จุฬาลงกรณ์มหาวิทยาลัย

ทุนวิจัย

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ฉบับสมบูรณ์

อุทกพลศาสตร์ของสารป้อนผสมในเครื่องฟลูอิไดซ์เบดแบบหมุนเวียน

โดย

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ชื่อโครงการวิจัย อุทกพลศาสตร์ของสารป้อนผสมในเครื่องฟลูอิไดซ์เบดแบบหมุนเวียน

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บทคัดย่อ

งานวิจัยนี้ทำการทดลองในเครื่องฟลูอิไดซ์เบดแบบหมุนเวียน ที่มีเส้นผ่านศูนย์กลางและความสูงของไรเซอร์เท่ากับ 5 และ 200 ซม. ตามลำดับที่อุณหภูมิและความดันปกติ โดยมีจุดประสงค์เพื่อศึกษาอุทกพลศาสตร์ของของผสมระหว่างทรายและชีวมวลชนิดต่าง ๆ 3 ชนิด คือแกลบ ขี้เลื่อย และชานอ้อย ที่อัตราส่วนร้อยละ 50 โดยปริมาตร ที่ความเร็วอากาศในช่วง 4.2-5.7 เมตรต่อวินาที ความเร็วของทรายที่เคลื่อนที่ในท่อไรเซอร์หาได้จากการใช้กล้องความเร็วสูง และโปรแกรมวิเคราะห์ภาพ ผลการทดลองพบว่าที่ความเร็วอากาศต่ำที่สุด ความเร็วของทรายในของผสมระหว่างทรายและชีวมวลมีความเร็วมากกว่าระบบที่มีทรายเพียงอย่างเดียว แต่ที่ความเร็วอากาศสูงที่สุดพบว่าความเร็วของทรายในของผสมระหว่างทรายและขี้เลื่อยมีความเร็วมากที่สุด ต่อมาได้ทำการทดลองกับของผสมระหว่างเม็ดแก้วและแกลบพบว่าในตอนล่างของท่อไรเซอร์ ความเร็วของเม็ดแก้วในของผสมมีความเร็วน้อยกว่าระบบที่มีเม็ดแก้วเพียงอย่างเดียว แต่เมื่อความสูงของไรเซอร์เพิ่มขึ้น ความเร็วของเม็ดแก้วในทั้งสองระบบมีค่าใกล้เคียงกัน

Project Title Hydrodynamic of Mixed-feed in Circulating Fluidized Bed

Name of Investigator Assistant professor Suchaya Nitivattananon

Year July, 2009

Abstract

The research was conducted in a circulating fluidized bed having diameter and height of riser of 5 and 200 cm., respectively, at ambient temperature and pressure. The objective was to study hydrodynamics of mixed-feed between sand and various biomasses including rice husk, sawdust, and bagasse at 50% by volume. The air flow rate was in the range of 4.2-5.7 m/s. The velocity of sand in the riser was obtained by using a high speed camera and an image processing software. The results showed that at the lowest gas velocity the velocities of sand in the mixture were higher than those in the single system. However at the highest gas velocity it was found that the sand velocity in the mixture of sand and sawdust was the highest among all mixtures. Next the experiment was conducted by means of mixture of glass beads and rice husk. It was found that in the bottom part of the riser the velocities of glass beads in the mixing system were lower than those in the single system. Nevertheless, the velocities of glass beads in both systems reached similar values at the top of the riser.

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Nomenclature

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U_{mf}	Minimum fluidization velocity	5
U_t	Terminal fluidization velocity	5
μ	Viscosity	5
d_p	Particle diameter	5
ρ_g	Gas density	5
ρ_s	Particle density	5
Ar	Archimedes number, $gd_p^3(\rho_s - \rho_g)\,\rho_g/\mu^2$	5
C	Instantaneous velocity	7
L	Streak length	7
t	Time elapsed by glass beads	7
α	Angle from horizontal	7
ΔP	Pressure drop	10
ε	Voidage	10
ΔH	Distance between two adjacent points	10

CHAPTER I
INTRODUCTION

1.1 Circulating Fluidized Bed

In a variety of industrial applications, the use of a circulating fluidized bed (CFB) provides various advantages, such as reducing environmental pollution and increasing process efficiency. The application of circulating fluidized bed technology contributes to the improvement of gas-solid contact, reduction of the cross-sectional area with the use of higher superficial velocities, the use of the solids circulation rate as an additional control variable, and superior radial mixing. Since CFBs have industrial applications such as power generation, chemical processing, petroleum refining, and catalytic cracker processing, applications in combustion and refining processes are described and discussed in this section.

Circulating fluidized bed (CFB) technology has proven itself during the last decade to be a viable concept for the clean combustion of coal and other solid fuels. Having met the most stringent environmental regulations in the world, CFB technology hence has established itself as the preferred choice for many new projects in the energy production industry. In addition to its capability to achieve low gaseous emissions without additional flue gas cleaning equipment, CFB technology has gained an advantage over the conventional coal burning technologies due to its fuel flexibility. With CFB technology, all types of coal can be utilized with minimal environmental impact, including the low-grade coals often available locally (and therefore economically) in many APEC economies. Additionally, CFB's can simultaneously burn biomass; thereby reducing operating costs and further reduces emissions and giving an overall improvement to the net CO_2 production. The first CFB unit in Thailand started up in 1993 by Foster Wheeler Energy Inc. And since then it successfully burnt local lignite together with bagasse pith and sludge from the paper mill. The output from the power plant is fed to EGAT (Electricity Generating Authority of Thailand) and the remainder of the power is sold to local customers of the industrial. Nowadays, circulating fluidized beds (CFBs) have found widespread applications in a variety of industrial processes. Some major applications for such systems are the fluid catalytic cracking (FCC), coal combustors and coal gasifiers. Despite their extensive applications, the hydrodynamics of CFBs is not well understood. In general, the riser is characterized by a heterogeneity in both axial and radial direction, i.e. solid rich in the bottom part and solid lean in the top part where a predominantly upward dilute phase core at the centre is surrounded by a predominantly downward dense annulus. (Lin, 1999)

In CFB riser, the surface of the bed could not be distinguished. The bed density is high in the bottom and decreases with the height of the riser. In the cyclone the bed material and un-burnt fuel is separated from the flue gas and returned to the bottom of the "bed". This enables a very long retention time for the coal rich parts of the fuel, which can circulate several rounds before they are completely combusted. In the CFB design, fuel and bed material are fed into the lower portion of the combustion chamber in the presence of fluidizing air, which causes the fuel, ash and bed material to circulate and rise through the combustion chamber, finally, entering the solid separator. The separator captures most of the circulating solids, including unburned fuel, and returns them to the furnace via return legs. This continuous circulation increases fuel residence time and results in very efficient combustion, while a relatively low combustion temperature of around 870^{0}C and the introduction of combustion air at various levels limits the formation of NO_x.

1.1.1 Combustion applications of CFB

The first example discussed in this section is a combustion application that has a single solids circulation loop and a single gas feed. These types of units have a single standpipe for the solids and a single reaction vessel. A circulating bed coal combustor in which limestone and injected coal are circulated by air is the common example of this type of CFB application. A typical schematic diagram of a circulating fluidized bed combustion (CFBC) system is shown in Fig 1.1. It consists of a furnace region, a recycle region, a cyclone, and a heat transfer unit. An aeration injection point can be located in either of two places, i.e. the bottom and middle points of the furnace region. However, the configuration possibilities for the CFBC depend on the fluidization velocity, primary to secondary air ratio, bed densities, and different heat transfer locations.

Biomass fuels represent rich energy resource with the advantage of being a cheap and plentiful and low polluting. Bagasse, the fiber left after extraction of the cane juice, is used primarily in the sugar mills for internal energy needs. Rice has always been Thailand's major agricultural product. Currently, there is low demand for rice husk in Thailand. Sawdust is produced in wood sawing and milling activities. Circulating Fluidized Bed (CFB) gasification is now undergo rapid commercialize for

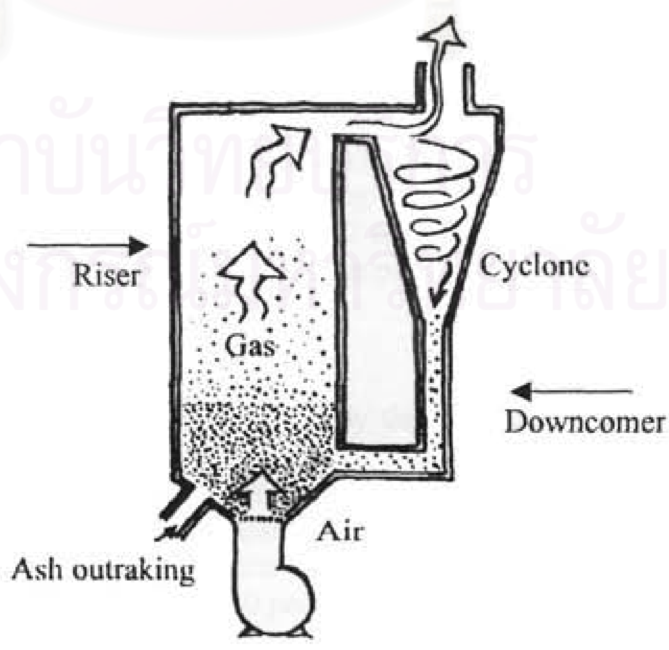

Figure 1.1 Typical Circulating Fluidized Bed (CFB)
(http://www.efe.or.th/download/biomass_training/Chapter3.pdf)

biomass. There are number of previous researches on biomass gasification in CFB (Kersten et al, 2003; Raskin et al, 2001; Chen et al, 2004; Li et al, 2004). Quantitative understanding of the hydrodynamics of circulating fluidized bed is needed for the design and scale-up of efficient new reactors (Avidan et al, 1990; Squires et al, 1985). Various techniques have been used to measure hydrodynamic flow behaviors such as pressure, velocity, flow rate and concentration (Zhang,1995)

1.1.2 Petroleum refining application of CFB

In this section, another typical application of the CFB, namely fluidized catalytic cracking (FCC) is presented and discussed. In fact, the earliest application of the circulating fluidized bed was the catalytic cracking process, developed after Eugene Houdry discovered that porous clay catalyzed the cracking reaction of gas/oil to produce high-octane gasoline at atmospheric pressure. The typical operation of FCC processes includes a preheated hydrocarbon charge with a hot, regenerated catalyst that enters the riser leading to the reactor. Next, the charge is mixed with a recycled flow within the riser, gasified, and enters the reactor at a temperature of $483^0C - 538^0C$. The charge is cracked in the riser under a pressure around of 68950 – 206850 Pa. The cracking continues until the cyclone separates the vaporized oil from catalyst. Next, the cracked product is sent to fractionators and is divided into several fractions. The heavy oil is recycled and fed back to the riser. In the regenerator block, preheated air regenerates and mixes the spent catalyst.

1.2 Previous Research Works

The hydrodynamics of CFB is strongly influenced by the distribution of particles, which is governed by the amount of particles, size, density, etc (Ibsen, 2000). A number of techniques have been applied to understand the hydrodynamic behavior of vertical gas-solid flow in a vertical pipe referred as a riser flow (Singh, 2003). For example, in 1992 Arastoopour et al used a laser Doper velocity meter to show that the particle velocity distribution for flow of a dilute solid-gas mixture is approximately Maxwellian. In 1995, Cody et. al. developed an acceleration probe and a method of measuring granular temperature in a commercial fluidized bed by Fourier analysis of noise. In 2000, Ibsen et al, using LDA/PDA as well as evaluate the modeling of the flow with a multiphase CFD code, showed that the solid velocity profile in the radial position shows core-annulus pattern.

1.3 Current Research Foci

The primary research focus is to study the hydrodynamic of mixed-feed at various gas velocities and solid circulation rates by means of the CCD camera to measure particle velocities at different locations in the riser. In the first part the mixtures were sand and various biomasses, including sawdust, rice husk and bagasse, at the ratio of 50:50 percent by volume. In the second part, the mixture was glass beads and rice husk at the ratio of 80:20 percent by volume.

CHAPTER II
EXPERIMENTAL SETUP

2.1 The Cold Flow Circulating Fluidized Bed (CFCFB)

The current research project is based on experimental data collected from a cold flow circulating fluidized bed (CFCFB) test facility installed at Chemical Technology Department, Faculty of Science. The system was built for studying the behavior and operation of circulating fluidized bed systems under ambient conditions. A simplified diagram of the CFCFB built is shown in Fig 2.1, with indicated dimensions.

The whole system is made of clear Acrylic for visual observation. It consists of a riser, cyclone, a standpipe (downcomer), and an L-valve to return solids to the base of the riser. The riser total height is 200 cm high with 5 cm ID and the downcomer is approximately 150 cm high with 10 cm ID. Fourteen pressure taps are mounted around solids circulating loop to enable the pressure drop to be accurately

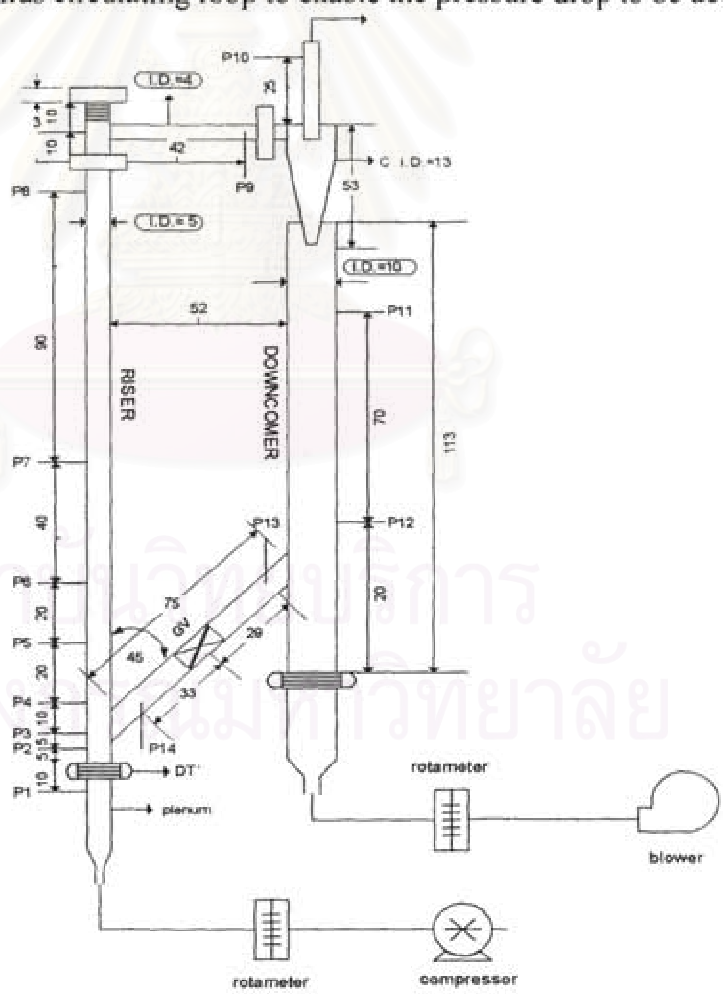

Figure 2.1 CFB apparatus

determined. The electronic pressure transducer, Yokogawa model EJA120 ranges from 0-600 mmH_2O with 0.2% accuracy, was used. Air, to riser and downcomer, provided by a compressor and blower, respectively, and the airflow rates were measured with rotameters. Solid particles from downcomer were transported to riser via the 45 degree inclined standpipes. Compressed air entered riser through a fine screen gas distributor at the bottom. At the top of riser, particles carried over were fed to cyclone in which most of them were removed from the air stream and returned to the downcomer. The exhausted air exited the system through a bag filter. Particles in the downcomer, however, were in bubbling fluidized state by air from blower.

The solid particles used in this experiment were three types of biomass (sawdust, rice husk, and bagasse), sand, and glass beads. The physical properties of sand and biomass used in this research are listed in Table 2.1. Detailed bed material characteristics for glass bead are shown in Table 2.2. Fig 2.2 presented glass beads particle size distributions.

Table 2.1 Properties of sand and biomasses

Material	Sand	Sawdust	Rice husk	Bagasse
Size range, μm	250-425	250-425	250-425	250-425
Mean diameter, μm	337.5	337.5	337.5	337.5
Particle density, kg/m^3	2312	1583	1484	630
Bulk density,	1401.0	333.1	375.8	75.8
Particle terminal velocity, m/s	2.4	1.9	1.8	1.0
Minimum fluidization velocity, m/s	0.0935	0.0647	0.0607	0.0261
Geldart's classification group	B	B	B	A-B
Archimede's number	2613	1788	1677	712
Particle shape	Compact grain	Spherical	Irregular plate	Short fiber

Table 2.2 Properties of glass beads

Material	Glass beads
Size range, μm	180-915
Mean diameter, μm	517
Particle density, kg/m3	2400
Bulk density,	1500
Particle terminal velocity, m/s	4.2
Minimum fluidization velocity, m/s	0.21
Geldart's classification group	B
Archimede's number	4653
Particle shape	Sphere

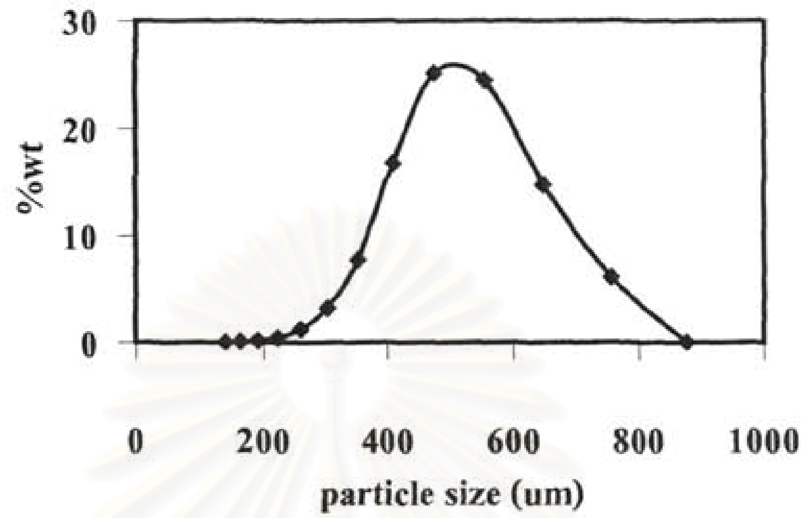

Figure 2.2 Particle size distributions of glass beads

The minimum fluidization velocity (U_{mf}) and terminal velocity (U_t) were calculated from (Basu, 1991);

$$U_{mf} = \frac{\mu}{d_p \rho_g}\left[\left\{(33.7)^2 + 0.0408\frac{d_p^3 \rho_g (\rho_s - \rho_g) g}{\mu^2}\right\}^{0.5} - 33.7\right] \qquad (1)$$

$$\frac{d_p U_t \rho_g}{\mu_g} = \left(\frac{Ar}{7.5}\right)^{0.666} \qquad (2)$$

$$Ar = \frac{\rho_g (\rho_p - \rho_g) d_p^3 g}{\mu_g^2} \qquad (3)$$

The operation of CFCFB is described as following. First, the mass of solids is aerated with a high air flow at the bottom of the riser. After reaching the top of the riser, the mass is transferred to a cyclone that separates gas from solids and vents the gas outside. The solids then fall down in the standpipe and accumulate to create the bed level. This free falling region is called the lean phase. The area below the bed level is the region defined as the dense bed, which is a fluidized flow of solids. The air injected at the base of the standpipe is referred to as move air and is one of the primary controls of the system.

2.2 PIV Technique

Particle Imaging Velocimetry (PIV) offers many advantages for the study of fluid flows. Lots of PIV techniques and PIV systems had been developed. However, there are no standard evaluation tools for the effectiveness and accuracy of PIV systems. The current status of the PIV technique is far from the popularization or generalization technique. To popularize the PIV technique for practical use, the PIV standards and the PIV guide tools should be settled. Radial particle velocity in the riser was measured using PIV technique first by Tartan (Tartan, 2004). This technique was capable of measuring particles instantaneous velocity in a control volume for measurements of a gas-liquid-solid fluidization. The system consists of a charge coupled device (CCD) camera, Sony model SSC-DC58AP, a fiber optic light source, a probe, and a personal computer with image processing software. The camera has 10 electronic shutter settings from 1/50 to 1/10000 sec. A metal probe of 0.6 cm ID and 10 cm length was used to obtain solid radial profiles. At the tip of the probe there was a thin glass piece cover to prevent solid from escaping the system. This probe made measurement of five radial positions inside of the riser intrusively. The camera is connected to a personal computer, which has a micro- imaging board and micro-imaging software for data measurement and analysis.

A CCD camera was used to measure instantaneous particle velocities. In order to get a good visualization of microscopic movement of glass beads, a fiber optic light was reflected on the field of view in opposite direction of the probe. A probe passing through the annulus regime was used in the experiments to get a view in the riser. The field of view in most experiment was 0.6 cm in diameter. The PIV setup and the probe locations can be seen in Fig 2.3. The camera was focused through the probe into the riser. The zoom and focus settings were set to maximum to get minimum depth of the control volume. Fig 2.4 shows typical streak lines generated on the computer screen. These streak lines represented the space traveled by the glass bead in a given time interval specified on the camera. The long thin lines corresponded to small particles while the short thick lines denoted large particles. The images were then captured and digitized by a micro-imaging board, and analyzed using Image-Pro Plus software. The particle velocity in radial and axial directions was estimated by dividing the respective distance by time as following;

$$\begin{aligned} C_r &= (L/t)\cos\alpha \\ C_z &= (L/t)\sin\alpha \end{aligned} \qquad (4)$$

Where L is the distance traveled or streak length, t is the time elapsed by glass beads, which is the inverse of the shutter speed of the camera, and α is the angle from horizontal.

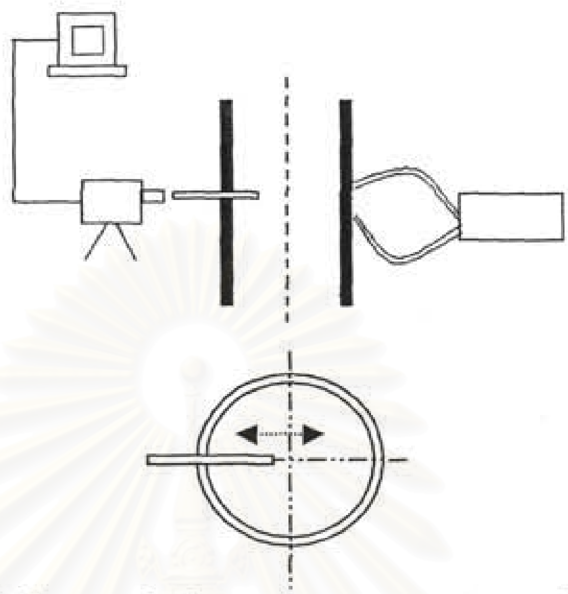

Figure 2.3 Particle image velocity measurement system and probe locations

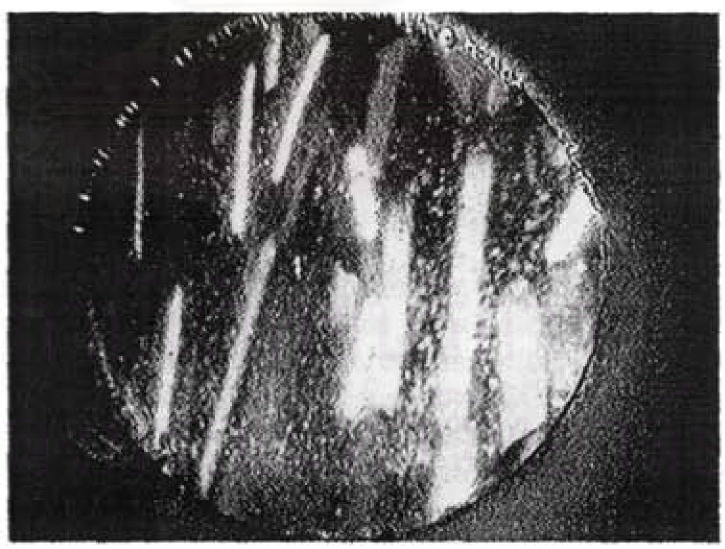

Figure 2.4 Typical streak lines captured by PIV technique

CHAPTER III
RESULTS AND DISCUSSIONS

As stated in the progress reported earlier, there are unexpected numbers of difficulties found during experiment tests. For example, the erosion of sand particle after several circulating tests caused the change in shape from spherical to irregular shape. This affects the length of the streak lines in the images taken by CCD camera. The solid velocities calculated are therefore varied from experiment to experiment. Another problem from sand particles arose when the unintentionally moist fluidized air was used. It caused the agglomerations of sand particles into small lumps causing the unsteady of bed circulation. The new particle with higher hardness that resists a great deal of collisions in the CFB riser was searched to displace the sand particles. Consequently the researcher decided to change from sand to glass beads, which are more rigid and not porous particles to solve the problems. The glass beads particle properties and size distributions are shown in Chapter 2.

The second problem came from the biomasses. The experimental results from three mixtures (sand/sawdust, sand/rice husk, sand/bagasse) sawdust seemed to be the promising biomass (Fig 3.5) for further investigation. However when moist fluidized air entered the system by chance, the sawdust was found to be the easiest particles among those three biomasses to agglomerate. And it was quite difficult to control the initial moisture of the sawdust before each run. For this reason the researcher selected rice husk instead of sawdust to mix with glass beads for additional research.

As a result, this chapter composed to two parts. Part one included the study of hydrodynamic of mixed-feed of sand and three types of biomass (sawdust, rice husk and bagasse) at various gas velocities and solid circulation rates by means of the CCD camera to measure solid particle velocities at different locations in the riser. Part two included only the hydrodynamic of mixture of glass beads and rice husk and the glass beads velocities in both systems (single phase and mixture).

It should be mentioned at this point that the solid velocities stated in this report mean only sand velocity (in part one) and glass beads velocity (in part two), not including any biomass velocity. Due to the limitation of the PIV technique, the images of biomasses (the streak lines captured by CCD camera) could not be taken. Since the focus of the CCD camera can be set for only one particle for each run. For better understanding, this research focused on an influence of each biomass in the mixtures on sand and glass beads velocities.

3.1 Hydrodynamic of mixed-feed of sand and biomasses

Tests were performed on CFCFB of differences feed; sand/ sawdust, sand/ rice husk and sand/ bagasse mixtures at the ratio of 50:50 percent by volume. The desired amount of mixed-feed was first load into the riser on the top. The entire solid was blown out to the downcomer preparing for the experiment. Air at designed value from a blower was introduced into the riser. The gate valve at the transfer line was gradually opened allowing solid to flow down to the riser until designed solid circulating rate was reached. The airflow rate was again adjusted. The first pressure data was taken after 10 minutes to ensure steady state of the system.

The ranges of experimental conditions are given in Table 3.1 for each of mixed feed tests. It was found that mixture of sand/ sawdust was circulated without much difficulty yielded the highest solid circulation flux. The difficulty was found when an effort was made to circulate mixture of sand/ rice husk. Due to rice husk's flaky nature and nongranular shape (Fang et al, 2004), the mixture was hard to transfer back to riser bottom. Mixture of sand/ bagasse, on the other hand, could not be circulated at all. This could be because bagasse is being fibrous and very light, so that it mats together. Therefore, the mixture was operated in bubbling mode, not a fast fluidization mode.

Table 3.1 Ranges of Operating Conditions

Material	Ug (m/s)	Gs (kg/m^{2}s)
Sand and sawdust	4.2-5.4	5.5-18.7
Sand and rice husk	4.8-5.9	0.8-18.0
Sand and bagasse	4.5-5.7	-

For a pressure balance in the CFB loop, the algebraic sum of pressure drop across each section of the circulation loop is equal to zero as shown in equation 5 as follows (Basu, 1991),

$$(P_2-P_8)+(P_8-P_9)+(P_9-P_{11})+(P_{11}-P_{13})+(P_{13}-P_{14})+(P_{14}-P_2) = 0 \quad (5)$$

where P_2-P_8 = pressure drop in the riser
P_8-P_9 = pressure drop between riser exit and cyclone inlet
P_9-P_{11} = pressure drop across cyclone
P_{11}-P_{13} = pressure drop in downcomer
P_{13}-P_{14} = pressure drop in transfer line

From pressure data at each position, the solid hold up can be calculated from equation of Li Z.Q. et al. (2004);

$$\varepsilon_S = \frac{\Delta P}{\Delta H g \rho_p} \quad (6)$$

where ε_s = solid hold up (-)
ΔP = pressure drop between two consecutive points (mmH_2O)
ΔH = distance between two consecutive points (cm)
ρ_P = particle density (kg/m^3)
g = gravitational force (m/s^2)

Solid holdup is one of the key parameters, which characterized a gas-solids system. In co-current gas-solids system, superficial gas velocity and solids circulation flux are the main operating variables influencing the solids holdup. Neglecting the wall friction or solids acceleration, the apparent cross-sectional average solids holdup can be obtained by measuring the average differential pressures across the sections of the riser and equating the static pressure drop to bulk weight in the riser sections.

3.1.1 Mixture of sand/sawdust

Fig 3.1 shows a pressure loop obtained from operating the mixture of sand/sawdust in the CFCFB. It can be observed that pressure in the riser decreases with height and the lowest pressure was found at the cyclone exit. In the downcomer side, the pressure increases as the level of solid increased and the highest pressure was found at P12, which is the position that the solid was transferred back into the riser again. Figs 3.2 and 3.3 show effect of superficial gas velocities on solid holdup of mixture of sand/sawdust in the riser at solid circulation rate of 5.5 kg/m^{2}s and 18.7 kg/m^{2}s, respectively. As can be seen, an increased of gas velocity results in a decrease in the solids holdup when solids circulation flux is fixed along the height of the riser. When the riser operates at a lower gas velocity, the solids transfer rate from the riser to the cyclone and downcomer is low. Thus, there is a dense phase near the bottom and a relatively dilute region near the top of riser. At lowest gas velocity of 4.2 m/s, the solid holdup shows that the system is in fast fluidization mode. On the other hand, from gas velocity of 4.5 m/s to the highest gas velocity of 5.4 m/s, it seems no particle accumulation at the riser bottom as solids were immediately entrained.

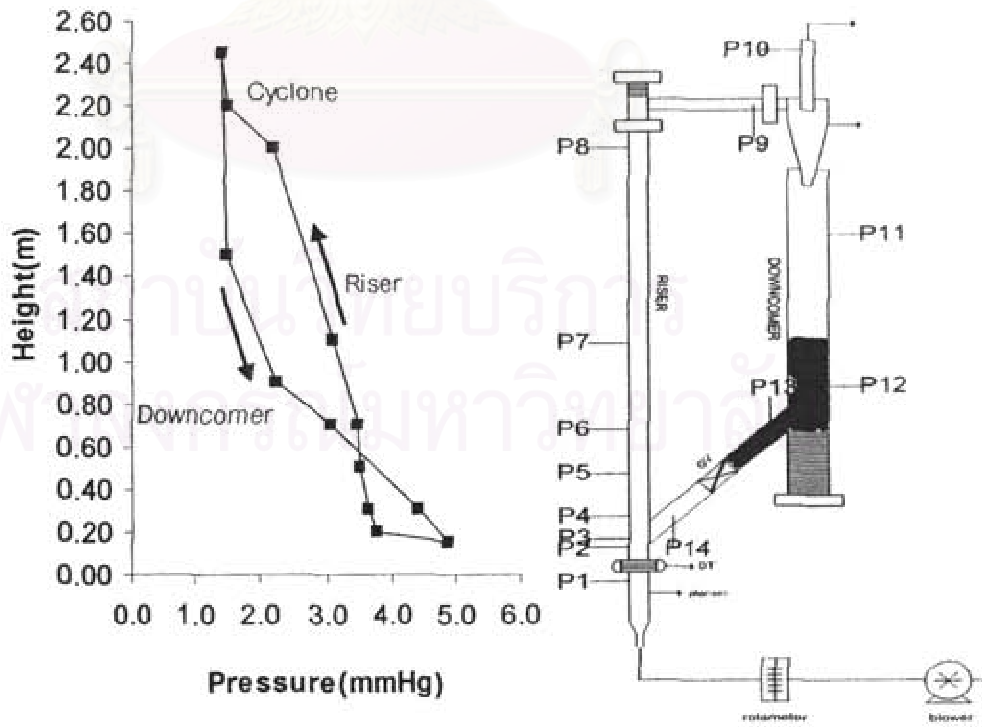

Figure 3.1 Pressure loop obtained from mixed-feed of sand/sawdust at 4.2 m/s and solid circulation rate of 5.5 kg/m^{2}s

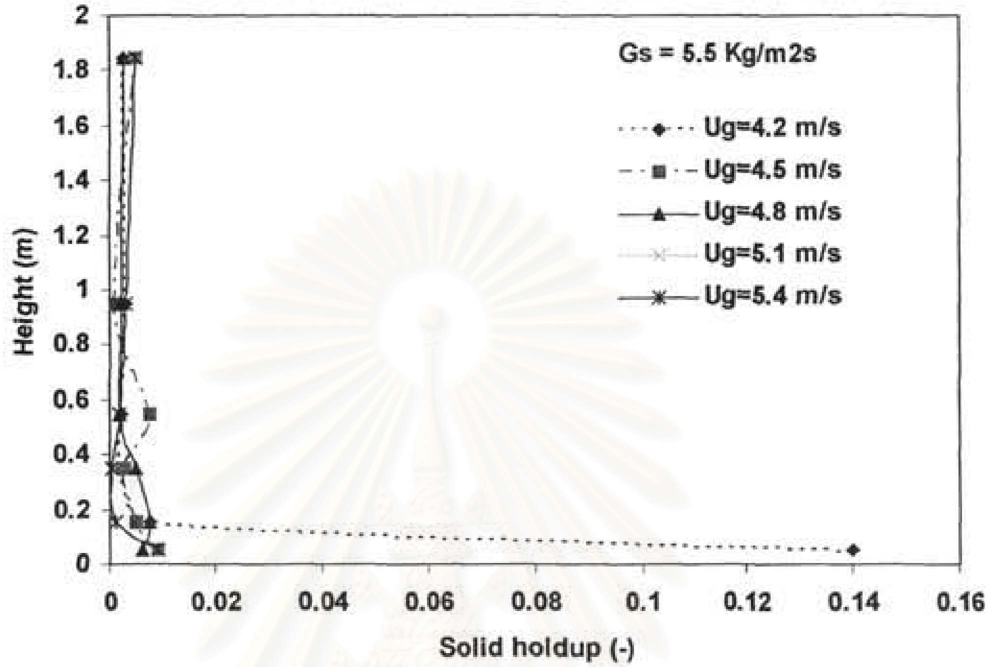

Figure 3.2 Axial solids holdup profiles at various gas velocities in riser of sand/sawdust mixture at solid circulation rate of 5.5 kg/m^{2}s

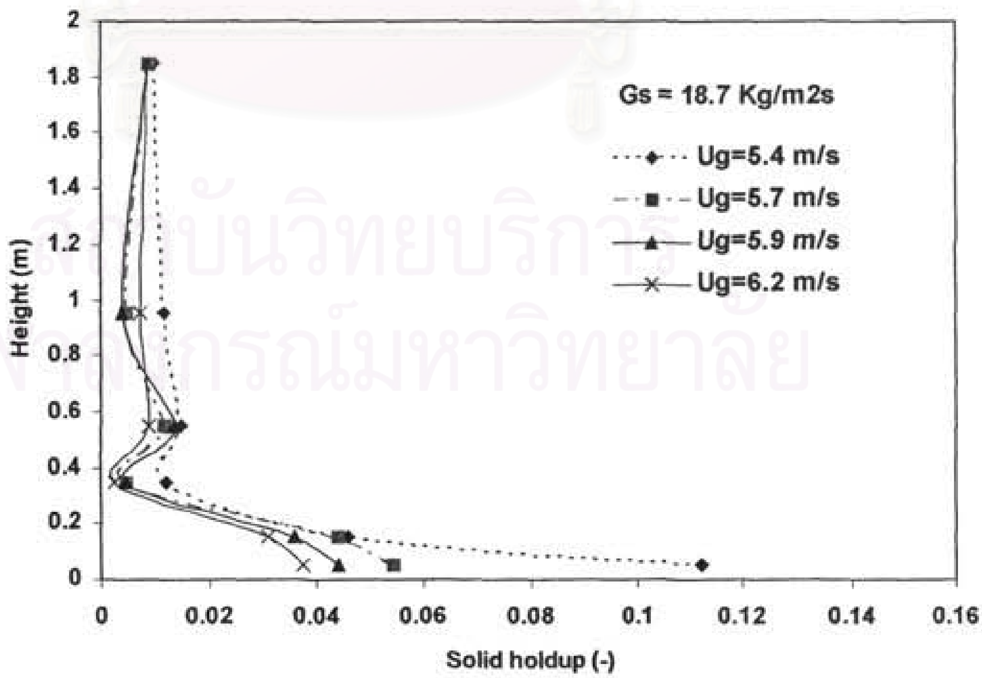

Figure 3.3 Axial solids holdup profiles at various gas velocities in riser of sand/sawdust mixture at solid circulation rate of 18.7 kg/m^{2}s

At lower solid circulation rate, the axial solid holdup distribution in the whole column becomes uniform. However, at higher solid circulation flux of 18.7 kg/m^2s, Fig 3.3 shows that the bed could be visibly divided into lower dense region and upper dilute region. As solid circulation rate is increased, a condition is reached at which superficial gas velocity is insufficient to entrain all the solids entering into the riser without solid accumulation at the bottom of the riser. Thus solid particles begin to accumulate at the bottom of the riser to form a dense phase. The riser then contains a dense phase transport region topped by region of dilute-phase refluxing transport (Namkung et al, 1999).

Fig 3.4 shows a relationship between superficial gas velocity and solid circulation rate on solid holdup in the riser. As can be seen, at constant gas velocity an increase of solid circulation flux causes an increase of solid holdup in the riser. This means that the riser becomes denser as the solid flux increases. Finally it would reach the point that the weight of solid in the riser was too heavy for the certain gas velocity to circulate and the system collapsed. However at constant solid circulation flux an increase of superficial gas velocity results in a diminishing of solid holdup. In this case the riser becomes more dilute.

At the lowest solid circulation rate of 5.5 kg/m2s, the superficial gas velocity and the solid holdup along the riser side could be related by regression analysis method as shown in Eqn (7) following;

$$\varepsilon_s = 4120.1 U_g^{-5.8754} \qquad (7)$$

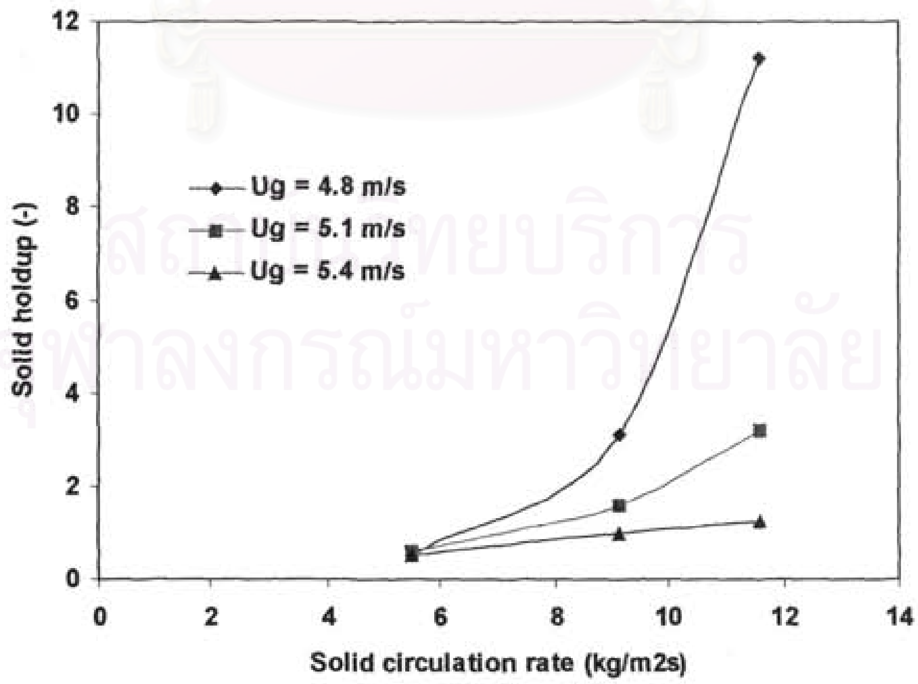

Figure 3.4 Effect of superficial gas velocity on solid holdup

3.1.2 Mixture of sand/ rice husk

Fig 3.5 shows a pressure loop obtained from operating the mixture of sand/ rice husk at ratio of 50:50 percent by volume. It can be seen that the pressure in the riser decreases along the height, as found in mixture of sand/sawdust. The pressure of sand/rice husk was less than that of sand/sawdust since the solid circulation rate of sand/ rice husk system was about 7 times less. The superficial gas velocity and the solid circulation rate used were in the range of 4.8-6.2 m/s and 0.8-18 kg/m^2s, respectively. At the lowest values of the gas velocity and solid circulation rate, 4.8 m/s and 0.8 kg/m^2s, the bottom part of the riser, 0-10 cm above gas distributor, remained dense phase. These values were much different from those of the mixture of sand/sawdust, which were at 4.2 m/s and 5.5 kg/m^2s. The reason might be because of the different in shape of sawdust and rice husk; spherical and irregular plate, respectively. The drag force acted on those solids was thus different.

Figs 3.6 and 3.7 show effect of superficial gas velocities on solid holdup of mixture of sand/ rice husk in the riser at solid circulation rate of 0.8 kg/m^2s and 1.8 kg/m^2s, respectively. The results were similar to those of mixture of sand/sawdust by means of an increased of gas velocity results in a decrease in the solids holdup when solids circulation flux is fixed along the height of the riser.

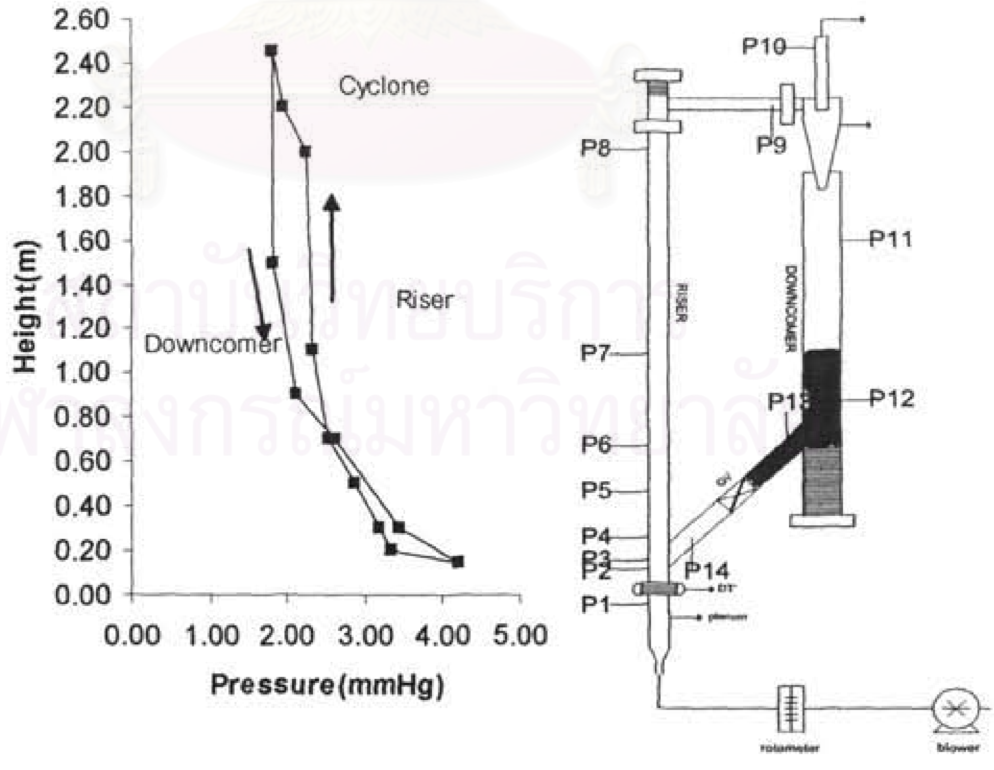

Figure 3.5 Pressure loop obtained from mixed-feed of sand/rice husk 4.8 m/s and solid circulation rate of 0.8 kg/m^2s

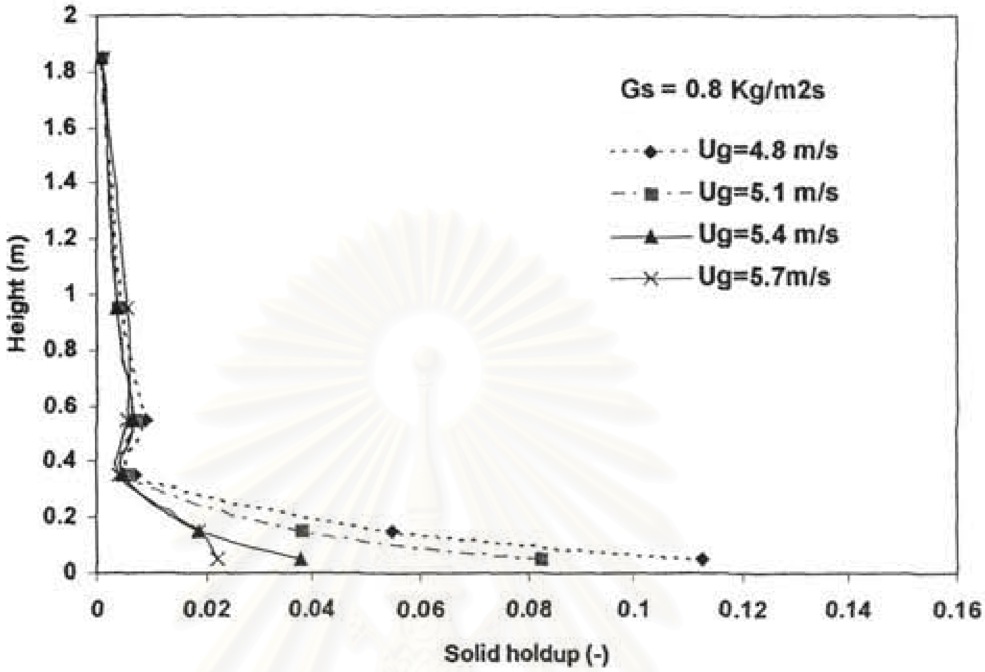

Figure 3.6 Axial solids holdup profiles at various gas velocities in riser of sand/ rice husk mixture at solid circulation rate of 0.8 kg/m^{2}s

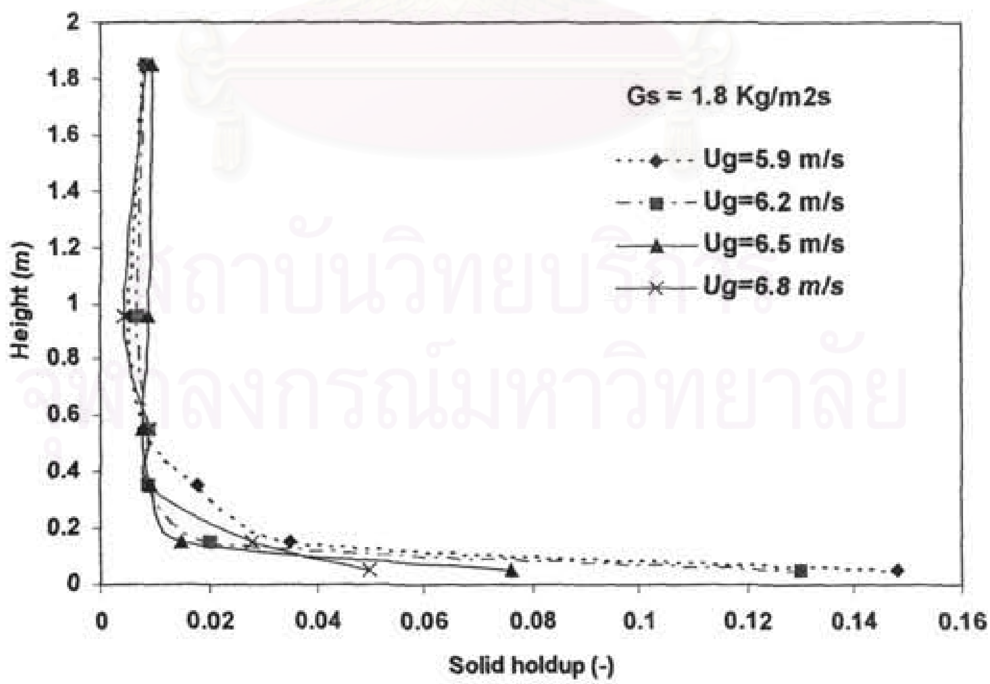

Figure 3.7 Axial solids holdup profiles at various gas velocities in riser of sand/ rice husk mixture at solid circulation rate of 1.8 kg/m^{2}s

3.1.3 Mixture of sand/bagasse

Bagasse used in this research was a short cylindrical fiber that tend to attach one anthers. After mixed with sand at the ratio of 50:50 percent by volume, it was found that the circulation of the mixture was quite difficult. Even though the researcher made an effort on increasing gas velocity and opening gate vale at transfer line. The circulation was achieved only in a short period of time before clogged. It was observed by eyes during experiment that the bagasse was layered as a tight net that produced a very high friction force. Thus, for mixture of sand/bagasse only the riser part was tested. The superficial gas velocity used was in the range of 4.2-5.4 m/s. Fig 3.8 shows a pressure loop obtained from operating the mixture of sand/ bagasse at ratio of 50:50 percent by volume.

Fig 3.9 shows effect of superficial gas velocities on solid holdup of mixture of sand/ rice husk in the riser. The results were also similar to those two mixtures by means of an increased of gas velocity results in a decrease in the solids holdup when solids circulation flux is fixed along the height of the riser.

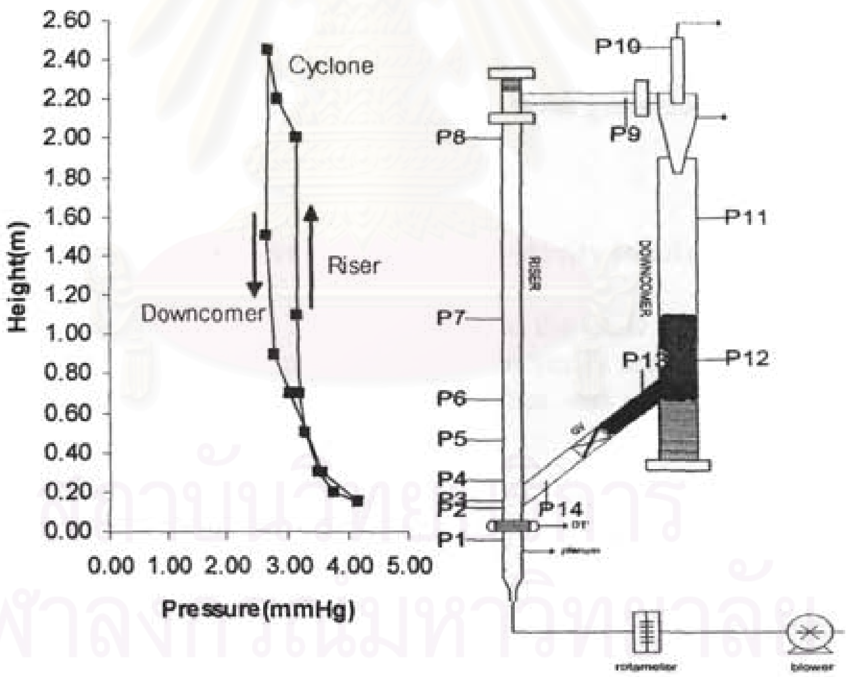

Figure 3.8 Pressure loop obtained from mixed-feed of sand/bagasse 4.5 m/s

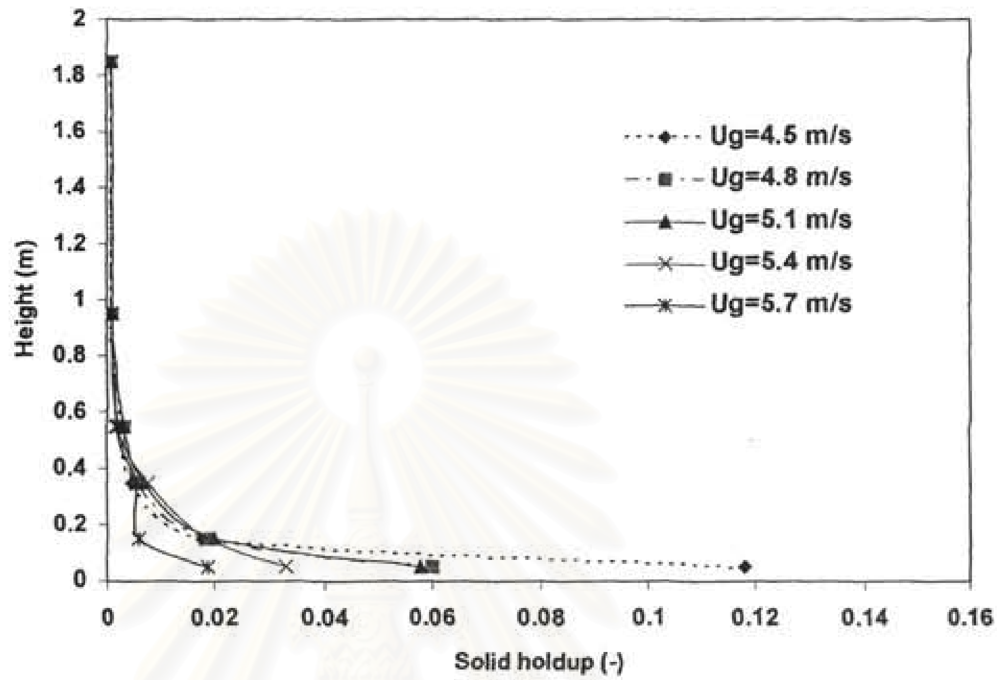

Figure 3.9 Axial solids holdup profiles at various gas velocities in riser of sand/ bagasse

3.2 Effect of superficial gas velocity on sand velocity in mixed-feed

As mention earlier the PIV technique and the CCD camera was use to measure the particle velocity experimentally. In order to verify the accuracy of this technique the cross-sectional averaged solid circulation flux was used to calculate the average particle velocity, (Parssinen, 2001).

$$u_p = Gs/(\rho_s \varepsilon_s) \qquad (8)$$

Where u_p = particle velocity, m/s
Gs = Solid circulation rate, kg/m^{2}s
ρ_s = particle density, kg/m^3
ε_s = solid hold up, (-)

The excellent agreement (average deviation of less than 13%) confirms the reliability of the CCD camera used in this research, as can be seen from Fig 3.10. An increased of superficial gas velocity causes an increase in solid velocity.

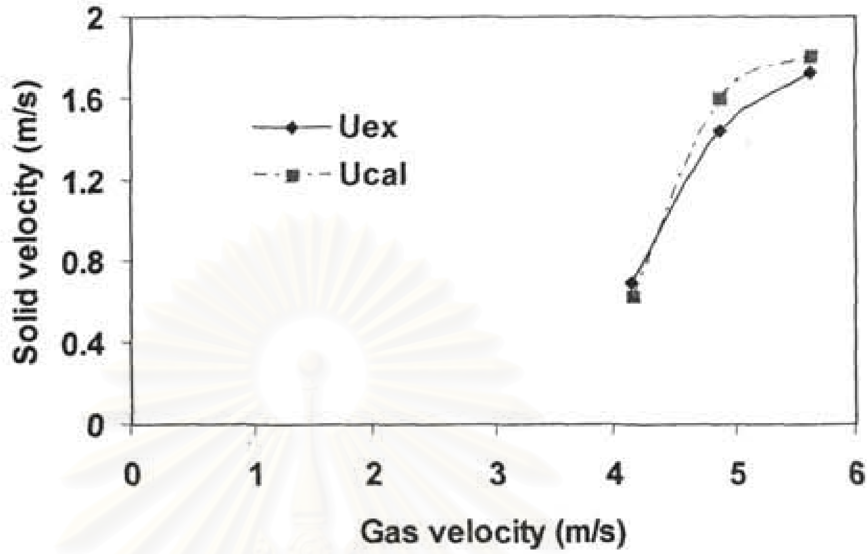

Figure 3.10 Comparison of solid velocity from CCD camera and calculation

3.2.1 Velocity of sand in mixture of sand/sawdust

It was found that as the superficial gas velocity is increased the sand velocity increased at the same elevation, as shown in Fig 3.11. The maximum values of sand velocity were found at the bottom part of the riser and gradually decreasing along the height. At the lowest gas velocity of 4.2 m/s, the sand velocity along the height of riser almost unchanged. This was different from the highest gas velocity that the sand velocity decreased along the way traveling up.

3.2.2 Velocity of sand in mixture of sand/rice husk

The sand velocity in mixture of sand/rice husk shows similar profiles as those in mixture of sand/sawdust. However, it can be observed that the maximum velocity of sand at highest gas velocity of 5.7 m/s was about 2 m/s, which was less than the maximum sand velocity in mixture of sand/sawdust at same operating condition, as can be seen in Fig 3.12.

3.2.3 Velocity of sand in mixture of sand/bagasse

Fig 3.13 also shows the same trend of sand velocity in the mixture of sand/bagasse, as in the first two biomasses. At high gas velocities of 4.9 and 5.7 m/s, it was found that the sand velocities were almost identical since at these gas velocities the riser was almost in the dilute transport regime.

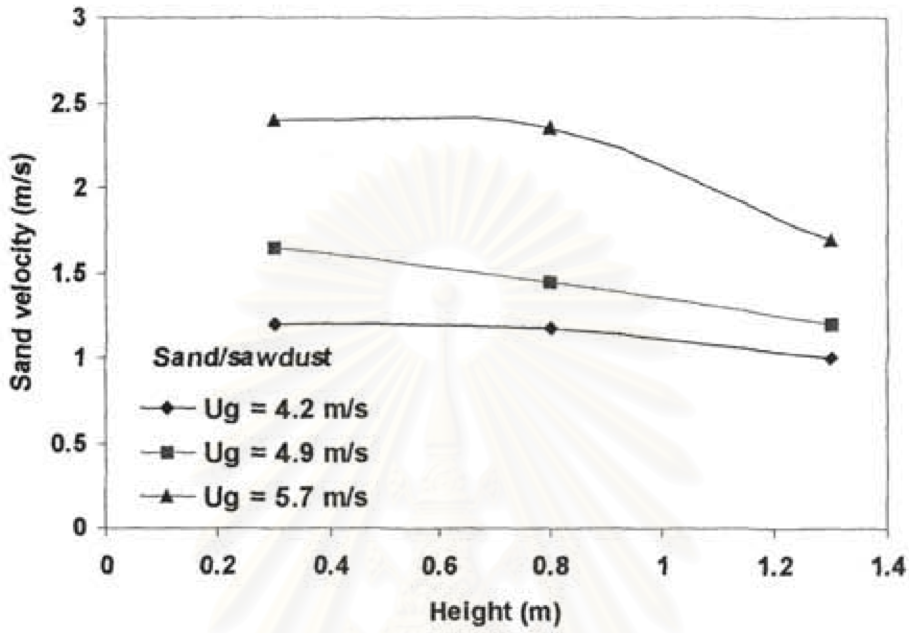

Figure 3.11 Velocity of sand in mixture of sand/sawdust

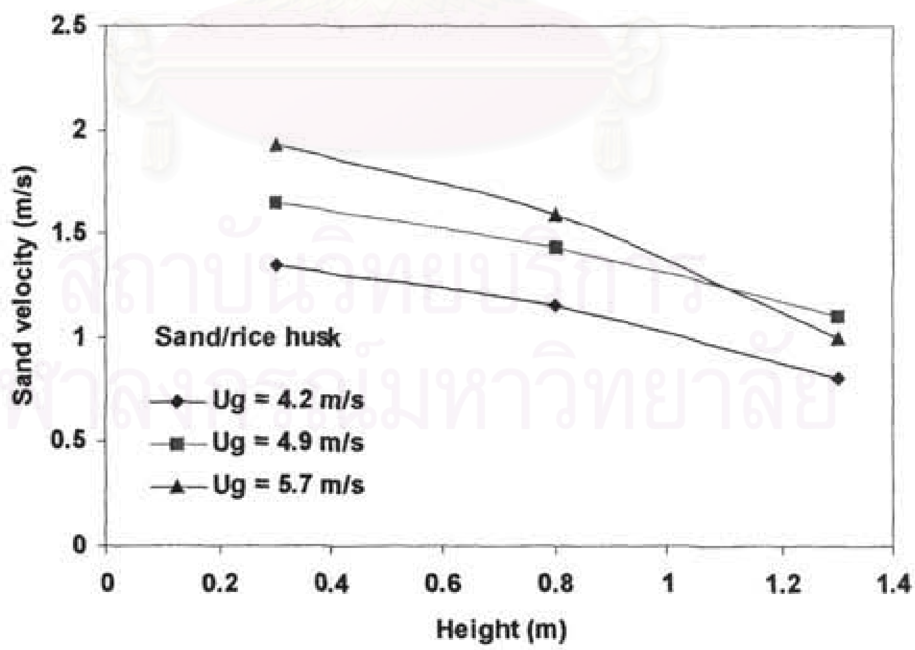

Figure 3.12 Velocity of sand in mixture of sand/rice husk

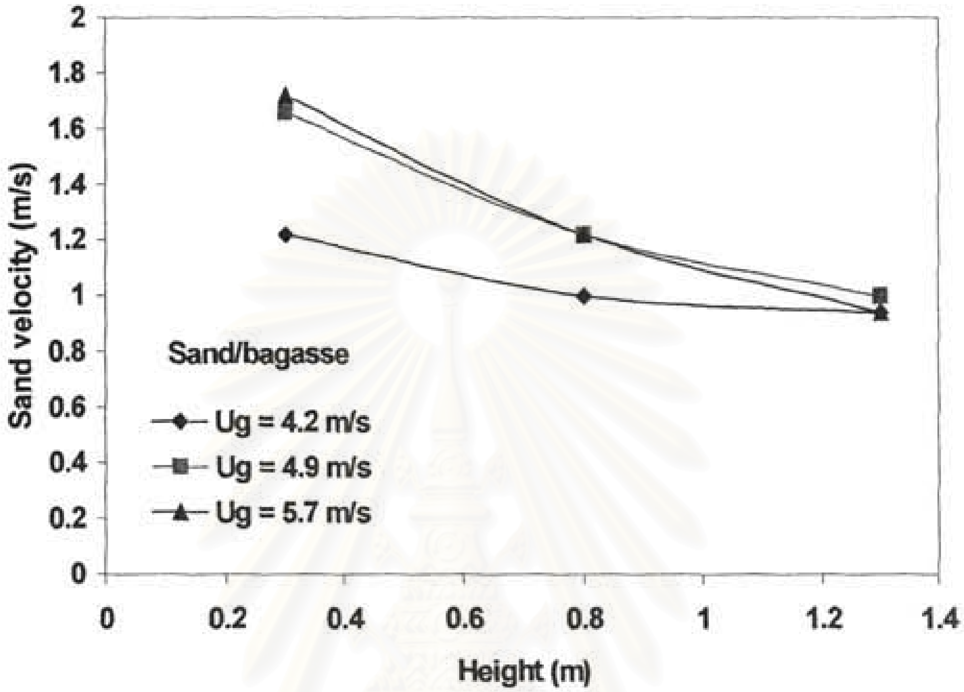

Figure 3.13 Velocity of sand in mixture of sand/bagasse

Fig 3.14 and 3.15 show effect of various biomasses on sand velocities along the riser at constant gas velocity of (a) 4.2 m/s and (b) 5.7 m/s. As can be seen from Fig 3.14, velocities of sand in the system that contains only sand particles were lower than those from the system consisting of sand/biomass mixtures at the same experimental conditions. The reason might be because of the density of the sand is higher than that of the biomasses (Table 2.1). The gravitation force of sand is also high. An adding of biomass into the system could develop higher drag force of the mixtures. The distributions of the drag force to the sand particles are more uniform. Therefore it causes an increase in sand velocities in the mixtures. At lower superficial gas velocity (4.2 m/s), the velocities of sand in the mixture were found to be independent of biomass types. Since all the mixtures display similar trends. However, at higher superficial gas velocity (5.7 m/s) in Fig 3.15, the influence of drag force was found to depend on particle's shape as sand velocities in mixture of sand/sawdust shows highest velocity. Sawdust is more or less spherical shape (Table 2.1); the drag force on sawdust is less that of rice husk and bagasse. Another reason might come from the mixing/segregation phenomena, which depends on many factors such as density ratio between particles, size ratio, shape of particles, and superficial gas velocity (Ozawa et al, 2004).

In conclusion for part one, it was found that the height of the bottom bed increased with solids circulation rate. The solids holdup along the riser increases with increasing solids circulation rate or decreasing superficial gas velocity. For various types of biomass in the mixture of sand and biomasses, sand velocities increase with superficial gas velocity and was found to decrease along the height of riser.

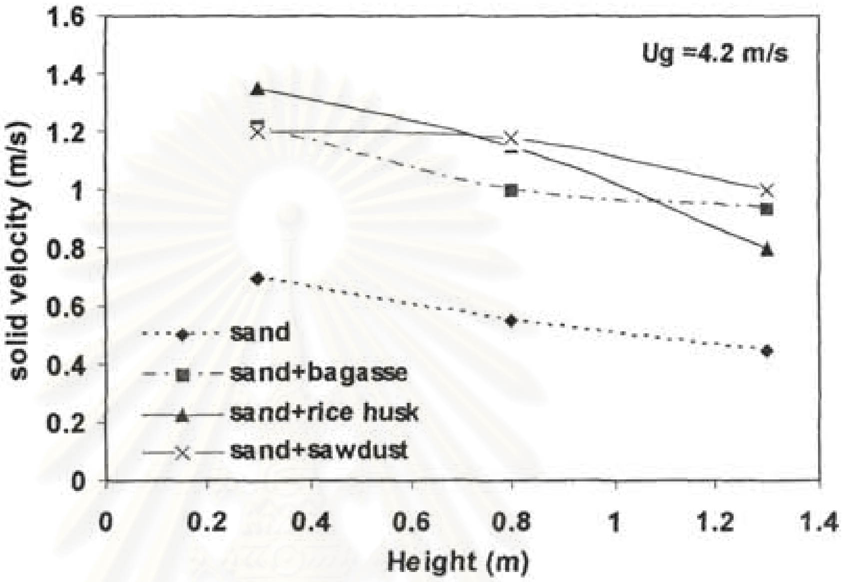

Figure 3.14 Effect of biomass on sand velocity at gas velocity of 4.2 m/s

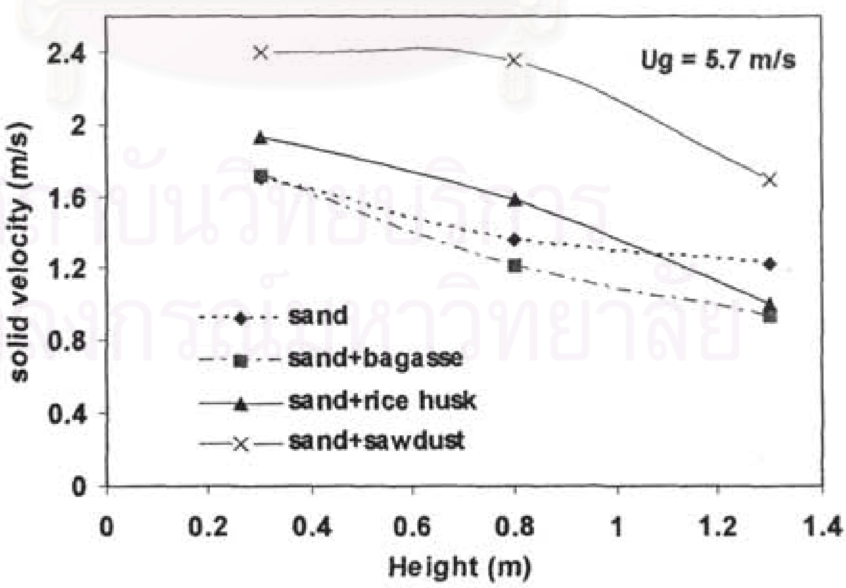

Figure 3.15 Effect of biomass on sand velocity at gas velocity of 5.7 m/s

3.3 Effect of superficial gas velocity on glass beads velocity

As mentioned earlier, sand particles were cracked into smaller particles after few runs since there was enormous amount of attrition force during the circulation of solids. For the researcher to complete collecting data on an experimental condition including setting a high speed camera and an image processing software, it roughly required 4 hours. Therefore a glass beads from A.P.C. INDUSTRIES CO., LTD replaced the sand particles. The surface of the glass beads was very rigid since it was manufactured for use as intermix and/or drop-on reflective materials with thermoplastic road marking materials and traffic paints on road. Since particle density of glass beads was higher than sand's particle density. The superficial gas velocities used were in the range of 7 to 9 m/s. However, the results were very much comparable to those of sand/biomass in the sense that as gas velocity increased solids holdup in the riser decreased at fixed solids circulation flux.

During performed experiment, problems occurred when the researcher attempted to operate the mixture at 50: 50 percent by volume of glass beads/rice husk in such as way that the mixture was packed in the transfer line. It was found that the solid, which packed most, was rice husk due to its slab shape. And this stopped the circulation of the bed system. Therefore, the amount of rice husk was gradually reduced from 50 percent by volume in the next few runs. Finally, it was found that at 20 percent by volume of rice husk, the cold flow CFB was circulated well at the same operating conditions of the previous experiment. Thus the following results belong to the mixture of glass beads and rice husk at 80:20 percent by volume. Again, to be reminded that the PIV technique used in this research was able to measure solely glass beads velocity.

Fig 3.16 shows solid hold up profiles along the height of riser of mixture of glass beads and rice husk at different gas velocities. Pressure in the riser increased with increasing superficial gas velocity but decreased along the height. Therefore, the axial solid holds up profiles show a dense section at the very bottom part of the riser, and then decreased as solid traveling upward. For constant solids circulation rate of 16 kg/m^2s and the superficial gas velocity increased from 7 to 9 m/s, the flow regime changed from dense phase flow to dilute flow. Typically the CFB's riser is divided into two distinct coexisting regions, the lower dense region and the upper dilute region.

The axial velocity of glass beads in mixture of glass beads/ rice husk along the height of riser at different gas velocities is shown in Fig 3.17. The high speed camera was set to snapped the images of the solid flow inside the riser at three location along the height of riser; 60,110 and 170 cm. above gas distributor. It is clearly seen that the glass beads velocity increases with height of riser for all gas velocities used. At gas velocity of 7 m/s, in the bottom part of riser, there is no obvious solids acceleration and the particle velocity almost unchanged. At riser height higher than 110 cm, glass beads begin to accelerate significantly.

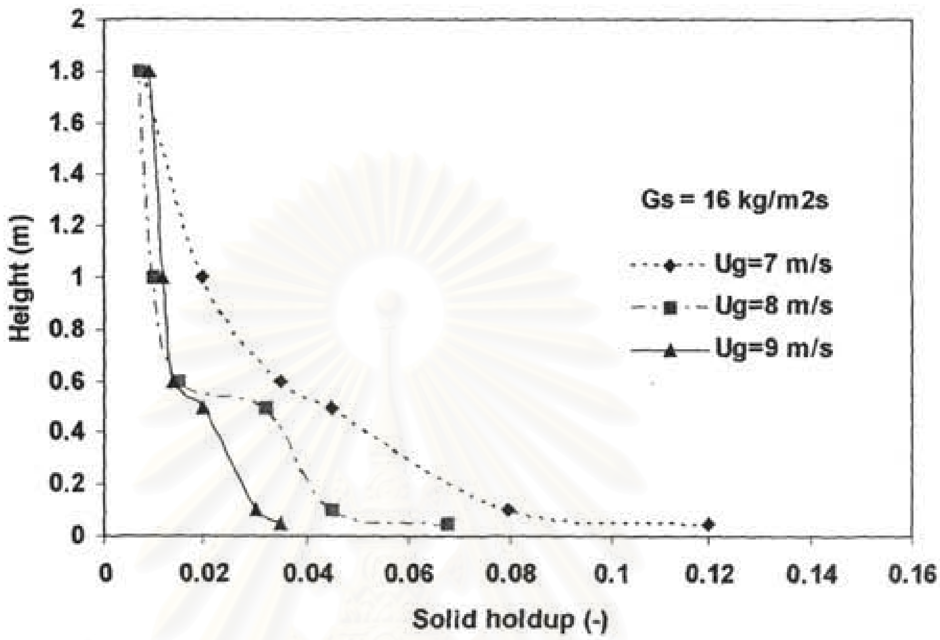

Figure 3.16 Axial solids holdup profiles at various gas velocities in riser of mixture of glass beads and rice husk at solid circulation rate of 16 kg/m^{2}s

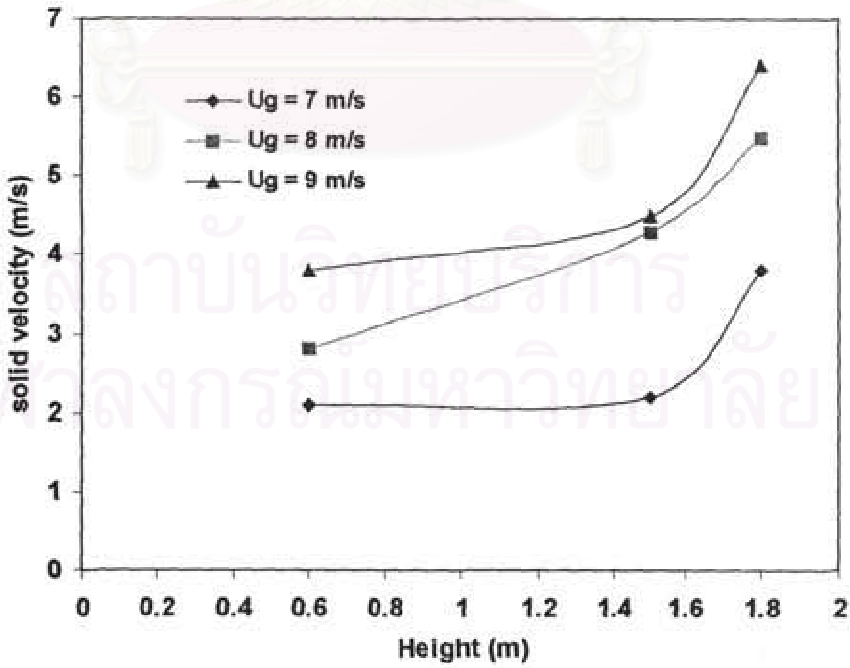

Figure 3.17 Effect of rice husk on glass beads velocity

As can be continuously observed, at gas velocities of 8 and 9 m/s glass beads were accelerated instantaneously through out the height of riser. Sabbaghan reported that the acceleration zone is where the solids are accelerated to a constant upward velocity, the fully developed zone is where the flow characteristics are invariant with height and the deceleration zone is where the solids are decelerated due to the exit geometry of the riser. Since the riser used in the research is fairly short, the whole riser represents only the acceleration zone (Sabbaghan, 2004). And in all operating conditions, particle velocities were less than their respective gas velocities.

As mentioned earlier, the two key parameters in this research were particle size and density. However, Sankar suggested that the effect of particle density appears to be of little significance in comparison with the effect of particle size on slip velocity for the vertical transport of glass beads, sand and steel shorts (Sankar, 1986). Fig 3.18 shows a comparison of axial velocity of glass beads in single phase (without rice husk) and in mixture (with rice husk at the ratio of 80:20 percent by volume) along the height of riser at gas velocity of 9 m/s. In the bottom part of the riser, the glass beads velocity in the mixture was much lower than that of in the single phase. However, both velocities became closed as the glass beads traveled toward the top of the riser. These result findings are similar to those found by Mastellone who study the effect of both particle size and density on the distribution of solids in the riser of CFB. They concluded that the influence of both parameters, namely particle size and density, was remarkable only in the entrance region of the riser (Mastellone, 1999).

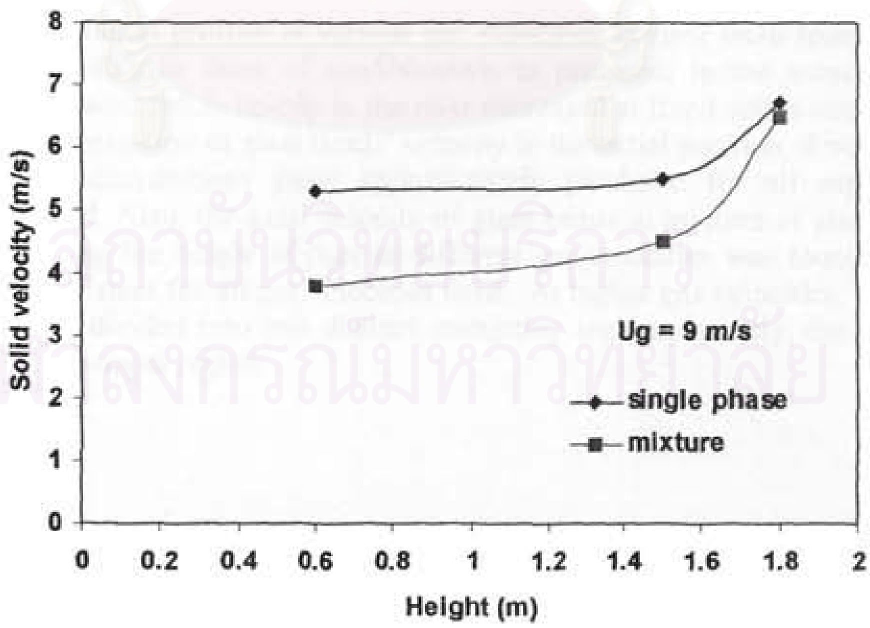

Figure 3.18 Comparison of glass beads velocity in single phase system and in mixture with rice husk

CHAPTER IV
CONCLUSIONS

This research composed of two parts. For part one, the hydrodynamic of mixed feed between sand and various biomasses including sawdust, rice husk, bagasse was studied by means of PIV technique using the CCD camera to measure particle velocities at different locations in the riser. The results show that axial solids holdup profiles at various gas velocities in riser of the all three mixtures (sand/rice husk, sand/sawdust and sand/bagasse) were similar. An increased of gas velocity results in a decrease in the solids holdup when solids circulation flux is low along the height of the riser. However, at higher solid circulation flux, the riser could be visibly divided into lower dense region and upper dilute region.

Due to the limitation of the PIV technique, the images of biomass (the streak lines captured by CCD camera) could not be taken. Since the focus of the CCD camera can be set for only one particle for each run. Therefore the solid velocities stated in this part were sand velocities since the sand belongs to more regular shape than biomasses. It was found that the velocities of sand in the system of single particle are lower than those from the system consisting of sand/biomass mixtures at the same experimental conditions. This could explain that the biomasses help the distributions of the drag force between solid particles so that the velocities higher and more uniform. The influence of drag force was found to be independent on particle's shape at low gas velocity as sand velocities in mixture of sand/sawdust shows highest velocity.

In the second part, the rice husk was selected to mixed with glass beads. The axial solids holdup profiles at various gas velocities in riser were found to be very much comparable to those of sand/biomass in part one, in the sense that as gas velocity increased solids holdup in the riser decreased at fixed solids circulation flux. After the investigation of glass beads' velocity in the radial position, it was found that the velocity distributions show approximately parabolic for all superficial gas velocities used. Also, the axial velocity of glass beads in mixture of glass beads and rice husk along the height of riser at different gas velocities was found to increase with height of riser for all gas velocities used. At higher gas velocities, 8 and 9 m/s, the riser was divided into two distinct coexisting regions, namely, the lower dense region and the upper region.

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