq}}}{X_{\mathrm{cr2}} - X_{\mathrm{eq}}} = \left[1 + \frac{\mathrm{d}(1-n)(\mathrm{d}X/\mathrm{d}t)_{\mathrm{cr2}}}{X_{\mathrm{cr2}} - X_{\mathrm{eq}}}t\right]^{\frac{1}{1-n}} \tag{6}$$

Since the normalized drying rate of the exponential model decreases much more slowly with the logarithm of time [Eq. (4)] than that of the power law model which decreases much faster with the time raised to a power more than unity [Eq. (6)], the exponential model describes the slow drying in the second falling rate period of paddy drying better.

Law *et al.* also proposed a new method to determine the second critical moisture content by locating it at the point where the drying rate gradient changes its value abruptly to a low value[14]. This method is based on the so called second drying curve which is a plot of the drying rate gradient versus moisture content as shown in Fig. 2[13]. The drying rate gradient is given by

$$\frac{\mathrm{d}N}{\mathrm{d}t}=\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}X}{\mathrm{d}t}\right) \tag{7}$$

where N is the drying rate.

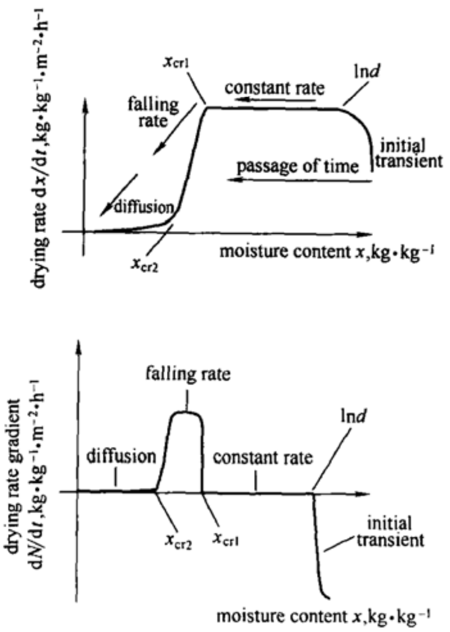


Figure 2 Drying rate periods and critical moisture contents in a typical drying process
(various drying periods and critical points are shown in first drying curve and second drying curve)

3 EQUIPMENT AND METHOD

Figure 3 shows the schematic diagram of the experimental setup and its details. The rectangular fluidized bed column is 3 m high with a cross sectional area of 0.61 m×0.15 m. A wind box of similar dimension is attached to the bottom of the column. A distributor plate perforated with 2 mm diameter holes and a layer of filter cloth were inserted between the column and the wind box. The wind box and the distributor distribute the air stream evenly across the fluidized bed. The distance between the vertical internal baffles and the column wall as well as the distance between the baffles is 20 cm.

Batch drying experiments were carried out using paddy as the feed material. The properties of paddy tested in this study are given in Table 1. Detailed account on various particle sizes and diameters are given in Refs. (1) and (2). Definitions on particle sphericity are summarized in Law *et al.*[15].

A hot air stream was admitted into the column at the desired temperature. The heater was switched on until the preset steady state temperature was attained. Wet paddy of moisture content of 30%—35% dry basis was then loaded into the column at a certain bed depth. Paddy samples were drawn out intermittently at regular intervals throughout the drying period. The sample moisture content was analyzed using the oven drying method. The sample was kept in an oven at (120 ± 0.4)℃ until a constant mass was obtained. The same procedure was repeated for the other experiments at different operating conditions of superficial gas velocities ($\pm0.1\,\mathrm{m\cdot s^{-1}}$) and air temperatures (±5℃). The bed depth was 9 cm while the operating temperature was in the range of 80℃ to 100℃. The superficial gas velocity was varied from $1.8\,\mathrm{m\cdot s^{-1}}$ to $2.4\,\mathrm{m\cdot s^{-1}}$. Reproducible experiments were carried. It was found that the maximum error was 5.8%, the mean error was 1.6% and the minimum error was 0.8%.

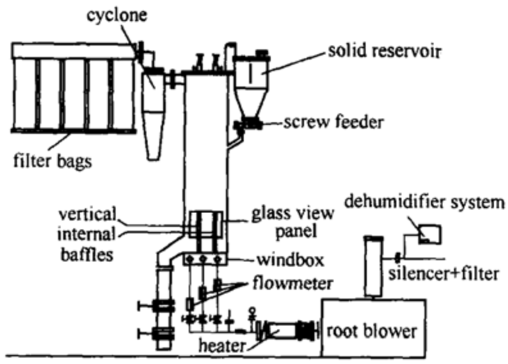


Figure 3 Schematic diagram of experimental apparatus and its detail

4 RESULTS AND DISCUSSION

4.1 Bubbles in unbaffled and baffled fluidized beds

Figures 4 and 5 show the visual observations of the behavior of paddy particles at the fluidized bed surface in systems with and without vertical internal

Table 1 Properties of paddy that was tested in this study

Properties	Definitions	Value
particle size, d_v	particle diameter of a sphere having the same volume with the particle	3130 μm
particle size, d_{sv}	particle diameter of a sphere having the same surface over volume ratio as the particle	2180 μm
sphericity, ψ	ratio of d_v over d_{sv}	0.70

baffles. Fig. 4 shows that bubble breaks into smaller ones due to the vertical internal baffles and that each fluidized bed section shows its own circulation pattern of particle flow.

The up and down flow of particles created significant circulation patterns of particle flow in the system. This improved the contacting efficiency between gas and solid phases and thus increased the heat and mass transfer. This in turn increased the drying rate of the system.

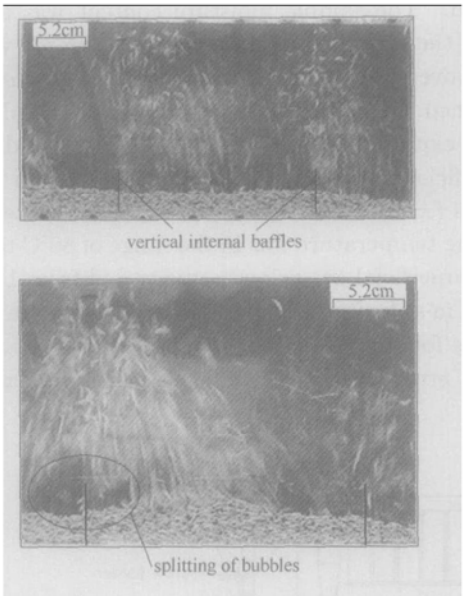


Figure 4 Visual observations of fluidized bed activities at bed surface at superficial gas velocity of 1.8 m·s^{-1}
(two vertical internal baffles were inserted in the fluidized bed dryer)

Figure 5 shows that in the fluidized bed system without vertical internal baffle large bubbles are formed which simultaneously erupted and burst at the bed surface. As a result, the circulation pattern was not significant and the mixing effect was relatively poor.

4.2 Paddy drying characteristics

The first drying curves of drying rate *versus* moisture content are plotted in Fig. 6 at different operating conditions. The figure shows that the constant drying rate period does not exist. The drying curves could be divided into two periods, namely the first falling rate period that follows the linear model where the drying rate declined quickly within a short drying time as the moisture content decreases, and the subsequent second falling rate period that follows the exponential model where the drying rate was relatively slow.

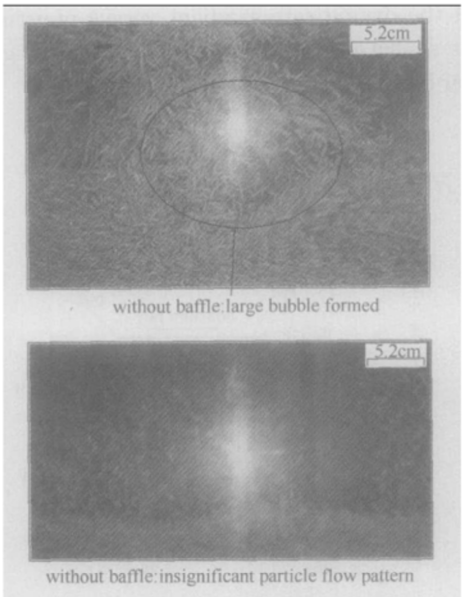
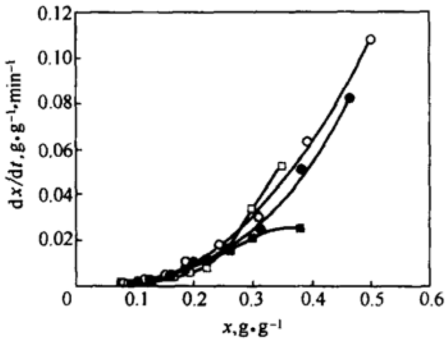
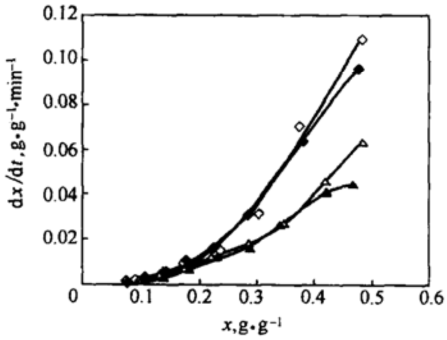


Figure 5 Visual observations of fluidized bed activities at bed surface at superficial gas velocity of 2.1 m·s^{-1}
(no baffle inserted into the fluidized bed column)



(a)

■ bed depth=9 cm, T = 80℃, 2.12 m·s^{-1};
□ bed depth=9 cm, T = 80℃, 2.12 m·s^{-1}, baffled;
● bed depth=9 cm, T = 100℃, 2.35 m·s^{-1};
○ bed depth=9 cm, T = 100℃, 2.35 m·s^{-1}, baffled

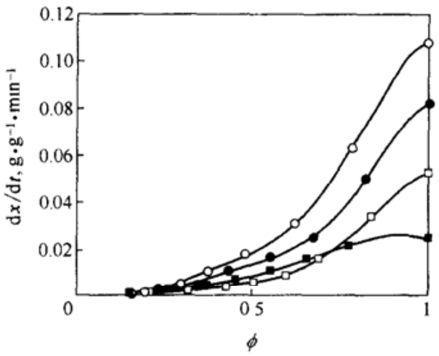


(b)

◆ bed depth=9 cm, T = 100℃, 2.0 m·s^{-1};
◇ bed depth=9 cm, T = 100℃, 2.0 m·s^{-1}, baffled;
▲ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1};
△ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1}, baffled

Figure 6 First drying curve of drying rate *versus* moisture content

Since the initial moisture contents of the respective drying curves are not the same, comparison of the drying kinetics exhibited by the fluidized bed dryer with and without vertical internal baffles might not reveal the actual situation or it may lead to misleading conclusions. Thus, the semi-normalized first drying curves of the drying rate versus normalized moisture content were plotted and they are shown in Fig. 7.



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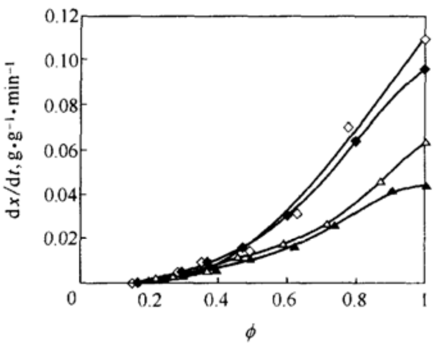

(b)
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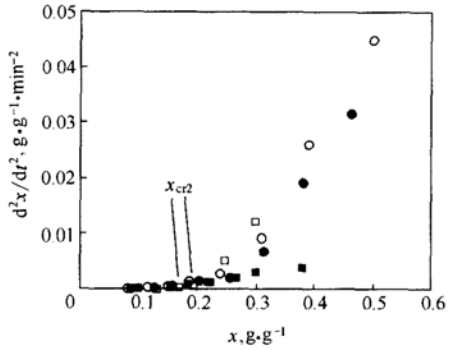
△ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1}, baffled

Figure 7 Semi normalized first drying curve of drying rate *versus* normalized moisture content

Comparison of drying rate given by fluidized bed system with and without vertical internal baffle in Fig. 7 shows that the vertical internal baffles increase the drying rate appreciably especially in the induction period and falling rate period by as much as 10% to 25%. This is due to the fact that the vertical internal baffles help to improve particle mixing in the fluidized bed and hence increase the contacting efficiency of both the gas and solid phases.

In order to see the difference of drying rate clearly, the drying curves were divided into the first falling rate and second falling rate periods by the second critical moisture content which is determined using the second drying curves as proposed by Law *et al.*[14]. Fig. 8 shows the second drying curves of fluidized bed system with and without vertical internal baffles and the location of the second critical moisture contents.



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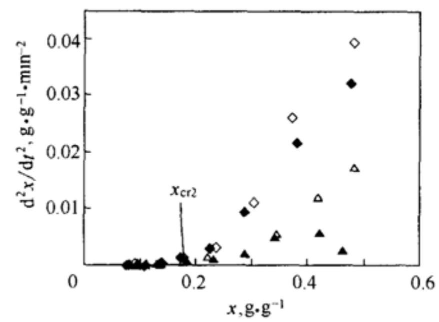

(b)
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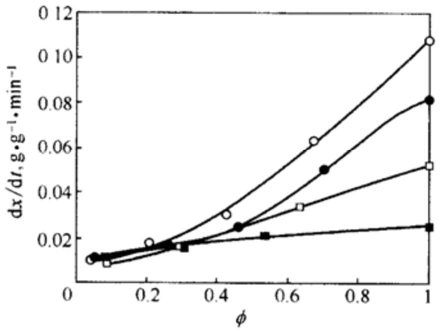
▲ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1};
△ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1}, baffled

Figure 8 Second drying curve of drying rate gradient *versus* moisture content

The drying rate and the moisture content were normalized using Eq. (1) for the falling rate period and using Eq. (3) for the second falling rate period. Semi-normalized first drying curves for both periods were plotted in Figs. 9 and 10, respectively.

Figure 9 shows that in the first falling rate period, the fluidized bed system with vertical internal baffles gave a higher drying rate compared to the system without vertical internal baffles. This is due to the fact that in the first falling rate period, the moisture removal rate is dependant on the evaporation rate of moisture at the material surface. Increasing the contacting efficiency between solid phase and gas phase resulted in appreciable increment in drying rate.

On the other hand, Fig. 10 shows that in the second falling rate period, the difference in drying rates in both systems is not significant. The moisture removal rate in the second falling rate period is highly dependant on the internal diffusion of moisture from within the material core towards the dry grain surface. The limiting factor in this period is moisture diffusion that does not depend on the contacting efficiency between the solid and gas phases. Thus the insertion of vertical internal baffles that enhances the contacting efficiency does not play an important role in increasing the drying rate in this period.



(a)

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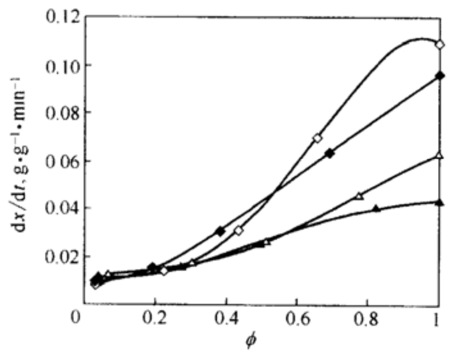

(b)

◆ bed depth=9 cm, T = 100℃, 2.0 m·s^{-1};
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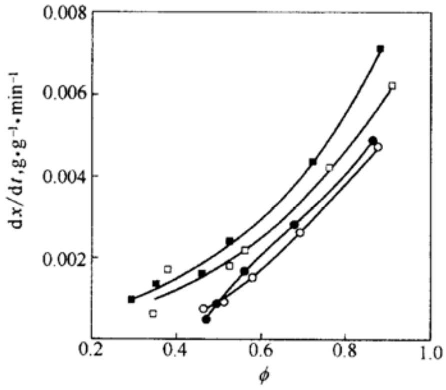
▲ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1};
△ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1}, baffled

Figure 9 Semi normalized first drying curves of drying rate *versus* normalized moisture content in falling rate period

Therefore, for the case of paddy drying, vertical internal baffles may be useful in the first stage rapid drying of paddy in the two stage drying strategy[16] that consists of a first stage of rapid drying at higher temperature and higher air consumption which is followed by a second stage of slow drying or tempering.

Since vertical internal baffles could significantly increase the drying rate especially at the induction period and the initial stage of the falling rate period, the possibility of inserting vertical internal baffles in the fluidized bed system should be considered in large scale operations that process group D particles.



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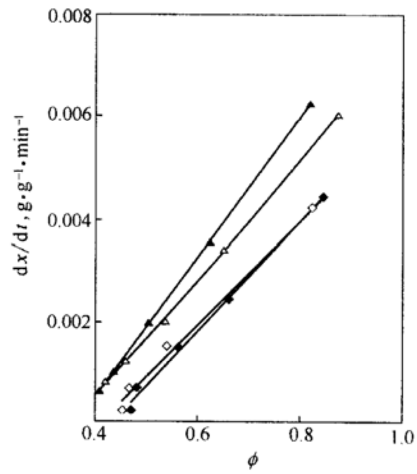


(b)

◆ bed depth=9 cm, T = 100℃, 2.0 m·s^{-1};
◇ bed depth=9 cm, T = 100℃, 2.0 m·s^{-1}, baffled;
▲ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1};
△ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1}, baffled

Figure 10 Semi normalized first drying curves of drying rate *versus* normalized moisture content in diffusion period

4.3 Thin layer drying model

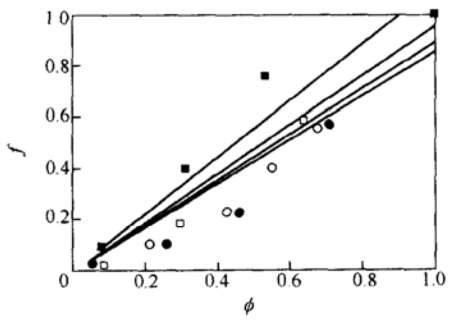
Second critical moisture contents were determined from second drying curves. Experimental data on the drying kinetics were separated into first falling rate and second falling rate periods. The drying rate and moisture content at the respective drying rate periods were normalized using equations given in Law *et al.*

Normalized first drying curves of normalized drying rate versus normalized moisture content were plotted and they are shown in Figs. 11 and 12, respectively

Table 2 Kinetics coefficients of a, b and c

Experiment	Falling rate period (linear model) coefficient a	Falling rate period (linear model) regression coefficient	Diffusion period (exponential model) coefficient b	Diffusion period (exponential model) coefficient c	Diffusion period (exponential model) regression coefficient
100℃, 2.35 m·s^{-1}, baffled	0.8863	0.9286	0.0117	4.6439	0.9677
100℃, 2.35 m·s^{-1}, unbaffled	0.8612	0.8988	0.0076	5.2071	0.8883
80℃, 2.12 m·s^{-1}, baffled	0.9533	0.9726	0.0387	3.4532	0.8664
80℃, 2.12 m·s^{-1}, unbaffled	1.1086	0.9077	0.0401	3.3803	0.9827
100℃, 2.0 m·s^{-1}, baffled	0.9093	0.9228	0.0030	6.6490	0.7632
100℃, 2.0 m·s^{-1}, unbaffled	0.9336	0.9645	0.0024	6.7883	0.7618
100℃, 1.77 m·s^{-1}, baffled	0.8869	0.9278	0.0170	4.3038	0.9397
100℃, 1.77 m·s^{-1}, unbaffled	1.0168	0.9698	0.0092	5.2941	0.8954

for falling rate and second falling rate periods. The normalized curves were regressed with linear function in falling rate period and exponential function in second falling rate period. The kinetics coefficient obtained in the respective drying rate periods are shown in Table 2.



(a)

■ bed depth=9 cm, T = 80℃, 2.12 m·s^{-1} (34.5Hz);
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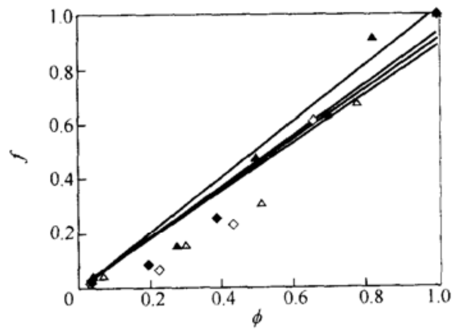
○ bed depth=9 cm, T = 100℃, 2.35 m·s^{-1} (38.5 Hz), baffled



(b)

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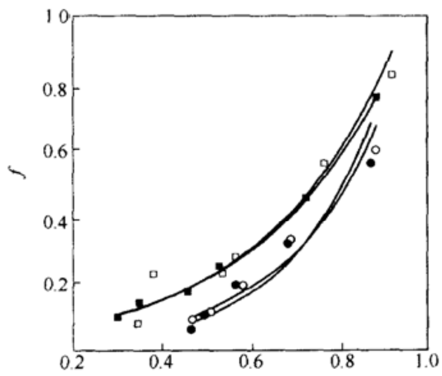
▲ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1} (28.5 Hz);
△ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1} (28.5 Hz), baffled

Figure 11 Normalized first drying curves of drying rate *versus* normalized moisture content in falling rate period

5 CONCLUSIONS

It could be concluded that the insertion of vertical internal baffles into a fluidized bed system improves the contacting efficiency of gas and particle phases through the creation of several smaller fluidized bed sections, the breaking up large bubbles into smaller ones and the resulting more vigorous circulation of both gas and particle phases. This in turn enhances the heat and mass transfer rate of the system.



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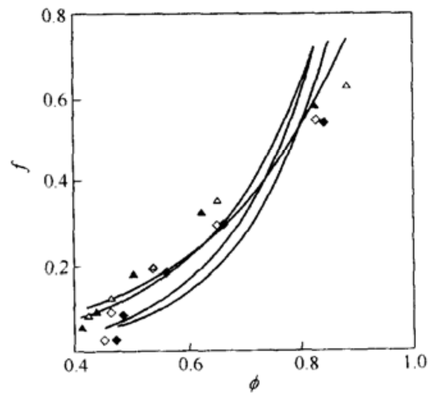

(b)

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◇ bed depth=9 cm, T = 100℃, 2.0 m·s^{-1}, baffled;
▲ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1};
△ bed depth=9 cm, T = 100℃, 1.77 m·s^{-1}, baffled

Figure 12 Normalized first drying curves of drying rate *versus* normalized moisture content in diffusion period

It was also found that the insertion of vertical internal baffles increased the drying rate of paddy drying in the fluidized bed system by as much as 10% to 25% in the initial falling rate period of the drying process. However, the drying rate in the second falling rate period was not improved because the moisture diffusivity does not depend on the gas and particle contacting efficiency.

It is concluded that large scale fluidized bed system processing group D particles should consider the possibility of inserting several vertical internal baffles in order to enhance the gas and particle mixing effect.

NOMENCLATURE

a, b, c	drying kinetics coefficient
n	real number
N, $\frac{\mathrm{d}X}{\mathrm{d}t}$	drying rate, $g \cdot g^{-1} \cdot s^{-1}$
t	drying time, min
X	moisture content dry basis, $g \cdot g^{-1}$

Subscript

1	falling rate period
2	diffusion period
cr1	first critical moisture content
cr2	second critical moisture content
eq	equilibrium moisture content

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