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Effects of Secondary Air Injection Upon the Fluidization Characteristics of the Lower Stage in a Two-Stage, Variable-Area Fluidized Bed Riser

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EFFECTS OF SECONDARY AIR INJECTION UPON THE FLUIDIZATION CHARACTERISTICS OF THE LOWER STAGE IN A TWO-STAGE, VARIABLE-AREA FLUIDIZED BED RISER

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ABSTRACT

A transparent scale model of a two-stage fluidized bed coal dryer with a small diameter lower stage and a large diameter upper stage, separated by a conical transition zone with secondary air injection ports, has been constructed to study the effects of secondary air injection upon the fluidization characteristics of the lower riser stage. The superficial velocity of the lower stage of the riser was held constant within the turbulent fluidization regime while the superficial gas velocity in the upper riser stage was varied by changing the volumetric flow rates of air introduced between the upper and lower riser stages. Through examination of time series pressure data via standard deviation, autocorrelation, spectral density plots and visual observation of dense bed height, it becomes apparent that secondary air injection has a dominant effect upon the fluidization characteristics below the injection location, leading to a transition from a dense to a dilute bed.

INTRODUCTION

While not commonly used for commercial drying of fine coal particles, many other industries have utilized fluidized beds for the drying of granular materials such as grains, fertilizers and chemicals [1,2,3,4]. Fluidized beds possess many advantages over more conventional drying techniques, among these advantages are: better temperature control, more uniform temperature distribution, higher thermal efficiency and intensity of drying, better gas-particle contact and less degradation of the particles. Unfortunately, there are also disadvantages associated with fluidized bed drying. These disadvantages include high pressure drops, non-uniform moisture content in the product (when operated in continuous mode) and the inability to adapt to counter-current operations [5,6,7,8].

While not commonly utilized in commercial coal drying applications, there has been some research conducted to study aspects of fluidized bed drying of coal. Diamond

[7] concluded in a study to determine the effects of temperature and particle size on the fluidized bed drying of northern Ireland lignite coal that drying rates increased as air temperatures increases, as well as when particle sizes decreased. Calban et al [5] obtained similar results while studying the drying characteristics of Turkish lignite in a batch bubbling fluidized bed. In addition to temperature and particle size considerations, Calban et al [5] determined that the velocity of the drying air had no significant effect on drying rates. In another study, Calban [6] investigated the effects of bed height and initial moisture concentration on drying rates of Turkish lignite. Rowan [9] examined the performance of a two-stage, variable area fluidized bed dryer with secondary air injection.

Commonly used in pulverized coal boilers, secondary air injection in fluidized beds typically consists of splitting the fluidizing gas supply and introducing it into the fluidized bed riser at multiple bed height locations. Ersoy et al [10] examined the hydrodynamics of a circulating fluidized bed with secondary air injection, finding that secondary air injection led to an increase in solids holdup in the zone below the injection height for both radial and tangential injection modes. Above the secondary air injection location, it was found that only tangential injection led to an increase in solids holdup. It was also found that using a higher ratio of secondary air to primary air (into the bottom distributor) also led to higher solids holdup values. Ersoy et al [10] also looked at the effects of secondary air injection on the axial particle velocities and noted a decrease in the primary zone below the injection location and an increase in the secondary zone above. Chen et al [11] examined the effects of secondary air injection on the distribution of solids concentration and proposed a correlation between the secondary air penetration distance and the velocity of secondary air.

In each of the previous studies, the fluidized beds used were of constant cross-sectional area, and the given superficial gas velocities were calculated by combining the flow rates of air into the bottom bed distributor as well as the secondary air. The current study utilizes a novel two-stage, variable area geometry, as described in the following section. In addition, the objective of the current study was to maintain a constant superficial gas velocity in the lower riser stage, U_L, while increasing the superficial gas velocity in the upper riser stage, $U_{U,}$ by increasing the amounts of secondary air injection. In this way, it was possible to characterize the effects of secondary air injection on the fluidization characteristics below the secondary injection location.

EXPERIMENTAL SETUP

The fluidized bed system shown in Figure 1 is a scale model of a larger system designed to be a warm air dryer of fine coal particles. The model riser is constructed primarily of transparent acrylic sections to allow for visual observation during operation. The lower stage has an inside diameter of 2.29 inches and a height of approximately 55.625 inches, the upper riser stage has an inside diameter of 4.0 inches and a height of 36.75 inches. The system also contains an air distributor at the bottom of the lower stage, and a second conical distributor located between the lower and upper riser stages. Both distributor plates are designed so that air is injected radially into the riser. In addition, the lower distributor has another air inlet that forms a vertical jet along the centerline of the riser. The air supply for both of the distributors and the bottom jet is supplied by a compressor and are individually controlled via rotameters.

Sand with a specific gravity of 2.65 and particle sizes ranging between 150 and 500 microns are supplied at a constant feed rate into a pneumatic transport line and enter the bottom of the fluidized bed riser through the bottom air jet. Particle-laden air exits the riser through an exit port in the upper riser stage and enters a cyclone, which separates the sand from the exhaust gases. The sand is then collected in a solids collection bin attached to the bottom cyclone exit and the air leaving the cyclone is passed through a water filtration drum to trap any sand not separated out by the cyclone.

Omega Engineering PX35k1- series pressure transducers are located along the height of the riser. Three are located within the lower riser stage; they are located at the bottom, middle and top, respectively. Another is located at the bottom of the upper riser stage, and the final is located just below the exit port at the top of the upper riser stage. Each of the pressure transducers measure absolute pressures in units of psia at a sample rate of 100 samples per second and the resulting signal was recorded for later analysis via an Omega Engineering OMB-DAQ-300 usb data acquisition system.

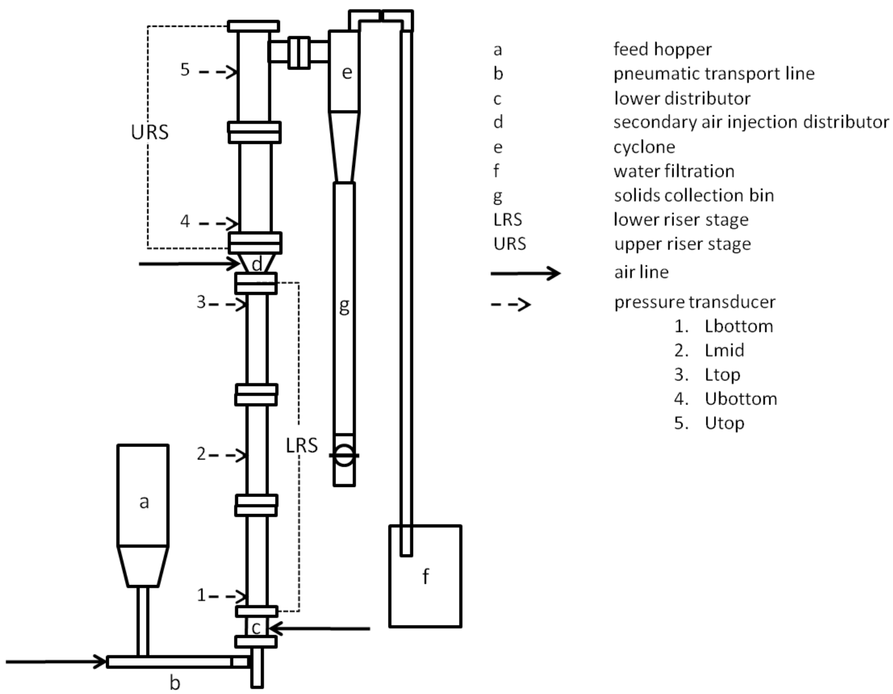

Figure 1: System diagram

RESULTS AND DISCUSSION

For this series of testing, the superficial gas velocity in the lower stage of the fluidized bed riser (U_L) was maintained at a constant 2.36 m/s, which was determined to be within the turbulent fluidization regime by prior fluidization regime mapping. The superficial gas velocity within the upper stage of the riser (U_U) was then varied from 1.42 m/s to 3.35 m/s by the addition of secondary air injection at the transition between the two stages. Table 1 shows all of the test conditions.

Table 1: Test point upper and lower riser stage superficial velocities

Test #	1	2	3	4	5	6	7
U_L (m/s)	2.36	2.36	2.36	2.36	2.36	2.36	2.36
U_U (m/s)	1.42	1.74	2.06	2.38	2.70	3.02	3.35

Figures 2 and 3 show the effects of increasing levels of secondary air injection upon the standard deviations of pressures in the lower and upper riser stages. Similar trends can be seen in both figures. Each exhibits an initial increase in the magnitude of standard deviation as the pressure fluctuations increase. This increase is then followed by a subsequent decrease and then leveling out in the values of standard deviation. The peak at U_L = 2.36 m/s and U_U = 1.74 suggests that both riser stages are undergoing transition to turbulent fluidization at those operating conditions. The curves in both figures, with the exception of the Lbottom location (Figure 1a), exhibit a transition to fast fluidization when the amount of secondary air injection leads to approximate superficial velocity matching between the two riser stages (i.e. U_L = 2.36 m/s and U_U = 2.38 m/s).

In addition, as can be seen in Figure 2, the relative magnitudes of the standard deviation decreases with increasing height within the lower riser stage, and the Lbottom location exhibits a more gradual transition to core-annular flow than seen at the Lmid and Ltop locations. This suggests that the effects of secondary air injection occur first close to the area of injection and propagate progressively lower down the riser with increasing amounts of secondary air injected, as denoted by increasing values of upper riser stage superficial velocity, U_U.

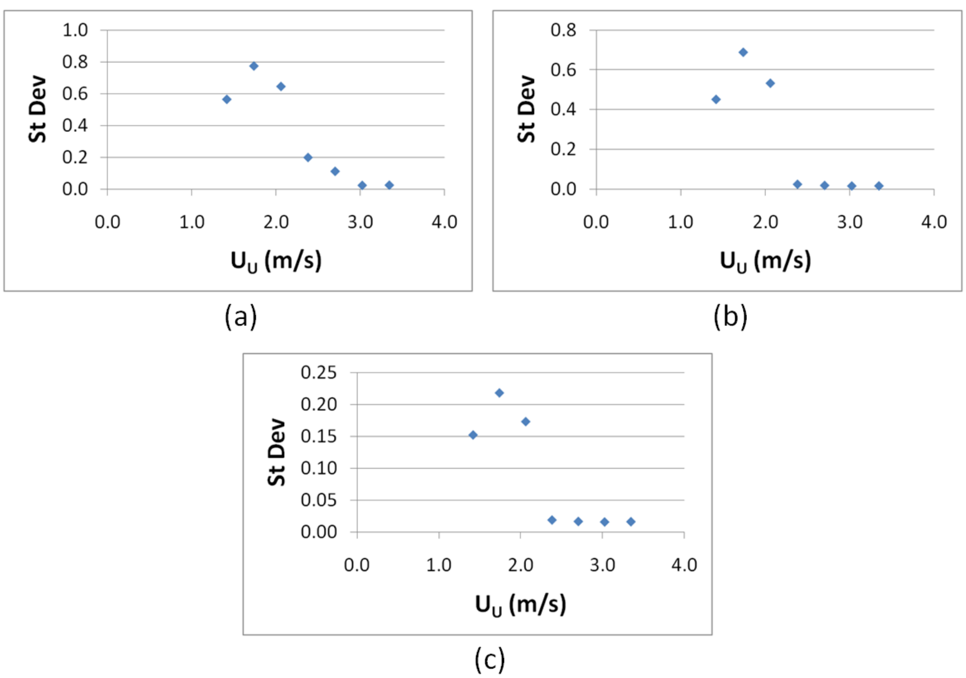

Figure 2: Lower riser stage standard deviation of pressure (a) Lbottom (b) Lmid (c) Ltop pressure transducer locations.

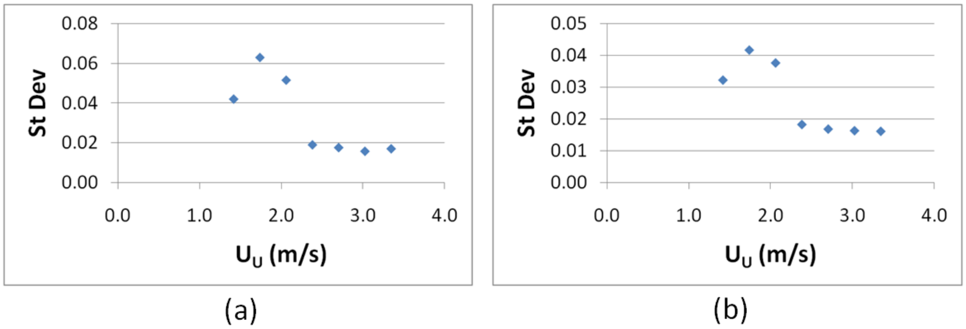

Figure 3: Upper riser stage standard deviation of pressure (a) Ubottom (b) Utop pressure transducer locations.

The effects of increases levels of secondary injection upon the fluidization characteristics within the lower stage of the two-stage fluidized bed can also be seen when examining the autocorrelation and spectral density plots shown in Figures 4 and 5. Due to space considerations, only data for the Lbottom pressure transducer location are presented here.

Figure 4 shows the effects of increasing amounts of secondary air injection upon the autocorrelation function of the Lbottom pressure transducer data. The autocorrelation curves in lots a-c show evidence of very little periodicity in the fluctuations of pressure. Plots d-g exhibit a higher frequency of extremely low magnitude oscillations about zero and are assumed to primarily represent signal noise in the instrumentation system due to a lack of bubble formation within the riser as it transitions from a dense bed to a dilute fluidization regime.

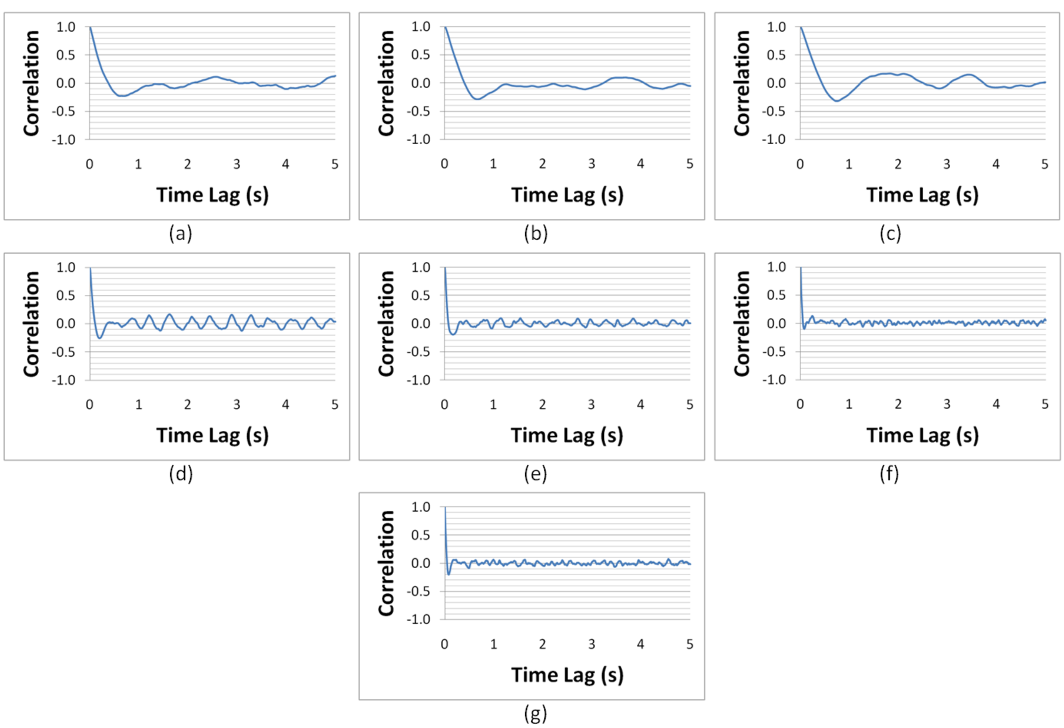

Figure 4: Autocorrelation of Lbottom pressure: U_L = 2.36 m/s, U_U = (a) 1.42 m/s (b) 1.74 m/s (c) 2.06 m/s (d) 2.38 m/s (e) 2.70 m/s (f) 3.02 m/s (g) 3.35 m/s.

Perhaps the most obvious indicator of the effects of secondary air injection upon the fluidization characteristics of the lower riser stage of the two-stage fluidized bed is the spectral density plots, as shown in Figure 5. For levels of secondary air injection resulting in upper riser superficial velocities $U_U \leq U_L$=2.36 m/s, the frequency of pressure fluctuations are concentrated within a range of frequencies between 0 and 2.5 Hz. In addition, the magnitude of power associated within these frequencies increases as U_U approaches the value of U_L. As the magnitude of U_U increases beyond U_L, there is a resulting widening of the range over which the pressure fluctuation frequencies are spread. In addition, there is a general shift towards higher frequency ranges and the amount of power associated with each frequency becomes several orders of magnitude less than seen with lower amounts of secondary air injection.

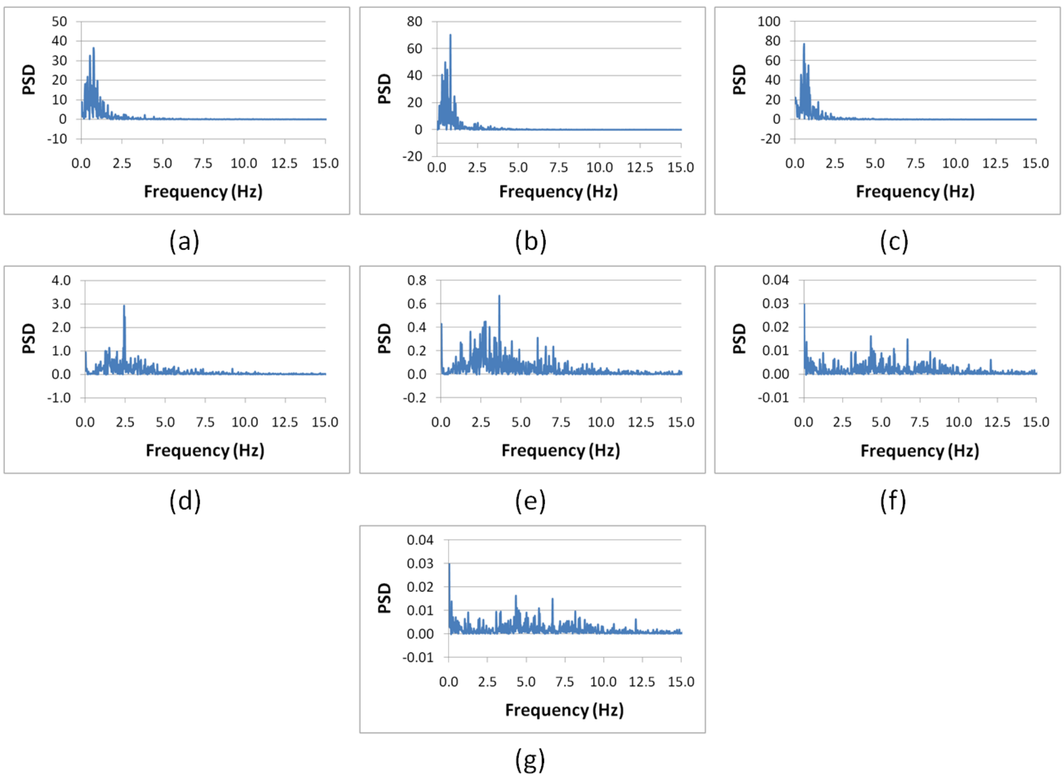

Figure 5: Spectral density of Lbottom pressure: U_L = 2.36 m/s, U_U = (a) 1.42 m/s (b) 1.74 m/s (c) 2.06 m/s (d) 2.38 m/s (e) 2.70 m/s (f) 3.02 m/s (g) 3.35 m/s.

Figure 6 shows the effects of increasing levels of secondary air injection (reflected by increasing upper riser stage superficial velocity U_U) upon the height of the visually observed interface between the dense turbulent bed and dilute fast fluidization in the lower riser stage. In the figure, the area above the curve exhibited visual indications of fast fluidization (or core annular flow), while the region below the curve appeared to be in a state of turbulent fluidization. As U_U increased, the height of the dense turbulent bed within the lower riser stage was observed to decrease. This supports the conclusion from examining Figure 2 that increasing levels of secondary air injection results in transition to fast fluidization progressively lower with the lower riser stage.

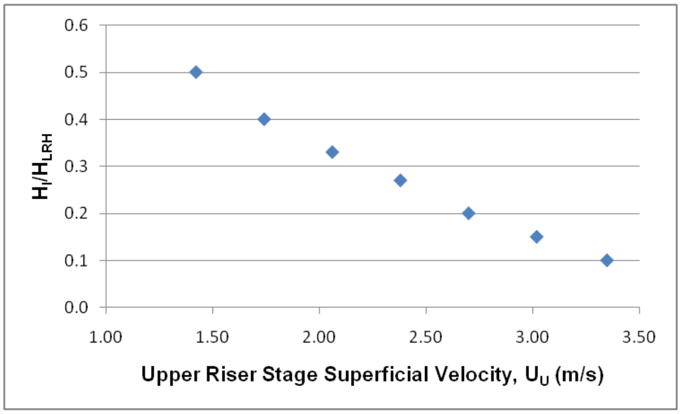

Figure 6: Effects of upper riser stage superficial gas velocity on normalized height of interface between dense bed and dilute regions of lower riser stage.

CONCLUSIONS

A transparent scale model of a two-stage, variable area fluidized bed was constructed in order to study the effects of secondary air injection when introduced above a lower riser stage operating within the turbulent fluidization regime. It was discovered that increasing levels of secondary air injection eventually leads to a transition from a dense bed turbulent regime to a dilute bed fast fluidization regime below the level of secondary air injection. It is assumed that this occurs because the solids carrying capacity above the secondary air injection point increases with increasing levels of secondary air, limiting the recirculation of solids particles from the upper riser stage back into the lower riser stage. This assumption is supported by visual observation of greater amounts of solid material being pneumatically conveyed out of the upper riser stage while operating at higher upper riser stage superficial velocities.

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NOTATION

U_L	lower riser stage superficial gas velocity
U_U	upper riser Stage superficial gas velocity
H_I	height of turbulent/fast fluidization regime interface
H_{LRH}	height of lower riser stage
Lbottom	Pressure transducer, located 2 inches above bottom air distributor
Lmid	Pressure transducer, located 27.5 inches above bottom air distributor
Ltop	Pressure transducer, located 53 inches above bottom air distributor

Ubottom	Pressure transducer, located 62 inches above bottom air distributor
Utop	Pressure transducer, located 92 inches above bottom air distributor

REFERENCES

1. Balasubramanian, N., Srinivasakannan, C. Drying of granular materials in circulating fluidized beds. *Advanced Powder Technology*, 18 (2007), 135-142.
2. Jumah, R.Y., Mujumdar, A.S., Raghavan, G.S.V. Batch drying kinetics of corn in a novel rotating jet spouted bed. *The Canadian Journal of Chemical Engineering*, 74 (1996), 479-486.
3. Kannan, C.S., and Subramanian, N.B. Some drying aspects of multistage fluidized beds. *Chemical Engineering Technology*, 21 (1998), 961-966.
4. Tatemoto, Y., Mawatari, Y., Sugita, K., Noda, K., Komatsu, N. Drying characteristics of porous materials in a fluidized bed under reduced pressure. *Drying Technology*, 23 (2005), 1257-1272.
5. Calban, T. and Ersahan, H. Drying of a Turkish lignite in a batch fluidized bed. *Energy Sources*, 25 (2003), 1129-1135.
6. Calban, T. The effects of bed height and initial moisture concentration on drying lignite in a batch fluidized bed. *Energy Sources*, 28 (2006), 479-485.
7. Diamond, N.C., Magee, T.R.A., McKay, G. The effect of temperature and particle size on the fluid bed drying of northern Ireland lignite. *Fuel*, 69 (1990), 189-193.
8. Nonhebel, M.A., Moss, A.A.H. *Drying of solids in the Chemical Industry*. Butterworth & Co. Publishers, 1971.
9. Rowan, S. *Analysis and Scaling of a Two-Stage Fluidized Bed for Drying of Fine Coal Particles Using Shannon Entropy, Thermodynamic Exergy and Statistical Methods*. Doctoral Dissertation, West Virginia University, Morgantown, WV, 2010.
10. Ersoy, L.E., Golriz, M.R., Koksal, M., Hamdullahpur, F. Circulating fluidized bed hydrodynamics with air staging: an experimental study. *Powder Technology*, 145 (2004), 25-33.
11. Chen, J., Lu, X., Liu, H. and Liu, J. The effect of solid concentration on the secondary air-jetting penetration in a bubbling fluidized bed. *Poweder Technology*, 185 (2008), 164-169.