SOLIDS FLOW STRUCTURES IN A TWO-DIMENSIONAL RISER OF A CIRCULATING FLUIDIZED BED

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A two-dimensional riser with transparent walls has been successfully operated in a CFB loop. Solids flow structures have been investigated through the glass front wall by means of a motion analysis system. Slugs and gas-percolated plugs are observed in the dense and dilute regions of the riser respectively. Particle aggregates in the riser have elongated shapes and are not dispersed but are structured as solids streaks flowing in converging and diverging branches. The latter appear like small slugs extending on a fraction of the riser width only.

Introduction

Different regions of a CFB riser may be operated under a variety of hydrodynamic conditions from bubbling fluidized bed to pneumatic conveying. Within these extremes there are the so-called "turbulent" and "fast" fluidized beds. For given apparatus geometry and gas solids properties, regime transitions are determined by gas velocity and flow rate of circulating solids.

A simple representation of varous flow structures assumes that at one extreme the continuous phase is made of solids at minimum fluidization velocity, whereas at the other extreme it is made of gas in which individual solid particles are dispersed. In intermediate regimes the continuous phase is made of an expanded solids suspension or of gas in which solids are suspended at different concentrations.

Measurements with capacimetric and light probes provide a quantitative basis for such representation.[1-7] The local voidage steps up and down from $\varepsilon \approx \varepsilon_{mf}$ to $\varepsilon = 1$ in bubbling and slugging beds, whereas it fluctuates in narrower ranges in high-velocity fluidization. These measurements, however, do not clarify whether the continuous phase of the riser is set up by expanded solids or by gas, a matter which is relevant to gas solids contact, solids segregation, and gas and solids mixing. The extension to high-velocity fluidization of X-ray photography[8-10] developed by Rowe and Partridge[11] for a single bubble in fluidized particles potentially solves the problem. It might provide instantaneous mapping of voids inside the bed, but at typical riser velocities more voids interfere, producing intricate signals which can only be treated statistically as average local densities of solids.

Two-dimensional transparent risers might clarify this aspect but the effects exerted by the front and rear walls on solids flow bring into the problem uncertainties similar to those pointed out in a study of the flow of individual bubbles in a flat fluidization column.[12] Therefore, as in similar cases,[13] the two-dimensional technique is here proposed only as a qualitative step towards the visualization of a complex phenomenon. A similar approach was followed many years ago by Zenz and Othmer[14] in a study of FCC beds, fluidized at velocities up to about 1 m/s.

Whereas a general consensus is found in the CFB literature[5,7,15,16] with regard to the presence of curtains of solids falling along the walls of cylindrical risers, different opinions have been expressed with regard to the flow structure inside the risers. Yerushalmi, Turner and Squires[15] and Li and Kwauk[16] conjecture that particles are segregated in relatively large clusters of nearby spherical shape or in dense strands of solids dispersed in a continuum of dilute phase. Hartge *et al.*[17] suggest that a mixture of clusters and voids is present inside the riser. A similar finding is reported by Horio *et al.*[7]

1. Experimental

1.1 Apparatus

The circulating fluidized bed apparatus is schemati-

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cally shown in **Fig. 1.** Basically it consists of a two-dimensional riser having 120 × 12 mm cross section and 6.4 m height, a solids collecting system and a 100 mm ID solids recirculation column. The two-dimensional fast column has a front wall made of glass for optical investigation and a rear wall made of Plexiglas. The latter is equipped with 12 electronic pressure transducers for determining axial average solids concentrations. Details of the fast column cross section, with the position of the pressure tap on the rear wall, is shown in Fig. 1A. The recirculation column, also made of Plexiglas, has the dual purpose of storing solids and providing the driving force for their circulation in the system. Air fed through a porous plate distributor at the bottom of the recirculation column helps in maintaining the descending solids in a state of gentle fluidization. Solids are subsequently injected into the two-dimensional fast column by means of a 45° inclined Plexiglas pipe, 41 mm ID. This ends with a pipe-fitting which smoothly conveys solids to the fast column through a 75 × 12 mm port. Solids feed rate is fixed at the desired value by means of a butterfly valve. The fast column air distributor consists of 5 nozzles (Fig. 1B), each equipped with a needle valve. Visually, independent air feed rate regulation eliminates inconveniences associated with the geometry of the solids feed point, improving its dispersion in the lower section of the riser. Air forced at the bottom of the fast and recirculation columns as well as in other points of the apparatus is properly humidified. Gas and solids are separated in the collecting section by means of a set of two cyclones: the first, a medium-efficiency cyclone, is made of Plexiglas; the second, a high-efficiency cyclone, is made of steel, Gas is exhausted through a bag filter.

Diverting three-way valves are placed along both the solids discharge lines of the cyclones to allow solids flowrate measurements. These valves are operated with a compressed air actuator. Solids samples, taken over electronically determined time intervals, are recharged into the system through the hopper above the recirculation column. The solids collecting time is measured by means of a photodiode connected to a quartz chronometer. Valve diversion time, typically 1 s, is short enough to have negligible effect on the solids head in the recirculation column and the solids flow rate in the unit during measurement. The apparatus is equipped with pressure transducers and pressure indicators as shown in Fig. 1. Pressure signals along the two-dimensional fast column, collected by means of DRUCK PDCR 130/C electronic transducers, are continuously monitored and stored by a HP 3852A data acquisition/control unit interfaced with a HP 86B computer. Acquisition frequency has been set at 150 Hz. A KODAK SPIN

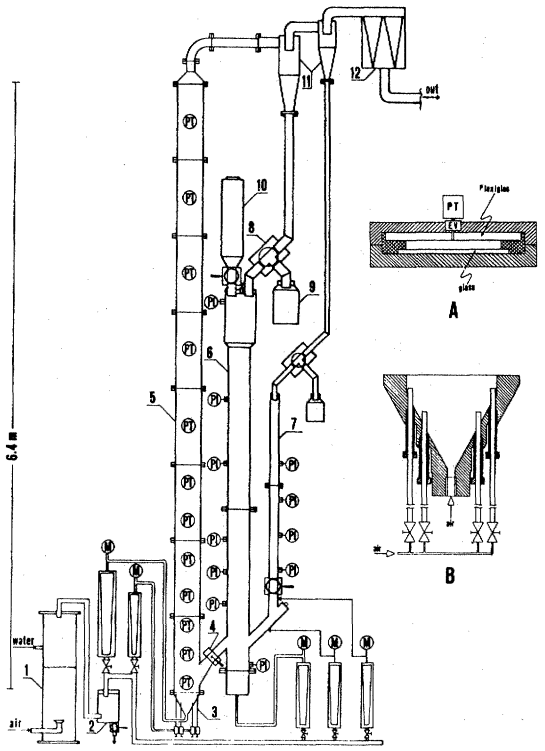


Fig. 1. Circulating Fluidized Bed unit. 1) Humidifier; 2) Demister; 3) Fast column air distributor; 4) Solids control butterfly valve; 5) Two-dimensional fast column; 6) Recirculation column; 7) Fines recirculation standpipe; 8) Three-way solids diverting valve; 9) Solids collecting bottle; 10) Feed hopper; 11) Cyclones; 12) Bag filter. PT = pressure transducer; PI = pressure indicator; M = manometer.
A) Fast column cross section: B) Fast column air distributor

Table 1. Material and operating variables tested

	Glass beads	
Material		
Particle size range, μm	70–125	
Particle Sauter mean diameter, μm	90	
Particle density, kg/m³	2543	
Particle terminal velocity, m/s	0.48	
Experimental conditions		
Superficial gas velocity, m/s	5	6
Solids mass flux, kg/(s*m²)	122; 220; 303; 420	250
Solids inventory, kg	30	30

PHYSICS SP2000 Motion Analysis System is used at speeds up to 2000 video frames per second. Each frame covers a riser front-wall area 120 mm wide and 144 mm high.

1.2 Material and techniques

Properties of glass beads tested are reported in **Table 1** together with ranges of operating variables.

The experimental procedure is the same as that previously described[18]. For a given amount of solids in the apparatus, superficial gas velocity and solids mass flux, the axial profile of solids volume fraction (1-ε) is determined from pressure drops with the

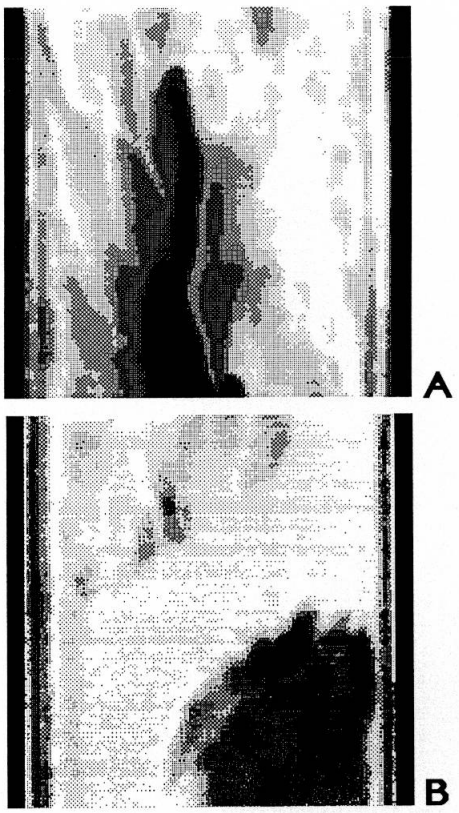


Fig. 2. Pictures of solid flow structure (here and in Figs. 3 and 4, black regions indicate gas phase; white and gray regions indicate solid-gas suspensions at various degrees of voidage). Slugs in the dense region of the riser. ($U_g = 5$ m/s; recording height = 0.60 m).
A) $G_s = 220$ kg/(s·m^2); average voidage = 0.916; B) $G_s = 420$ kg/(s·m^2); average voidage = 0.749

assumption that $\Delta P = \rho_s g(1-\varepsilon)\Delta z$. Video films are recorded simultaneously with pressure measurements in a time interval of about 10 s, at different levels along the fast column. Captions of **Figs. 2, 3** and **4** give average voidages at the level at which video film recordings were made. Pictures in the same figures were obtained by means of a digitalization process: black regions indicate $\varepsilon \approx 1$; white and gray regions indicate solids-gas suspensions at various degrees of solids concentration. The KODAK SPIN PHYSICS Motion Analysis System allows a frame by frame analysis of video-recordings. For each video frame a series of "data frames" are available on the monitor screen. These include the elapsed time, i.e. the time elapsed from the beginning of each recorded event, and the position of the two axes of a movable reticle. Using these data it is possible to obtain information about average velocity and size of different solids flow structures (e.g. sluge, plugs) showing up during video recordings.

2. Results and Discussion

In spite of wall effects the riser behaviour is, at least qualitatively, what one would expect if the flat col-

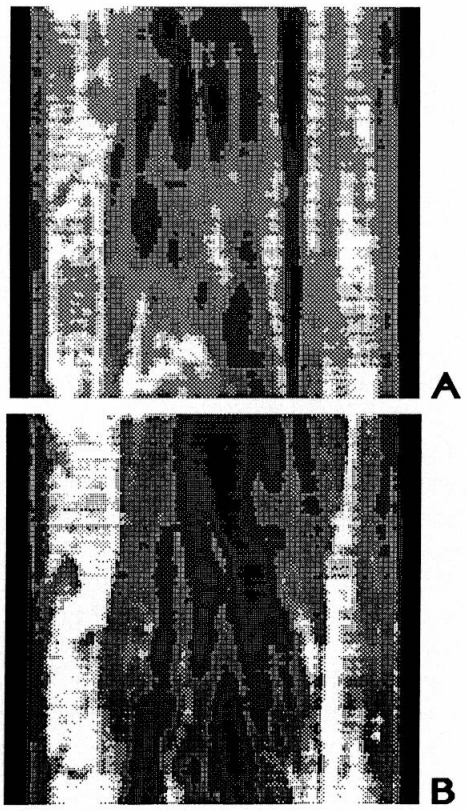


Fig. 3. Pictures of solid flow structure
Percolated plugs in the dilute region of the riser. ($U_g = 5$ m/s; $G_s = 303$ kg/(s·m^2); average voidage = 0.931; recording height = 4.7 m)

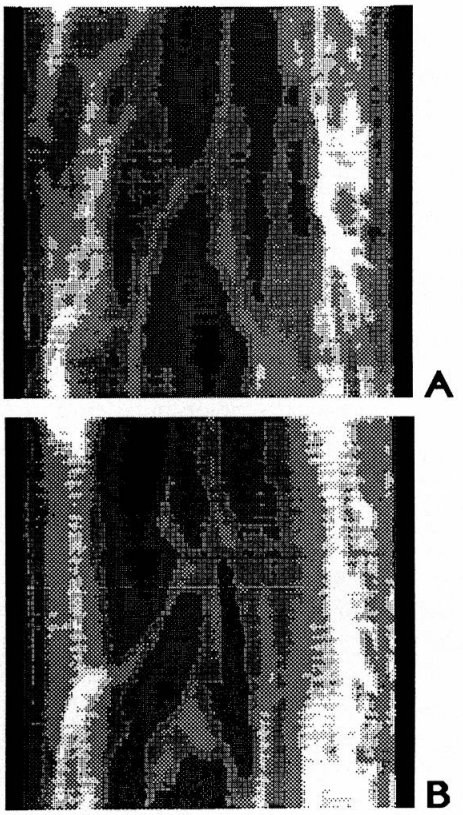


Fig. 4. Pictures of solid flow structure.
Typical converging and diverging streaks of solids in the dilute region. ($U_g = 5$ m/s; $G_s = 220$ kg/(s*m^2); average voidage = 0.951; recording height = 4.70 m)

umn were a diametral slice of the 120 mm ID riser previously tested.[19] Solids are seen to move upwards through the front wall of the riser, with the exception of the layers close to the side walls, where the material generally moves downwards. The motion of these layers corresponds to that observed at the walls of cylindrical risers. There is no evidence of solids falling down along the front wall of the column.

A dilute region extends over the whole riser in experiments at $U_g = 5$ m/s and $G_s = 122$ kg/(s·m^2). Dense and dilute regions are observed in experiments at $U_g = 5$ m/s and $G_s \geq 220$ kg/(s·m^2), and at $U_g = 6$ m/s and $G_s = 250$ kg/(s·m^2). Measured voidages are in the range of $\varepsilon = 0.749$—0.916 in the dense phase and of $\varepsilon = 0.918$—0.975 in the dilute phase.

Cavities show up with a frequency of 4—5 Hz in the dense region. They recall slugs in two-dimensional slugging beds although their walls are not always clear-cut in the particulate phase, as is shown by the change of solids concentration around the voids (Fig. 2A). At higher solids concentration the shape of the slugs is more defined (Fig. 2B).

A sort of upward moving solids plugs, somewhat percolated by vertical gas streams (Fig. 3), appears in the dilute region at $G_s \geq 220$ kg/(s·m^2) with a frequency of about 8 Hz. These plugs are seen for about 20% of the recording time. It is still to be determined whether they originate from the evolution of the particulate phase between the slugs developed in the dense region or are the consequence of phenomena entirely occurring in the dilute region. Moreover, it should be also ascertained whether streaks of solids typical of the dilute region (Fig. 4) are generated by the plugs or are the result of perturbation of the flow inside the slugs, or both.

It is noteworthy that percolated plugs interfere in the dilute region with lateral layers of solids moving downstream. Plugs collect these solids so that fresh material from the interior of the riser can reach side walls. This finding could be suggestive of key mechanisms in heat and mass transfer phenomena inside a CFB.

Isolated solids aggregates do not appear in video recordings of the dilute region of the riser even in the case of low solids concentrations ($\varepsilon = 0.975$). Instead, solids segregate into streaks which move, somewhat inclined to each other, from one side to the other of the column cross section.

Two streaks originated somewhere from the riser axis may converge into a single streak, whereas a streak may divide into two diverging streaks, probably because of flow instabilities. This sets up a coherent net structure (Figs. 4A and 4B). Video recording analysis shows that individual meshes of the net can be seen as elongated bubbles or more properly as void wedges eventually turning into small, small-

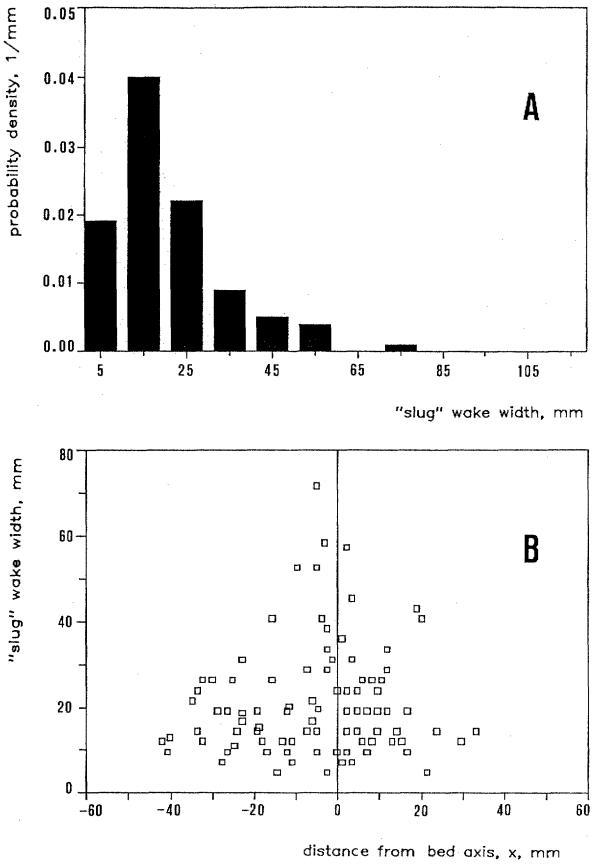


Fig. 5. "Slug" sizes.
A) Width distribution of "slug" wakes; B) Wake width of "slug" at various distances from bed axis
($U_g = 5$ m/s; $G_s = 122$ kg/(s·m^2); average voidage = 0.975; recording height = 4.7 m)

scale "slugs". Each of these "slugs" is confined by nearby "slugs" or by solids layers along the side walls. The noses of these unusual "slugs" travel up at velocities higher than solids velocities in the wakes. The width of a wake increases as the distance from the noses increases, until the "slug" merges into other wakes or noses of interacting "slugs". A comparison of video recordings of flows at various G_s shows that network structure vanishes at low solids concentrations in the riser.

Wake widths of "slugs" measured at their largest values are within the range of 5 to 70 mm. For a sample of 100 "slugs" the most probable wake width is between 10 and 20 mm, as indicated by the probability densities in **Fig. 5A**. **Figure 5B** suggests that wakes of these sizes shown up with approximately uniform distribution within a distance x from the axis between $x = -40$ mm and $x = +40$ mm. Larger wakes appear in narrower intervals. "Slugs" with wakes as large as 60 mm only appear when their axis is more or less the same as the riser axis. It is likely that the observed distribution of locations of "slugs" of different size is influenced by the presence of side walls of

the column and by descending solids layers down such walls.

Rise velocities of the 100 "slugs" whose wake widths are reported in Figs. 5A and 5B are shown in **Figs. 6A** and **6B**. They are within the range between 4 and 9 m/s. The more probable "slug" velocity is about 7 m/s, i.e. a velocity 40% larger than superficial gas velocity U_g in the riser. This finding is in agreement with results by Hartge *et al.*[17] and Horio *et al.*[7] for cylindrical risers. The exceptionally high values of "slug" velocities in respect to U_g might be explained as the result of uneven gas flow across the riser similar to what happens in vigorously bubbling beds.[20] Velocities of "slugs" vary with their location with respect to the riser axis. Higher-velocity "slugs" show up at $x=0$ mm.

Conclusions

Digital image processing of video recordings of solids flow in a two-dimensional transparent riser provides useful informantion on the structure of fast fluidization in a CFB.

Slugs similar to those of an ordinary slugging bed are observed at the bottom of the riser when a dense region is present. Percolated plugs, which might have a key role in the transfer mechanism at the CFB walls, develop in the upper dilute region of the riser.

Isolated solid aggregates are not shown by the video recordings. Solids segregate into streaks, originating a coherent network structure whose meshes can be seen as unusual, small-scale "slugs". These are generally smaller than the column width and move considerably faster than gas superficial velocity in the riser.

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Nomenclature

g	=	acceleration due to gravity	[m/s^2]
G_s	=	solids mass flux	[kg/s*m^2]
ΔP	=	pressure drop	[Pa]
U_g	=	superficial gas velocity	[m/s]
x	=	lateral distance from bed axis	[m]
z	=	riser height coordinate	[m]
ε	=	voidage	[—]
ε_{mf}	=	voidage at minimum fluidization	[—]
ρ_s	=	solids density	[kg/m^3]

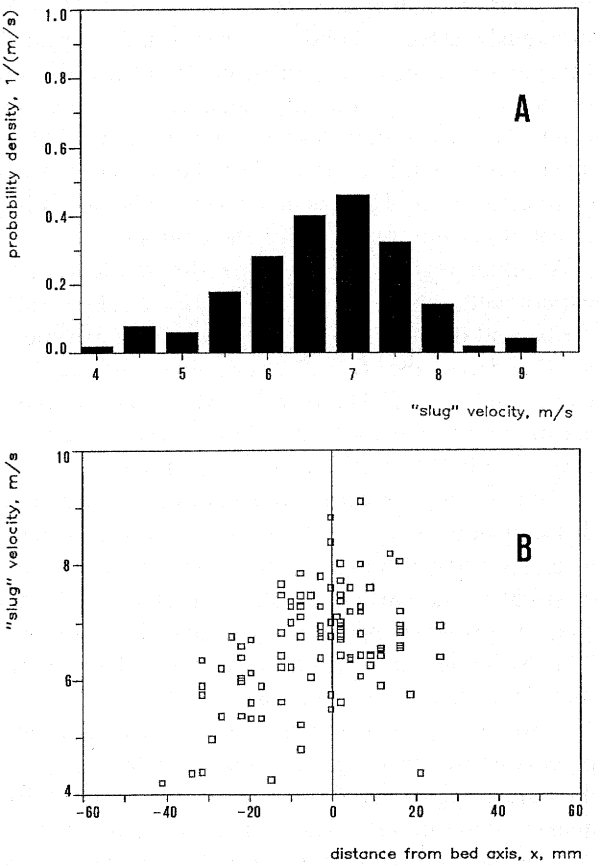


Fig. 6. "Slug" velocities.
A) "Slug" velocity distribution; B) "Slug" velocity at various distances from bed axis
($U_g=5$ m/s; $G_s=122$ kg/(s·m^2); average voidage=0.975; recording height=4.7 m)

Literature Cited

1) Lanneau, K. P.: *Trans. Inst. Chem. Eng.*, **38**, 125 (1960).
2) Massimilla, L.: *AIChE Symp. Ser.*, **69**, No. 128, 11 (1973).
3) Carotenuto, L., S. Crescitelli and G. Donsi: *Quad. Ing. Chim. Ital.*, **10**, 12 (1974).
4) Thiel, W. J. and O. E. Potter: *Ind. Eng. Chem. Fund.*, **16**, 24 (1977).
5) Hartge, E. U., Y. Li and J. Werther: Circulating Fluidized Bed Technology, ed. by P. Basu, Pergamon Press, 153 (1986).
6) Hartge, E. U., Y. Li and J. Werther: in Fluidization V, ed. by K. Ostergaard and A. Sorensen, Eng. Foundation, New York, 345 (1986).
7) Horio, M., K. Morishita, O. Tachibana and M. Murata: Circulating Fluidized Bed Technology II, ed. by J. F. Large and P. Basu, Pergamon Press (1988).
8) Kehoe, P. W. K. land J. F. Davidson: *Inst. Chem. Eng. Symp. Ser.*, **33**, 97 (1971).
9) Weinstein, H., M. Shao and M. Schnitzlein: Circulating Fluidized Bed Technology, ed. by P. Basu, Pergamon Press, 201 (1986).
10) Yates, J. G., V. Bejeck and D. J. Cheesman: Fluidization V, ed. by K. Ostergaard and A. Sorensen, Eng. Foundation, New York, 79 (1986).
11) Rowe, P. N. and B. A. Partridge: Symp. on the Interaction between Fluids and Particles, Inst. of Chem. Eng., London (1962).
12) Collins, R.: *J. Fluid Mech.*, **22**, 763 (1965).

13) Hussain, A. K. M. F.: *J. Fluid Mech.*, **173**, 303 (1986).
14) Zenz, F. A. and D. F. Othmer: "Fluidization and Fluid-Particle Systems," Reinhold Publish. Corp., New York, 283 (1960).
15) Yerushalmi, J., D. H. Turner and A. Squires: *Ing. Eng. Chem., Process Des. Dev.*, **15**, No. 1, 47 (1976).
16) Li, Y. and M. Kwauk: Fluidization, ed. by J. R. Grace and J. M. Matsen, Plenum Press, New York, 537 (1980).
17) Hartge, E. U., D. Rensner and J. Werther: Circulating Fluidized Bed Technology II, ed. by J. F. Large and P. Basu, Pergamon Press (1988).
18) Arena, U., L. Massimilla and D. Pirozzi: FBC Comes of Age, ed. by J. Mustonen, Proc. of The 9th Int. Conf. on FBC, Amer. Soc. of Mech. Eng., 762 (1987).
19) Arena, U., A. Cammarota, L. Massimila and D. Pirozzi: Circulating Fluidized Bed Technology II, ed. by J. F. Large and P. Basu, Pergamon Press (1988).
20) Weimer, A. W. and D. E. Clough: *AIChE J.*, **29**, No. 3, 411 (1983).