Studies on Microscopic Flow Structure Inside a Rectangular Circulating Fluidized Bed Through Image Analysis

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A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy
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STUDIES ON MICROSCOPIC FLOW STRUCTURE INSIDE A RECTANGULAR CIRCULATING FLUIDIZED BED THROUGH IMAGE ANALYSIS

(Thesis format: Integrated Article)

by

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Abstract

The microscopic flow structure is studied systematically and comprehensively through a visualization system in a narrow rectangular circulating fluidized bed (CFB) transparent Plexiglas riser with a height of 7.6 m and a cross section of 19 mm × 114 mm. A visualization system consisting of a high-speed video camera, a light source, and image processing and analyzing programs is designed and developed to enable the flow structure to be visualized directly and studied quantitatively. FCC particles of 67 μm are used as the bed materials under different operating conditions with superficial gas velocity \( U_g \) and solids circulation rate \( G_s \) in the range of 3.0-12.0 m/s and 50-150 kg/m²s respectively.

To study the microscopic flow structure quantitatively, for the first time, a new calibration method is developed to correlate the solids holdup of the FCC particles and the grayscales of the images obtained by the high-speed video camera, based on the light illumination consistency verified by a reference plate. To achieve stable and homogeneous fluidization with uniform solids holdup, the calibration experiment is conducted in a well-designed liquid-solid bed. The obtained calibration curve and equation are used as the basis for the entire study. With the calibration method, cluster can be “peeled-off” by given solids holdup thresholds through transforming the original gray images into binary images. The change in cluster population with operating conditions consistent with previous researchers further proves that the image calibration method developed in this study is effective and very useful.

To further verify the newly developed image calibration method, an optical fiber probe is applied as a reference for the measurements of the solids holdup of the FCC particles. The solids holdup distribution profiles obtained from the two methods under identical operating conditions have good agreement, reflecting the reliability of the image calibration method. Further comparison of the results of image calibration method from the current study with the measurement results of optical fiber probe from other researchers also show good agreement under the same operating condition. These comparisons clearly confirm the feasibility and accuracy of the image calibration method.

Using the image calibration method, the mean solids holdup under different operating conditions can be calculated from the mean grayscale of the images. The results show that
the mean solids holdup increases with the increasing $G_s$ and decreases with $U_g$. The transformation from grayscale images into Hue, Saturation and Value (HSV) images using various solids holdup thresholds allows the dense and dilute phases with obviously different solids holdup to be clearly visualized under different operating conditions in the fully developed region. A term “relative dense phase area” is introduced to quantify the solids phase separation. A critical solids holdup value of $\varepsilon_{sc} = 0.04$ is chosen by carefully examining the variation profiles of the relative dense phase area with solids holdup thresholds, to demarcate the dilute and dense cluster phases. The cluster fraction is then obtained through the $\varepsilon_{sc}$ value and ranges from 1 % to 59 % under the different operating conditions of present research. With images divided into three regions along the lateral direction, it is found that cluster fraction at the wall region is higher than that of the core and the middle regions.

With further examining the solids holdup distribution of the microscopic structures, the dense (or cluster) phase is considered as a “compound” of core clusters and intermediate dispersed particles, which is in the processing of coalescence or breakup, with higher solids holdup than the dilute phase. To identify stable existing core clusters, a systematic cluster identification process is presented by adopting a threshold selection method to obtain the cluster threshold solids holdup ($\varepsilon_{sct}$) so that clusters can be identified under different operating conditions. The cluster fraction is calculated by dividing the total number of pixels belonging to the core cluster with the total pixels number of the entire image. Based on the $\varepsilon_{sct}$, a cluster equivalent diameter ($d_c$) is determined by the area of the cluster in the binary image. At the same time, the cluster solids holdup can be determined by converting the grayscale of the cluster from the original image to the solids holdup. Moreover, cluster vertical velocity can be determined by the shift of clusters between sequential binary images. Typical dense ($U_g = 3.0$ m/s; $G_s = 100$ kg/m$^2$s) and dilute ($U_g = 9.0$ m/s; $G_s = 50$ kg/m$^2$s) operating conditions are selected to compare the variation of the cluster size and velocity.

**Keywords**

Image calibration, image processing, high speed video camera, clusters, microscopic flow structure, solids holdup, cluster size, cluster velocity
Co-Authorship Statement

**Title:** A novel method based on image processing to visualize clusters in a rectangular circulating fluidized bed riser

**Authors:** Jingsi Yang and Jesse Zhu

The experimental setup for the image calibration method was designed and modified by Jingsi Yang together with Jianzhang Wen under the guidance of supervisor Dr. Jesse Zhu. The experimental setup for the visualization system was designed and modified by Jingsi Yang together with Michael Zhu under the guidance of supervisor Dr. Jesse Zhu. Jingsi Yang carried out the experiments, image processing and data analysis under the guidance of supervisor Dr. Jesse Zhu. All experimental work was conducted by Jingsi Yang and the draft of this manuscript was written by Jingsi Yang. Revisions were carried out under the close supervision of Dr. Jesse Zhu. The final version of this paper has been accepted for publication in Powder Technology, POWTEC-D-13-01489.

**Title:** An alternative method for mapping solids holdup in a rectangular CFB riser through image calibration

**Authors:** Jingsi Yang and Jesse Zhu

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**Title:** Visualization of solids phase separation in a rectangular CFB riser using a novel image calibration method

**Authors:** Jingsi Yang and Jesse Zhu

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and the draft of this manuscript was written by Jingsi Yang. Revisions were carried out under the close supervision of Dr. Jesse Zhu. The final version of this paper was submitted to the Chemical Engineering Science, CES-D-13-01757.

**Title:** Cluster identification in a rectangular circulating fluidized bed using image processing

**Authors:** Jingsi Yang and Jesse Zhu

Jingsi Yang carried out the experiments, image processing and data analysis under the guidance of supervisor Dr. Jesse Zhu. All experimental work was conducted by Jingsi Yang and the draft of this manuscript was written by Jingsi Yang. Revisions were carried out under the close supervision of Dr. Jesse Zhu. The final version of this paper is ready for submission.

**Title:** Determination of cluster size and velocity by means of image processing in a rectangular circulating fluidized bed

**Authors:** Jingsi Yang and Jesse Zhu

Jingsi Yang carried out the experiments, image processing and data analysis under the guidance of supervisor Dr. Jesse Zhu. All experimental work was conducted by Jingsi Yang and the draft of this manuscript was written by Jingsi Yang. Revisions were carried out under the close supervision of Dr. Jesse Zhu. The final version of this paper is ready for submission.
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Chapter 1

1 General Introduction

A newly developed image calibration method in combination of the image processing is applied to study the microscopic flow structure in this work. An introduction of the research background, objectives and the thesis structure are presented in this Chapter.

1.1 Research background

In gas-solid circulating fluidized beds (CFBs), the flow structure is complex due to the formation of particle aggregates. The existence of particle aggregates has been widely accepted by many studies since the concept of “clusters” was introduced by early researchers (Yerushalmi and Squires, 1975; Grace and Tuot, 1979). Further studies indicate that the presence of clusters is also responsible for high gas-solid slip velocity and the core-annulus flow development (Rhodes, et al., 1989; Horio and Kuroki, 1994; Kuroki and Horio, 1994; Bai et al., 1995). With the progressing of studies on the microscopic flow structure, it is found that particle clustering causes the significant alteration to the gas drag exerted on the particles and thus makes the experimental understanding and the modelling of the gas-solids two phase flow extremely difficult. These make the study of the micro-flow structure very necessary. In addition, the cluster structure and other properties as well as their mechanisms of formation and breakup are still unclear. Therefore, more investigations are needed before further insights about the characteristics and hydrodynamics of clusters can be obtained.

Generally speaking, published experimental measurement techniques that were used to study the characteristics and structure of clusters in gas-solid systems can be divided into two categories: intrusive probes (Horio et al., 1992; Manyele et al., 2002) and non-intrusive visualization systems (Rhodes et al., 1992; Shi et al., 2008) (also including some ‘inside bed imaging’ systems such as a high-speed video camera attached with a bore-scope (Takeuchi et al., 1991; 1996; 1998) and a video camera connected with an optic fiber micrograph probe (Li et al., 1991; Zou et al., 1994)). The former is advantageous for use in dense regions and in determining local flow properties such as
solids holdup and particle velocity. The latter, however, is preferable due to the little disturbance to the flow. Comparing to the intrusive techniques, visualization techniques were first utilized as a non-intrusive method only providing qualitative indications and mapping the overall flow structures. However, with the development and improvement of modern video cameras and application of imaging process and analysis methods, more and more quantitative information are provided by the non-intrusive methods (Zou et al., 1994; Lim et al., 1996; Lackermeier et al., 2001; Casleton et al., 2010; Cocco et al., 2010; Xu and Zhu, 2011; 2012; Shaffer et al., 2013; McMillan et al., 2013).

Both intrusive (Brereton and Grace, 1993; Zhou et al., 1994; Li et al., 1995; Pandey et al., 2004; Xu and Zhu, 2010) and non-intrusive methods mentioned above have revealed that clusters varies in shapes, sizes and velocities, studies about the cluster characteristics are still far from enough. Based on three guidelines to identify the clusters, cluster characteristics including solids holdup in cluster, occurrence frequency, duration time and time fraction for cluster existence are obtained using a capacitance probe technique (Soong et al., 1993; 1995; Tuzla et al., 1998; Sharma et al., 2000). Manyele et al. (2002) reported their investigation of the aggregate properties in a high-flux and high-density riser using a fiber optic probe. The aggregate frequency, time fraction, existence time, average solids concentration and cluster vertical dimension were established using sensitivity analysis. They also revealed the dependence of the aggregate properties on the operating conditions. Xu and Zhu (2011; 2012) adopted the sensitivity analysis and studied the cluster characteristics including cluster time fraction, cluster mean existence time, cluster frequency and cluster size and velocity as well. Lackermeier et al. (2001) studied the particle aggregates properties by applying high-speed video technique in combination with the laser sheet technique. By adding the image sequences, cluster image were obtained with cluster size and velocity calculated.

From the reported studies so far, both intrusive probes and visualization methods has been used to identify the clusters. The intrusive probes are one-point measurement methods, which can provide information at various time scales but limited spatial variation. The visualization method, on the other hand, can practically provide
information at any point within the measurement zone. The specialties of the two kinds of methods lead to their own criterion to identify the clusters.

For a number of reported experimental studies which identify clusters using the intrusive probes, cluster information are obtained from the local instantaneous probe signals (Soong et al., 1993; Tuzla et al., 1998; Sharma et al., 2000; Manyele et al., 2002; Xu and Zhu, 2011, 2012). Based on a suggested criterion, a cluster would be identified if the local instantaneous solids holdup is significantly greater than the mean solids holdup. One of the major discussion on cluster identification for the following studies is concentrated on how to select the number of standard deviation of the detected solids holdup signal above local time-mean solids holdup, n. Manyele et al. (2002) proposed a sensitivity analysis to determine the value and found it was in the range of 1.0-1.4. Xu and Zhu (2011) adopted the sensitivity analysis and determined the value of n to be 2.

Comparing to intrusive probes, a particular advantage of the image processing method is the exact geometrical determination of the measuring area which is needed for the calculation of velocities and sizes of clusters. However, there are less studies for cluster identification with visualization methods. Burkhardt and Bredebusch (1996) and Lackermeier et al. (2001) calculated a threshold to identify clusters from the histograms of gray values for each pixel of obtained images over time. Based on the comparable relationship between grayscale and solids holdup, they set the threshold to the gray value which leads to the same value of the cluster volume (or area) fraction as was obtained from corresponding fiber optical measurements. Xu and Zhu (2012) also applied image processing to characterize the cluster size and velocity. The threshold is set to the mean gray value of the whole image. Mondal et al. (2013) used the similar criterion as that of Soong et al. (1995) to choose a threshold grayscale to convert the original image into binary image so that the clusters can be clearly separated from its surroundings. To ensure that the grayscale value of the clusters is higher than the local average grayscale, the number of standard deviation of the local grayscale above the mean grayscale was chosen as 1 by visual inspection and the comparison to the original image,
While it is most commonly agreed that the solids holdup of clusters is significantly greater than that of its surroundings, the criterion to separate cluster from its surroundings are still not clear and the selection of the threshold solids holdup are still more a trial and error than systematic. Therefore, a systematic method is needed to identify the clusters so as to provide more information about the cluster characteristics.

The current study aims to provide an initial attempt and also a new path to quantitatively characterize clusters from the image processing point of view so that to give some guidance in understanding the dominate effects and mechanisms which govern the cluster formation inside the CFB.

1.2 Research Objectives

To study the microscopic flow structure inside the rectangular CFB riser via a high-speed video imaging, the major objectives of this study are listed in the following:

1) Develop a new method to correlate the grayscale (image information) with the solids holdup (flow characterization parameter). This correlation is used as the basis for the following quantitatively study.

2) Verify the feasibility and the accuracy of the newly-developed method, i.e. the image calibration method, by measuring the solids holdup. The optical fiber probe is used as a reference to compare the results with those obtained by the new method.

3) Map the radial distribution of solids holdup and the average solids holdup in the CFB riser. Use the image calibration method to visualize and quantitatively study the solids phase separation. At the same time, cluster fraction and distribution are also objectives for studying.

4) Identify the clusters from their surroundings systematically and accurately.

5) Determine the cluster size and velocity by means of image processing. The solids holdup inside the clusters is another objective of studying.
1.3 Thesis structure

This thesis follows the “Integrated-Article Format” as outlined in the UWO Thesis Regulation Guide.

Chapter 1 gives a general introduction of the current research background and specific research objectives.

Chapter 2 is a detailed literature review mainly introducing basic measurements of the riser including the intrusive and non-intrusive techniques. The microscopic study in the CFB including the cluster identification, characteristics and especially the cluster studies with the visualization method are also reviewed.

Chapter 3 provides the details about the experimental apparatus including the CFB, the visualization system, the measurement techniques corresponding to different parameters and the conditions of operating and measurement in this study.

Chapter 4 introduces the newly-developed image calibration method, with which a one-to-one correspondence between the grayscale of the image and the solids holdup of the bed material, i.e. FCC particles is built for the first time. To ensure the reliability of this method, a reference plate is made to verify the light illumination consistency. The calibration experiment is conducted in a well-designed water-solid bed with the image reflections of the two medium are pre-compared. The consistency of cluster visualization and the results between this study and that of previous research proves the developed image calibration method is effective and very useful.

Chapter 5 reports the accuracy and the feasibility of the image calibration method by comparing the measurement results with those obtained by the optical fiber probe (OFP). The radial distribution profiles of the solids holdup obtained by the image calibration method coincide well with that of OFP in this study under identical operating conditions. Further comparison between the results of the image calibration method in the current study and that of OFP from other researchers also show good agreement under the same operating condition. These comparison confirm the reliability of this newly-developed image calibration method.
Chapter 6 presents the visualization of the solids phase separation and quantitative studying of the cluster distribution using the image calibration method. By transforming the original images into the HSV images, the solids holdup distributions under different operating conditions are clearly visualized. Through carefully examining the variation profiles of the relative dense phase area with different solids holdup thresholds, a critical solids holdup value of 0.04 is selected to demarcate the dilute and the cluster phases. The cluster distribution in the lateral direction of riser is also studied. It is found that the cluster fraction at the wall region is higher than that of the middle and the core regions. In addition, the cluster faction increases with the mean solids holdup of the measurement section in the riser.

Chapter 7 exhibits the further examination of the solids holdup distribution in the riser, by which the dense (or cluster) phase is regarded as the core clusters with highest solids holdup and intermediate dispersed particles, which is in the processing of coalescence or breakup. To identify the core clusters from its surroundings, a cluster threshold solids holdup is obtained by a systematic process adopting a threshold selection method. With the cluster threshold solids holdup, the cluster image can be obtained by transforming the original image into the binary image under different operating conditions. Clusters with different shapes and sizes can be visualized clearly and identified accurately.

Chapter 8 determines the cluster size by a cluster equivalent diameter calculated from the area of cluster in the binary image. At the same time, the solids holdup inside the clusters can also be determined by the grayscale of the cluster from the original image through the calibration equation. Moreover, cluster vertical velocity can be determined by the shift of clusters between sequential binary images. It is found that clusters with higher solids holdup and smaller size are prone to form at the dense operating condition \((U_g = 3.0 \text{ m/s}; G_s = 100 \text{ kg/m}^2\text{s})\), while cluster with lower solids holdup and relative larger size are incline to form at the dilute operating condition \((U_g = 9.0 \text{ m/s}; G_s = 50 \text{ kg/m}^2\text{s})\).

Chapter 9 presents the general conclusions of the studies mentioned above. At the same time, based on the research so far, it is believed that the newly developed image
calibration method has great application potential. Therefore, recommendations for future work are provided as well.

References


Chapter 2

2 Literature Review

Based on the hydrodynamic studies inside the circulating fluidized bed, previous research about non-intrusive visualization measurements, flow structure and solids distribution inside the bed, the existence of cluster and cluster characteristics are reviewed in this chapter.

2.1 Introduction

Circulating fluidized bed (often abbreviated as CFB) technologies have achieved many successful commercial industrial applications such as coal combustion and gasification, fluid catalysis crackers and gasification of biomass over the past decades, due to typical advantages such as improved gas-solid contacting, easier to have continuous process and reduced axial gas dispersion, etc. The characteristics of the gas-solid flow in circulating fluidized beds, nevertheless, are not yet well understood due to the complexity of the axial and radial variations in particle velocity and solids holdup caused by the formation of clusters, which increases the difficulties for the study and quantitative characterization of the multiphase system.

In CFBs, it has been observed that the gas-solid flow exhibits a core-annulus structure which is characterized by a rapidly rising dilute core and a denser falling annulus. Many research works reported that particles grouped together at the annulus region near the wall, and also identified the particle clustering at the core region. The particle groups have been described by many terms such as “dense packets”, “streamers” and “strands” (sometimes interchangeable). As there has been few common understandings on the definition and classification of clusters so far, to avoid confusion, the ‘clusters’ is adopted in this study as a generalized conception, which refers to all forms of particle agglomeration.

Wilhelm and Kwauk (1948) produced experimental evidence of clusters in fluidized beds. Later on, comprehensive analysis of the microstructure of the gas–solid suspension
has identified that particles tend to aggregate together and form clusters, which flow quite differently from the single particles (Li Y. and Kwauk M. 1980; Bi H. T. et al. 1993). A number of researchers have corroborated the clustering phenomenon with experimental evidences. Grace and Tuot (1979) proposed that particles form clusters as a result of flow instability. Geldart and Rhodes (1986), on the other hand, believed that the high slip velocity in a fast fluidized bed could be explained simply on the basis of radial non-uniformity in all flowing gas-solid systems. The formation of clusters has been suggested as one of the key contributing factors for the high average slip velocities.

Clusters play a major role in predicting radial and axial gas-solid flow patterns and mixing phenomena due to its effects on the key operation characteristics such as solids hold-up, pressure drop, heat and mass transfer, reaction kinetics, and axial gas and solids mixing. Researchers who incorporated the concept of clusters into hydrodynamic models of fast fluidized bed led to improved predictions of experimental behavior (Fligner et al, 1994; Xu and Li, 1998). Clusters have also been successfully incorporated into riser solids residence time distribution models (Wei et al., 1996). Knowledge of cluster behavior at both core and annulus regions are critical for designing and operating the circulating fluidized bed combustion equipment and also important for predicting and eliminating erosion in industrial units. Lints and Glicksman (1993) have illustrated that even small protrusions into the annular flow region of a riser can have a dramatic effect on wall erosion.

There are also attempts to improve understanding of mechanism of heat transfer at the wall of a circulating fluidized bed riser from the perspective of cluster properties. Using cluster-based approach, Karimipour et al. (2007) proposed a model to evaluate the heat transfer coefficient in fluidized bed. By taking the size of the cluster and the heat transfer coefficient of the gas into account, their model is able to predict the heat transfer coefficient satisfactorily in bubbling, turbulent and fast fluidization regimes. A CFD model for gas-to-cluster inter-phase heat and mass transfer provides a good basis for understanding the complicated heat and mass transfer characteristics in CFB riser (Wang et al., 2009). The optimum design and scale-up of CFB risers require a fundamental understanding of the mixing patterns of phases including the variations on the solid
distributions, the continuous formation and dissipation of clusters, and the solid down-
flows (Almuttahar and Taghipour, 2008).

Based on what has been mentioned above, it is now widely accepted that cluster is a
special existing form of aggregated particles, whose solids holdups is significantly higher
and whose hydrodynamic behaviors is quite different from single particles. The methods
and techniques that are used to study the flow structure and clusters inside the CFB will
be introduced next.

2.2 Measurement techniques

Generally speaking, published experimental measurement techniques used to study the
characteristics and structure of clusters in gas-solid systems can be divided into two
categories: intrusive probes (Horio et al., 1992; Manyele et al., 2002) and non-intrusive
visualization methods (Rhodes et al., 1992; Shi et al., 2008) (as well as “inside bed
imaging” systems such as a high-speed video camera attached to a bore-scope (Takeuchi
et al., 1991; 1996; 1998) and a video camera connected to a optic fiber micrograph probe
(Li et al., 1991; Zou et al., 1994)). The former is advantageous for using in dense regions
and determining local flow properties such as solids holdup and particle velocity. The
latter, however, is preferable due to their little disturbance to the flow.

2.2.1 Intrusive measurement technique

Intrusive measurement techniques including capacitance probe, sampling probe and
optical fiber probe are effectively used for obtaining solids holdup and particle velocity.
As the optical fiber probe is commonly applied, more emphasis will be put on describing
the optical fiber probe, while the other two methods will be introduced briefly.

Capacitance probe

The capacitive measurement of the solids holdup is physically based on the measurement
of the relative dielectric constant of the fluid-solids suspension which depends directly on
the volumetric concentration of the two phases. Thus, the relative dielectric constant of a
suspension of solid particles in a fluid is a function of the relative dielectric constants of
the fluid and the solids respectively, and the solids volume concentration (Weisendorf and Werther, 2000). The capacitive probe is effective to measure the instantaneous solids holdup and particle velocity. It is simple and effective to measure the local flow properties. However, its measuring volume is hard to define. Moreover, it is sensitive to the humidity, temperature, electrostatics and the interference of the electromagnetic field, which limits its measurement.

**Sampling probe**

The sampling probes includes isokinetic and non-isokinetic probes. The isokinetic sampling probe is restricted to apply in the flow system in absence of significant velocity gradients (Rhodes and Laussmann, 1992). The unsteady flow systems are adverse conditions for its application due to the intense turbulence flow in the denser region and discontinuous solids distribution. Non-isokinetic sampling probe has been successfully used for determination of solid flux to understand and explain the complex flow behaviour in CFBs (Rhodes, 1990, Rhodes and Laussmann, 1992). It collects an unbiased amount of sample particles in a specified time from which solid flux can easily be calculated and can be used to very dilute, homogeneous suspensions of fine particles.

**Optical fiber probe**

Optical probes have long been used by a number of researchers to measure particle velocity and solids holdup (Oki et al., 1975; 1977; Patrose and Caram, 1982; Qin and liu, 1982; Hartge et al., 1988; Kato et al., 1990; Herbert et al., 1994; Werther et al., 1996; Zhang et al., 1998; Issangya et al., 1999; Parssinen and Zhu, 2001a, 2001b; Liu et al., 2003a, 2003b; Xu and Zhu, 2010). As a simple and relatively inexpensive intrusive technique, it is known to be beneficial in measuring the local solids holdup and particle velocity from dilute to dense conditions for several powder types in both the gas and liquid systems of the riser. In addition, its immunity from interference of temperature, humidity, electrostatics and electromagnetic fields is another attractive advantage. In addition, it is often considered that its small size does not significantly disturb the overall flow structure in CFB risers if properly designed.
The multi-fibers reflective-type optical probe is used very often. Its principle to measure the solids holdup is that the intensity of the light reflected by a small volume of particles in front of the probe tip is proportional to the solids holdup within that volume. The light reflected by the moving particles are magnified by a photo-multiplier and then converted into voltage signals. Since it is proved that the relationship between the voltage signals and the solids concentration in the measurement volume is nonlinear, a reliable calibration becomes a key factor which ensures the accuracy of the measurement (Qi et al., 2008).

Particle velocity can also be measured by the optical fiber probe through the equation of \( V_p = L_e/T_{AB} \), where \( L_e \) is the effective distance between the two bundles of fibers, and \( T_{AB} \) is the particle transit time between fiber bundle A and B. \( T_{AB} \) is obtained from the time lag at which the cross-correlation function, \( \Phi_{1,2}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T I_1(t)I_2(t+\tau)dt \) reaches a maximum (Horio et al., 1988, Hartge, 1988). With precise calibration and cross-correlation applied between the bundles of optical fibers, solids concentration and particle velocity are obtained. Details of the calibration process and calculation of velocity are specifically introduced in previous literatures (Zhang et al., 1998, Liu et al., 2003a; 2003b).

However, with a complicated calibration procedure, deficiencies such as the measuring volume at the probe tip decreases as the solids holdup increases (Reh and Li, 1990; Liu et al., 2003a) and the unquantified amount of disturbance from the probe to the flow (Zhang et al, 1998), can cause measurement inaccuracies in the use of the probe techniques (Chen and Fan, 1992), even though the interference is small in comparison to the other intrusive methods available for local properties measurements (Cocco et al., 1995).

2.2.2 Non-intrusive measurement techniques

Comparing to the intrusive measurement techniques, the non-intrusive techniques can be accomplished by placing the instrument outside the CFB system, which are preferable due to their little disturbance to the flow. Laser Doppler Anemometry (LDA), Particle Imaging Velocimetry (PIV) and Visualization system with the high speed video cameras all belong to this type of measurements.
Laser Doppler Anemometer (LDA)

Laser Doppler Anemometer (LDA), also known as laser Doppler velocimetry (LDV), is a typical non-intrusive solids velocity measurement technique. The basis of this technique is that the frequency of light scattered by a moving solid is subject to a Doppler shift and the solid velocity can be determined by measuring the shift. This method is able to accurately measure gas/solids velocities in gas-solid suspensions (Yianeskis, 1987). However, particles in the laser beam directly in front of the measurement volume may influence the accuracy of the determined particle velocity. Moreover, in higher concentrated fluid-solid flows, the more difficult for the laser light to pass the opaque particles layers on its way from the probe to the particles and back (Werther et al., 1996).

Particle Imaging Velocimetry (PIV)

PIV techniques are used to measure gas-solid flow characteristics and obtain instantaneous information of a multiphase system in CFB. Typical PIV apparatus consists of a camera (normally a digital CCD camera), a high power laser, an optical arrangement to limit the physical region illuminated (normally a cylindrical lens), a synchronizer to act as an external trigger for control of the camera and laser, the particles and the fluid under investigation. A fiber optic cable or liquid light guide often connects the laser to the lens setup. The common data analysis technique for a photographically recorded particle image is the beam readout technique. By taking the pictures of illuminated particles, the flow track of the particles is reconstructed. Based on this, the velocities of the activated particles are calculated. Cluster sizes and velocity distributions in dilute fluidized bed are also determined from the video image analysis. However, when the high density wall layer is formed, the diffusion of the laser light results in difficult measurements inside the CFB columns. In other words, the PIV technique is effectively used under conditions of low solids concentration, but is less effective in denser regions.

Visualization system

Visualization techniques were first thought only capable of providing the qualitative references and mapping the overall flow structures under dilute solids holdup conditions.
However, with the development and improvement of modern video cameras and application of imaging process and analysis methods, those limitations are in the process of being overcome with more and more quantitative details stressed, such as solids holdup measurement, cluster size and velocity determination and the cluster formation mechanism (Lackermeier et al., 2001; Cocco et al., 2010; Casleton et al., 2010; Xu and Zhu, 2012; Shaffer et al., 2013; McMillan et al., 2013).

Basically, the visualization system consists of the light source, video camera recording and image processing. Although different video cameras and settings and equipment designs may vary with different researchers, what is common for the study of visualization systems is that information are obtained from processing and analyzing the image, which makes the knowledge of image processing a requirement.

It is worthwhile to note that the choice of the ordinary light source makes the application of rectangular CFB necessary. Caicedo et al. (2003) conducted a study on the behaviour of bubbles in a 2D gas-solid fluidized bed using digital image analysis with a strobe light used as the light source. Goldschmidt et al. (2003) also studied the bed expansion and segregation dynamics in a 2-D dense gas-fluidized bed by using digital image analysis. Continuous high intensity uniform illumination of the bed was obtained with six 500W halogen lamps. It seems that applying the image analysis in the 2-D fluidized bed systems is an effective and direct way to identify the hydrodynamics of the flow (Caicedo et al., 2003; Goldschmidt et al., 2003; Shen et al., 2004; Bokkers et al., 2004; Cheng et al., 2005; Wang et al., 2006; Lim et al., 2007).

In addition, studies including some “inside bed imaging” systems such as a high-speed video camera attached with a bore scope (Takeuchi et al., 1991, 1996, 1998) and a video camera connected with an optic fiber micrograph probe (Li et al., 1991; Zou et al., 1994) are also classified as non-intrusive techniques in the present study.

### 2.3 Microscopic studies in the CFB

The hydrodynamic characteristics of the gas-solid flow structure in the riser of the CFB have important effects on many industrial applications such as catalytic reactions, solid
fuel combustion and gasification. However, due to the formation of the clusters, the gas-solid two phase flow structure is more complicated and far from well understood. Therefore, the cluster studies are paid more and more attention.

### Table 2.1 Clusters studies using different measurement techniques

<table>
<thead>
<tr>
<th>Author</th>
<th>Particles</th>
<th>Particles properties</th>
<th>Operating conditions</th>
<th>Riser dimensions</th>
<th>Measurement technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horio et al. (1988)</td>
<td>FCC</td>
<td>61 1780 0.016-16.5 0.15-1.3 0.2 1.6</td>
<td>Laser sheet technique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li et al. (1991)</td>
<td>FCC</td>
<td>54 930 7.3-64.6 1.3-3.5 0.09 11</td>
<td>Optical fibre micrographs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li et al. (1991)</td>
<td>FCC</td>
<td>54 929.5 7.32-64.65 1.31-3.49 0.09 10</td>
<td>Video camera</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhodes et al. (1992)</td>
<td>FCC</td>
<td>74.9 2456 2-80 3-5 0.305 6.6</td>
<td>High-speed video</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lim et al. (1995)</td>
<td>Sand</td>
<td>213 2640 10-60 4.5-8 0.146×0.146 9.14</td>
<td>Video recording</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zou et al. (1994)</td>
<td>FCC</td>
<td>54 930 9.3-64.7 1.3-3.5 0.09 10</td>
<td>Video camera</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soong et al. (1995)</td>
<td>Sand</td>
<td>251 n/a 45 5 0.15 11</td>
<td>Dual capacitance probes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wei et al. (1995)</td>
<td>FCC</td>
<td>54 1389 18-215 1.2-8.5 0.186 8</td>
<td>Photomultiplier</td>
<td></td>
<td></td>
</tr>
<tr>
<td>van den Moortel et al. (1998)</td>
<td>Glass beads 60,120,330 2400 0.002-0.16 0.3-1.5 0.2×0.2 2</td>
<td>Laser sheet technique</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Takeuchi et al. (1998)</td>
<td>FCC</td>
<td>57 930 45.6 2.03-2.42 0.1 5.5</td>
<td>High-speed video system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lackermeyer et al. (2001)</td>
<td>Sand</td>
<td>140 n/a 6 3 0.4 15.6</td>
<td>High-speed video and laser sheet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shi et al. (2008)</td>
<td>Glass beads 250, 333,420 2379, 2478, 2514 4.35, 10.5, 45 5.2, 5.57 0.2×0.2 4</td>
<td>PIV</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

n/a: data not given in the paper.

#### 2.3.1 Micro-flow structure inside CFB

In CFBs, particles are often found to exist in aggregated forms with relatively high solids holdup compare to the mean solids holdup in the riser. This phenomenon is reported by
Many earlier researchers (Yerushalmi and Squires, 1975; Li and Kwauk, 1980). Later on, the existence of aggregated forms (i.e. clusters) was confirmed in many published studies using a wide range of experimental techniques, including optical fiber probes, laser sheet techniques, capacitance probes and video camera, see Table 2.1.

Figure 2.1 Illustration of proposed particle aggregation processes (Bi et al., 1993)

Many terms have been used to describe the particle groups or the ‘dense clouds’ of particles with far more particles per unit volume than the surrounding dilute regions in the riser such as “agglomerates”, “clusters”, “streamers”, “strands”, “ribbons”, “swarms”, “dense packets”. There were also some discussions about these terms. Yerushalmi et al. (1976) used “streamers”, “strands”, “ribbons” and “dense packets” interchangeably, while Horio and Clift (1992) suggested that there are differences between agglomerates and clusters in fluidized systems, i.e. an agglomerate consists of a group of particles held together by inherent inter-particle forces (Van der Waals forces, liquid bridge forces, electrostatic forces, etc.), while a cluster is a group of particles held together as a result of external imposed effects (most commonly hydrodynamic). Zethraeus and Ljungdahl (1993) defined clusters as a set of particles close to each other that move with a similar overall slip velocity because of their momentum interchange. Bi et al (1993) suggested that particle clusters refer to a group of several to several dozens of particles aggregated...
together in the riser in order to reduce the effective drag force exerted on them. They also identified four possible forms which are summarized in Table 2.2. A possible particle aggregation process proposed by Bi et al. (1993) is shown in Figure 2.1. Helland (2007) suggested that a cluster is a group of particles held together as a result of hydrodynamic effects. Based on the assumption that two antagonistic drag effects co-exist on an individual particle depending on the inter-particle distance within a cluster, they investigate a model approach accounting for two different classes of clusters: dilute and dense. As mentioned at the beginning of this chapter (Section 2.1), since there still has been few common understandings on the definition and classification of clusters so far, to avoid confusion, the “clusters” are adopted in this study as a generalized conception, which refers to all forms of particle agglomeration.

Table 2.2 Summary of solids aggregation forms in CFBs (Bi et al., 1993)

<table>
<thead>
<tr>
<th>Forms of Aggregation</th>
<th>Region</th>
<th>Shape</th>
<th>Characters</th>
<th>Scale</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>particle clusters</td>
<td>core and annulus</td>
<td>sphere</td>
<td>$D_e &lt; 1 \text{ cm}$ \hspace{1cm} $\epsilon \approx \epsilon_{mf}$</td>
<td>micro-scale</td>
<td>1. interparticle force \hspace{1cm} 2. particle-wake interaction</td>
</tr>
<tr>
<td>particle streamers /strands</td>
<td>core</td>
<td>stripe</td>
<td>$L_e &gt; 1 \text{ cm}$ \hspace{1cm} $\epsilon \approx 0.7-0.95$ \hspace{1cm} $U_e &gt; 0$</td>
<td>meso-scale</td>
<td>1. resemble of clusters. \hspace{1cm} 2. breakup of particle sheets \hspace{1cm} 3. non-uniform introduction of particles</td>
</tr>
<tr>
<td>particle swarms</td>
<td>annulus</td>
<td>swarm</td>
<td>$L \approx 1-1.5 \text{ cm}$ \hspace{1cm} $U_e \approx -0.3-0.4 \text{ m/s}$</td>
<td>meso-scale</td>
<td>1. wall-particle interaction</td>
</tr>
<tr>
<td>particle sheets</td>
<td>annulus</td>
<td>layer</td>
<td>$\delta_e \approx 0-3 \text{ cm}$ \hspace{1cm} $U_e \approx -1 \text{ m/s}$</td>
<td>macro-scale</td>
<td>1. resemble of particle swarms \hspace{1cm} 2. particles diffusing to the wall region and swarms</td>
</tr>
</tbody>
</table>

$D_e$ - equivalent size \hspace{1cm} $L_e$ - equivalent length \hspace{1cm} $U_e$ - average velocity \hspace{1cm} $\epsilon$ - average voidage \hspace{1cm} $\delta_e$ - average thickness of particle sheets
Numerous descriptions of the observed clusters were presented by many published papers. Li et al. (1991) reported that clusters have rather irregular shapes and highly variable sizes by using a video camera provided with a special optic fiber micro-graph probe. Clusters were observed to transform from strands at the center of the bed into near-spheres adjacent to the wall, see Figure 2.2. Furthermore, by applying multiple laser sheets technology, Horio and Kuroki (Horio and Kuroki, 1994) observed that the typical shape of a cluster is a parabola or a horseshoe shape heading downward enclosing a gas wake in the upper side (Figure 2.3). From a cluster, particles were shed to the dilute phase continuously from the periphery and absorbed again by other clusters.

For the vertical operating risers, Horio and Kuroki (1994) observed clusters in both the core and annulus regions within the fast fluidization regime. According to the observation, clusters in the annulus tend to travel downward whilst those located in the core usually travel upward. Typical downward velocities in the annulus region lie in the
range 0.5-2 m/s. Clusters at the wall of a riser have been observed to form, descend, break-up, travel laterally from the annulus to the core and then be re-entrained in the upward flowing core. Kuroki and Horio (1994) contributed to the internal solids mixing process within a riser. Clusters have been observed in both dilute and dense phase flow regimes. Xu and Zhu (2011) clearly observed clusters in annulus (Figure 2.4) and core region (Figure 2.5) by using the high speed video camera in a narrow rectangular circulating fluidized bed riser, which indicates that the low particle density and small particle size contribute to the cluster formation. In the downer, the existence of solid clustering phenomena is also observed by means of the micro-video action shot which confirms that the configurations of clusters are anomalous and often in the form of floc and stick structures (Lu et al., 2005), as is shown in Figure 2.6.

Figure 2.3 Photographs in the dilute transportation regime (Horio and Kuroki 1994)
Figure 2.4 Clusters at the annulus region (Xu and Zhu, 2010)

Figure 2.5 Clusters with U-shape at the core region (Xu and Zhu, 2010)
2.3.2 Cluster identification

From the reported studies so far, both intrusive probes and visualization methods can be used to identify clusters. The intrusive probes are one-point measurement methods, which can provide information at various time scales but limited spatial variation. The visualization methods, on the other hand, can practically provide information at any point within the measurement zone. The specialties of the two kinds of methods leads to their own criterion to identify the clusters.

For a number of reported experimental studies which identify clusters using the intrusive probes, cluster information are obtained from the local instantaneous probe signals (Soong et al., 1993; Tuzla et al., 1998; Sharma et al., 2000; Manyele et al., 2002; Xu and Zhu, 2011, 2012). Based on a suggested criterion, a cluster would be identified if the local instantaneous solids holdup ($\varepsilon_{sl}$) is significantly greater than the mean solids holdup ($\bar{\varepsilon}_{sc}$), i.e. $\varepsilon_{sl} = \bar{\varepsilon}_{sc} + n\sigma$. One of the major discussion on cluster identification for the following studies is concentrated on how to select the value of $n$. Manyele et al. (2002) conducted a sensitivity analysis to determine the value of $n$ and found that $n$ was in the
range of 1.0-1.4. Xu and Zhu (2011) adopted the sensitivity analysis and determined the value to be 2.

Comparing to intrusive probes, a particular advantage of the image processing method is the exact geometrical determination of the measuring area which is needed for the calculation of velocities and sizes of clusters. However, there are less studies for cluster identification with visualization methods. Burkhardt and Bredebusch (1996) and Lackermeier et al. (2001) calculated a threshold to identify clusters from the histograms of gray values for each pixel of obtained images over time. Based on the comparable relationship between grayscale and solids holdup, they set the threshold to the gray value which leads to the same value of the cluster volume (or area) fraction as was obtained from corresponding fiber optical measurements. Xu and Zhu (2012) also applied image processing to characterize the cluster size and velocity. The threshold is set to the mean gray value of the whole image. Mondal et al. (2013) used the similar criterion as that of Soong et al. (1995) to choose a threshold grayscale to convert the original image into a binary image so that the clusters are separated from their surroundings. The grayscale value of the clusters (δₙ) is higher than the local average grayscale (δ̅ₙ), i.e. δₙ = δ̅ₙ + kσₙ, where σₙ is the standard deviation of the local grayscale intensity. By visual inspection and the comparison to the original image, the k value was chosen as 1.

While it is all agreed that the solids holdup of clusters is significantly greater than that of its surroundings, the criteria to separate a cluster from its surroundings is still not clear and the selection of the threshold solids holdup are still more a trial and error than systematic. Therefore, more studies on the systematical cluster identification methods are required.

2.3.3 Cluster characteristics

Knowledge of clusters has proven to be useful in predicting radial and axial gas-solids flow patterns and mixing phenomena, understanding of heat and mass transfer in risers and eliminating erosion in industrial units (Harris et al., 2002). Therefore, studies relating to clusters characteristics, especially cluster mean solids holdup, size and velocity, have potential industrial significance.
Cluster mean solids holdup

When the average solids holdup in clusters is measured by optic fiber probe or capacitance probe, researchers often take the number averaged solids holdup in clusters. Time integration of instantaneous solids holdup from starting to ending time of cluster occurrence gives the time-average solids holdup for a particular cluster. A number average of such solids holdups over the number of clusters, n, gives:

\[
\bar{\varepsilon}_{sc} = \frac{1}{n} \sum_{i=1}^{n} \varepsilon_{st}
\]  

(2.1)

An equation (Eq. 2.2) based on other researchers’ experimental data was derived by Harris et al. (2002) summarizing the correlation between solids concentration of cluster and the mean solid concentration of bed section (\( \bar{\varepsilon}_s \)) in the riser. The correlation coefficient (R²) of the equation is 0.90, which showed a good validity.

\[
\bar{\varepsilon}_{sc} = \frac{0.58\bar{\varepsilon}_s^{1.48}}{0.013 + \bar{\varepsilon}_s^{1.48}}
\]  

(2.2)

Figure 2.7 Radial variations of solids holdup inside clusters (Sharma et al., 2000)
Sharma et al (2000) found that the average solids holdup in clusters decreased significantly with increase in gas velocity (Figure 2.7) and the average solid holdup in the cluster phase could reach as high as 0.12, almost three times that of the corresponding bed. Figure 2.8 shows the radial profiles of the average solids concentration inside clusters at different operating conditions in the developed flow section (Z = 6.34 m). Manyele et al (2002) found clearly that higher $\bar{\varepsilon}_s$ leads to higher $\bar{\varepsilon}_{sc}$, and vice versa. Therefore, higher $G_s$ leads to higher $\bar{\varepsilon}_{sc}$. The low-flux condition ($U_g = 8.0$ m/s and $G_s = 100$ kg/m$^2$/s) leads to lower solids concentration inside the clusters.

Figure 2.8 Radial profiles of the mean solids holdup inside cluster at different operating conditions (Manyele et al., 2002)

Cluster size

As clusters are in a dynamic equilibrium of coalesce and breakup, the cluster size varies both radially and axially within a riser (Horio et al., 1988; Li et al., 1991; 1995). Based on this fact, the cluster size discussed here is the mean cluster vertical length reported by many researchers.
Wei et al. (1995) discovered that, increasing superficial gas velocity and/or decreasing solids circulation rate can reduce the cluster size. The captured cluster signals by optical fiber probe are shown in Figure 2.9 (Li et al., 1995). The vertical ordinate represents the reflected light intensity and the horizontal one represents time. Clusters passed the two probe tips with certain time interval and there was a time lag, $t$, between the two signals curves associated with one cluster, which is known by comparing the time of corresponding peaks, valleys, or some characteristic points. Then cluster velocity $V_c$ is calculated from:

$$V_c = \frac{d}{t} \quad (2.3)$$

The corresponding cluster vertical length is calculated from:

$$L_c = V_c \times T \quad (2.4)$$

where $d$ is the distance between centers of two optic fiber probe heads. $T$ in Figure 2.9 represents the traveling time of a cluster passing through a probe head.
Their study shows that the mean cluster vertical length in lower dense section is larger than that in the upper dilute section, which may be caused by the gas entrainment and gravity segregation.

Cluster size is expressed as a function of voidage or solid holdup by Zou et al (1994) through Eq. 2.5:

\[
\frac{\bar{D}_c^e}{d_p} = 1.853 \left[ \frac{(1-\varepsilon)^{0.25} \varepsilon^{-1.5}}{(\varepsilon - \varepsilon_m)^{2.41}} \right] + 1 \quad (2.5)
\]

Subbarao (2010) developed an equation to estimate the size of clusters considering ‘volume ratio of cluster to void to be equal to the volumetric fraction ratio of cluster to void in the bed’, i.e.:

\[
\frac{D_{cl}^3}{D_v^3} = \left[ \frac{\delta_c}{1-\delta_c} \right] \quad (2.6)
\]

where \(D_{cl}\) is diameter of cluster, \(D_v\) is diameter of void, \(\delta_c\) is cluster fraction.

Recognizing that cluster size is larger than the size of particles and all the particles move in clusters formation with a voidage of \(\varepsilon_c\) in high velocity fluidization regimes, the cluster size is obtained from:

\[
D_{cl} = \left( \frac{1-\varepsilon}{\varepsilon_c-\varepsilon_c} \right)^{1/3} \frac{2u_t^2}{g} \left( 1 + \frac{u_t^2}{u_{sr}^2} \right)^{-1} + D_p \quad (2.7)
\]

where \(u_t\), \(u_{sr}\), \(\varepsilon\), \(\varepsilon_c\) and \(D_p\) are terminal velocity of a single particle, slug rise velocity, bed voidage, cluster voidage and diameter of particle, respectively.

Slug rise velocity \(u_{sr}\) depends on column diameter as:

\[
u_{sr} = 0.35(gD_t)^{1/2} \quad (2.8)
\]

where \(D_t\) is the column diameter.
With the development of the image processing, the cluster size is obtained from the processed image. Lackermeier et al. (2001) measured the cluster vertical length by transforming the original image into the binary image with the size of image known.

**Cluster velocity**

Many researchers have reported that $\bar{U}_c$ lies within the range 0.5-2 m/s irrespective of the experimental conditions. Based on an emulsion layer model, neglecting inertia effects and assuming viscous flow with appropriate boundary conditions, an expression for the mean flow velocity of the annular film was given as (Mahalingam and Kolar, 1991):

$$\bar{U}_c = \frac{\rho_{film} g \delta_{film}^2}{3 \mu_{film}} \quad (2.9)$$

$\rho_{film}$ is the wall film bulk density, $\delta_{film}$ is the wall film thickness and $\mu_{film}$ is the viscosity of the wall film emulsion.

Lim et al. (1996) predicted the falling velocities of a single cluster using a force balance:

$$F_d + F_m + F_w + F_b = F_g \quad (2.10)$$

$$F_g = A \delta g \rho_p (1 - \varepsilon) \quad (2.11)$$

$$\frac{\delta}{D} = 0.5 \left[ 1 - \sqrt{1.34 - \frac{1.3(1 - \bar{\varepsilon})^{0.2} + (1 - \bar{\varepsilon})^{1.4}}{1.34}} \right] \quad (0.80 \leq \bar{\varepsilon} \leq 0.9985) \quad (2.12)$$

$$F_d = C_D \rho_g A \delta u_{rel}^2 \quad (2.13)$$

$$F_m = G_n (V_{cl} - V_p) A \quad (2.14)$$

$$F_w = A \tau_w; \quad \tau_w = k_w \rho_p (1 - \varepsilon) V_{cl} \quad (2.15)$$

$$F_b = A \delta g \rho_p (1 - \varepsilon) \quad (2.16)$$

where, $F_d$ is the drag force; $F_m$ is the momentum exchange force between cluster and the surroundings; $F_w$ is the force on the cluster due to wall friction; $F_b$ is the buoyancy force and $F_g$ is the gravitational force; $A$ is the cross-sectional area of the riser; $\delta$ is wall layer
thickness; $\rho_p$ is the particle density; $\varepsilon_{cl}$ is the internal voidage of the cluster; $\bar{\varepsilon}$ is the mean voidage across the column; $C_D$ is the effective drag coefficient; $\rho_g$ is the gas density; $u_{rel}$ is the relative velocity between clusters and surrounding gas; $G_h$ is the lateral solids flux from adjacent dilute phase to cluster; $V_{cl}$ is the velocity of descent of cluster; $V_p$ is the vertical component of velocity of solids entering clusters; $\tau_w$ shear stress; $k_w$ constant; $\varepsilon_a$ is mean voidage in the annulus.

Pandey et al. (2004) reported that downward velocity of cluster is in the range of 0.8-1.4 m/s and the downward cluster velocities are independent of the operating conditions in a pilot scale circulating fluidized bed.

Based on the cross-correlation technique, Lackermeier et al. (2001) achieved a vector of displacement for a sequence of frames. As it is possible to calculate a value which is connected to the probability of the existence of a cluster in the images, it is possible to connect these sequences. The velocities of clusters are calculated according to their profiles. The cluster velocity in the horizontal direction is not considered due to its small value.

### 2.3.4 Cluster studies using visualization measurement techniques

In gas-solid circulating fluidized beds (CFBs), particle groups, since referred to as “clusters” in the so called “fast fluidization” realized in CFBs in the 1970s (Yerushalmi and Squires, 1975; Grace and Tuot, 1979) have been studied comprehensively, starting from finding the evidence of their existence to attempting to observe their formations and movements. Later on, with the application of visualization techniques, further studies have revealed that there are different types of clusters with different shapes and significantly varying sizes existing in the CFB riser. Both relatively small and large chaotic dense packets are noted to exist and move rapidly at two vertical heights along the riser. Besides, strands with parabolic shape pointing upward were relatively often observed. (Takeuchi and Hiram, 1991; Takeuchi et al., 1996; 1998). Li et al. (1991) visualized that cluster shapes are in general irregular but appear strands-like in the core region and spherical near the wall. Cluster sizes are also found highly variable. Rhodes et al. (1992) identified three flow forms: dilute, dense and swarm flow. The dense flow
form was found least stable, agglomerating to produce swarm flow. Moreover, typical arch-shaped particle swarms with downward velocity were observed and size of vertical particle strands are often longer than 0.1 m. Bi et al. (1993) identified four possible particle aggregation forms and illustrated their evolution and transformation through observation made in a two-dimensional circulating fluidized bed. With “internal” and “external” picturing systems, Kuroki and Horio (1994) were able to obtain “internal and external” images of clusters with $G_s$ in the ranges of 0.2-16.5 and 0.016-0.60 kg/m$^2$s, respectively. The cluster shape changed frequently but its typical shape from the observation was a paraboloid heading downward and having a long skirt upward. In the dilute phase, particles from clusters were shed to the dilute phase continuously and were absorbed again by other clusters. The cluster sizes were rather uniform under a given operating condition but decreased with increased solid mass flux (Horio and Kuroki, 1994). The high-speed video observations from Matsuda et al. (1996) indicated that most particle swarms in the central region of the CFB riser are descending ones and the packing density of particle swarms was as high as that of a fixed bed. Particle aggregates and void regions was used to characterize gas-solid flow structure first (Van den Moortel and Tadrist, 1996) and then reported that up-flowing particle clusters exhibited horseshoe shapes heading upward with thin downward tails, while the downward-moving cluster also exhibited a horseshoe shape but heading downwards with thin tails upward. The tails were formed by the motion of gas pockets on both sides (Van den Mootel et al., 1998). Shi et al. (2008) captured visual images and the micro-structure of various clusters. According to the distance between particles and the shape and appearance position, clusters are classified into four categories. The understanding of clusters has been progressing with improvements to studying means and methods. Compared to complicated calibration procedures and undesirable physical flow disturbances of intrusive probes, visualization techniques are attracting more researchers in recent years. Visualization measurement, using video cameras to study clusters are listed in Table 2.3.

To summarize the previous cluster studies with video cameras, it is worthwhile to note that, firstly, most frame rates of the video camera setups were lower than 1000 fps with longer shutter times. In order to study the behavior and properties of clusters comprehensively, higher frame rates are required.
Table 2.3 Clusters studies with visualization techniques in gas-solid flow

<table>
<thead>
<tr>
<th>Author</th>
<th>Measurement Technique</th>
<th>Video camera setup</th>
<th>Particles</th>
<th>Particle properties</th>
<th>Operating conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Frame rate (fps)</td>
<td>Shutter time (μs)</td>
<td>dₚ(μm)</td>
<td>ρₚ(kg/m³)</td>
</tr>
<tr>
<td>Takeuchi and Hirama (1991)</td>
<td>High speed video system</td>
<td>400</td>
<td>200</td>
<td>FCC</td>
<td>57</td>
</tr>
<tr>
<td>Li et al. (1991)</td>
<td>Video camera with Optical fibre micrograph probe</td>
<td>n/a</td>
<td>n/a</td>
<td>FCC</td>
<td>54</td>
</tr>
<tr>
<td>Rhodes et al. (1992)</td>
<td>High speed video camera</td>
<td>1000</td>
<td>n/a</td>
<td>FCC</td>
<td>74.9</td>
</tr>
<tr>
<td>Kuroki and Horio (1994)</td>
<td>Laser sheet &amp; TV camera</td>
<td>n/a</td>
<td>4000</td>
<td>FCC</td>
<td>61.3</td>
</tr>
<tr>
<td>Horio and Kuroki (1994)</td>
<td>Laser sheet &amp; TV camera</td>
<td>60</td>
<td>10000</td>
<td>FCC</td>
<td>61.3</td>
</tr>
<tr>
<td>Zou et al. (1994)</td>
<td>Video camera with Optical fibre micrograph probe</td>
<td>n/a</td>
<td>n/a</td>
<td>FCC</td>
<td>54</td>
</tr>
<tr>
<td>Takeuchi et al. (1996)</td>
<td>High speed video system</td>
<td>1000, 2000</td>
<td>100</td>
<td>FCC</td>
<td>57</td>
</tr>
<tr>
<td>Matsuda et al. (1996)</td>
<td>High speed video system</td>
<td>2000, 3000</td>
<td>n/a</td>
<td>Glass beads</td>
<td>400</td>
</tr>
<tr>
<td>Lim et al. (1996)</td>
<td>Video camera</td>
<td>n/a</td>
<td>4000</td>
<td>Sand</td>
<td>213</td>
</tr>
<tr>
<td>Van den Moortel and Tadrist (1996)</td>
<td>Laser sheet &amp; video camera</td>
<td>25</td>
<td>n/a</td>
<td>Glass beads</td>
<td>120</td>
</tr>
<tr>
<td>Van den Moortel et al. (1998)</td>
<td>Laser sheet &amp; video camera</td>
<td>25</td>
<td>n/a</td>
<td>Glass beads</td>
<td>60, 120, 230</td>
</tr>
<tr>
<td>Takeuchi et al. (1998)</td>
<td>High-speed video system</td>
<td>1000</td>
<td>100</td>
<td>FCC</td>
<td>57</td>
</tr>
<tr>
<td>Lackerm eier et al. (2001)</td>
<td>High-speed video technique and laser sheet</td>
<td>1000</td>
<td>100</td>
<td>Sand</td>
<td>140</td>
</tr>
<tr>
<td>Shi et al. (2008)</td>
<td>PIV</td>
<td>n/a</td>
<td>n/a</td>
<td>Glass beads</td>
<td>250, 333, 420, 2379, 2478, 2514</td>
</tr>
<tr>
<td>Coco et al. (2010)</td>
<td>High-speed video camera</td>
<td>3000-6000</td>
<td>20</td>
<td>Polyethylene, FCC</td>
<td>70, 76</td>
</tr>
</tbody>
</table>

n/a: data not given in the paper.
Secondly, almost all of the studies were conducted under lower solids circulation rates (< 80 kg/m²s) and superficial gas velocities (< 8.0 m/s). Taking into account the industrial applications of fluidized beds, cluster and flow structure visualization under higher operating conditions deserves further study. Lastly, there was no discussion about relationships to correlate the image information (shown as various degrees of grayscale) and characteristics of clusters in the former image-based studies. However, in order to “extract” and process useful information from obtained images for a quantitative analysis, it is very necessary to build such a relationship before image processing methods applied. Based on the above analysis, corresponding improvements especially a newly developed image calibration method is implemented in the present thesis.

**Nomenclature**

- \( a \) Semiaxis of cluster, m
- \( A \) Cross section area of the riser, m²
- \( C_{D} \) Effective drag coefficient, -
- \( d_p \) Particle mean diameter, m
- \( d \) The distance between two probe tips, m
- \( D \) The hydraulic diameter of the column, m
- \( D_{cl} \) Diameter of Cluster diameter, m
- \( D_p \) Diameter of particle, m
- \( D_t \) Column diameter, m
- \( D_v \) Diameter of void, m
- \( \bar{D}_{cl}^e \) Cluster mean equivalent diameter, m
- \( F_b \) Buoyancy force, N
\( F_d \) Drag force, N
\( F_g \) Gravitational force, N
\( F_m \) Momentum exchange force between cluster and the surroundings, N
\( F_w \) The wall friction force, N
\( g \) Acceleration due to gravity, m/s\(^2\)
\( G_{h} \) Lateral solids flux from the adjacent dilute phase to the cluster, kg/m\(^2\)s
\( G_s \) Solids circulation rate, kg/m\(^2\)s
\( k \) Parameter for determine cluster separation, -
\( k_w \) Constant, 0.016
\( L_c \) Cluster vertical length, m
\( L_e \) Effective distance between two fiber bundles, m
\( n \) Number of standard deviation above the mean value, -
\( t \) Time lag between two signal curves, s
\( T_{AB} \) Time lag between the signal of one particle detected by two channel, s
\( T \) Cluster traveling time through a probe tip, s
\( u_{rel} \) Relative velocity between clusters and surrounding gas, m/s
\( u_{sr} \) Slug rise velocity, m/s
\( u_t \) Terminal velocity of a single particle velocity, m/s
\( \bar{U}_{cl} \) Mean cluster (or wall film) velocity, m/s
\( U_g \) Superficial gas velocity, m/s
$V_c$  Mean cluster velocity, m/s

$V_{cl}$  Velocity of descent of cluster, m/s

$V_p$  Local particle velocity, m/s

Greek Letters

$\delta$  Wall layer thickness, m

$\delta_c$  Cluster fraction, -

$\delta_{film}$  The wall thickness, m

$\delta_g$  Grayscale value of clusters, -

$\bar{\delta}_g$  Local average grayscale, -

$\varepsilon$  Local voidage, -

$\varepsilon_a$  Mean voidage in the annulus, -

$\varepsilon_c$  Cluster voidage, -

$\varepsilon_{cl}$  Internal voidage of cluster, -

$\varepsilon_{mf}$  Incipient fluidization voidage, -

$\varepsilon_s$  Instantaneous local solids holdup, -

$\varepsilon_{sl}$  Local instantaneous solids holdup, -

$\bar{\varepsilon}$  Mean voidage across the column, -

$\bar{\varepsilon}_s$  Cross-sectional averaged solids holdup, -

$\bar{\varepsilon}_{sc}$  Cluster mean solids holdup, -

$\mu_{film}$  Viscosity of wall film emulsion, kg/m·s
\( \rho_{\text{film}} \)  Wall film bulk density, kg/m\(^3\)

\( \rho_g \)  Gas density, kg/m\(^3\)

\( \rho_p \)  Particle density, kg/m\(^3\)

\( \sigma \)  Times of standard deviation above the mean value, -

\( \sigma_g \)  The standard deviation of the local grayscale, -

\( \tau_w \)  Shear stress, N/m\(^2\)

References


Lints, M., Glicksman, L.R., 1993. The structure of particle clusters near the wall of a circulating fluidized bed. AIChE Symposium Series 89, 35-47.


Chapter 3

3 Experimental systems and Measurements

The whole project mainly concentrates on studying the hydrodynamics and microscopic characteristics of FCC particles in a rectangular circulating fluidized bed (CFB) with non-intrusive means. Therefore, a novel image calibration method based on image processing is originally developed by adopting a high speed video camera in a cold-model rectangular (CFB) transparent Plexiglas riser. This chapter describes the detailed information about the experimental apparatus and the measurement methods.

3.1 Experimental systems

There are two major experimental systems in this study: fluidization and visualization systems. Both have their own specific design and characteristics, which will be introduced separately in the following sections.

3.1.1 Fluidization system

All the experiments were performed in a cold-model rectangular CFB system that consists of a 7.6 m high riser with a rectangular cross section of 19 mm×114 mm and a 3.85 m high downcomer of 38 mm×203 mm with a 1.85 m cylindrical storage column of 203 mm i.d. on top, including two cyclones, a bag house filter, flapper valves on the cylindrical storage section for solids circulation rate measurement and a gas distributor at the bottom of the riser (Figure 3.1). A flip valve is used to control the solids flow rate. Air enters from the bottom of riser through the distributor, mixes with the particles fed from the downer and carries the particles up the riser into the first cyclone where solids are separated from the air. The separated particles flow down into the downcomer, where they are fed into the riser again. Solids escaped from the first cyclone pass into the secondary cyclone for further separation, with the last gas-solids separation being carried out by a bag filter. Fine particles collected at the bottom of the secondary cyclone and the large capacity bag filter are also fed back to the downcomer. High pressure steam is supplied to the windbox of the riser with the primary air to eliminate the static electricity so as to avoid the misleading effects inside the riser.
Figure 3.1 Schematic diagram of the rectangular circulating fluidized bed
3.1.2 Visualization system

The visualization system developed in the present study consists of three major parts: light source, high speed video camera and image processing and analyzing system (see Figure 3.2).

![Visualization system diagram](image)

**Figure 3.2 Visualization system**

**Light source**

A 500Watt quartz halogen bulb (4-5/8” T-3 lamp, L-16, The Designers Edge, USA) with a lifetime of 1500 hours is selected as the light source (as shown in Figure 3.3). The reasons for the selection are that halogen bulb have higher luminance (Ellenberger and Young, 2000) and possess constant brightness on constant voltage (Zubler and Mosby, 1959). Moreover, the illuminance of the bulb is about 95000 lx, which eliminates the hotspot appearing in the images. A diffusion panel is applied to make the recorded area uniformly illuminated and eliminate undesirable shadows as well as intensity gradients. The panel also acts as an insulator to prevent overheating of the wall of the CFB riser from the radiation of the lamp. A digital illuminance meter or lux meter (LX-1330B, Easy Life Product, Hong Kong) is used to measure the illuminance before the experiment to make sure that every image is shot under the same luminance flux (see Figure 3.4).
The high speed video camera is the MotionScope M2 from Redlake (as shown in Figure 3.5). The camera allows frame rates up to 16000 fps (frame per second) and a maximum resolution of 1280×1024 pixels at 500 fps leading to a record time of 4s for the built in memory. Its equipped sensor, MI-MV13 (see Figure 3.6), contains special self-calibrating circuitry that enables it to reduce its own column-wise fixed-pattern noise. It also has an
IR cut-off optical filter to block infrared light from entering the optical path so as to avoid its interference on the actual image. A Pentax C21228TH 12.5mm F1.8 manual lens is chosen to capture images of solids flow in the riser. During the whole experimental time span, the camera with the lens and the section of videoed column are covered by a black box to avoid the disturbance of external lightings.

![Figure 3.6 1.3-megapixel CMOS active-pixel digital image sensor](image)

From the video camera settings, it is known that for the resolution of the camera’s CMOS sensor, the higher the resolution, the lower the frame rate. Therefore, considering the frame size, speed and the illuminance of backup light, the frame speed of 2000 fps with a resolution of 1280×256 pixels and 500 μs shutter time were chosen during the whole experiment. Output images are uncompressed full frames without any loss of original information, which guarantees the precision of later image processing. With these settings, the valuable information, like flow patterns, shape and behavior of clusters, can be provided without any intrusion from the original recorded images. At least 100 images were taken under every operating condition at each shooting height to guarantee the statistical credibility of the observed results.

**Image processing and analyzing**

A desktop is used for real-time video monitoring and image storage and a laptop for digital image programming analysis. Through a standard Firewire (IEEE-1394) interface, the software from Redlake, Motionscope 2.0.3 allows the shooting video to be monitored in real-time and image sequences captured by the camera can be transferred to the
desktop and stored as well. Self-developed MATLAB programs enable the original images to be transformed into binary images so as to obtain the cluster equivalent diameter. The image arithmetic and logical operations enable the solids holdup inside the cluster and cluster velocity to be determined.

### 3.2 Measurements

Different methods and techniques are employed to measure different parameters in this study. As this study is mainly about hydrodynamic and microscopic study in the rectangular CFB riser, following major parameters need to be determined: 1) Superficial gas velocity, $U_g$; 2) Solids circulation rate, $G_s$; 3) Local solids holdup, $\varepsilon_s$.

#### 3.2.1 Measurements of superficial gas velocity

Superficial gas velocity, $U_g$, was measured by a rotameter, which was pre-calibrated by the manufacturer with the same fluid media (air) under the standard calibration condition ($P_s = 101325$ Pa, $T_s = 293.15$ K). However, the actual flow rate readings need to be modified by the following equation:

$$Q_{actual} = Q_{reading} \sqrt{\frac{P_s T_a}{P_a T_s}}$$

(3.1)

where $P_a$ is the actual upstream pressure of the rotameter in Pa; $T_a$ is the actual air temperature in K.

#### 3.2.2 Measurement of solids circulation rate

Solids circulation rate is measured by a device located at the cylindrical storage section with a diameter of 203 mm. A central vertical plate divides the column into two halves with two flapper valves fixed at the top and bottom respectively. Thus, falling particles can be lead to the half column which is sealed by the bottom valve through appropriately flipping the top valve $45^\circ$ to the other half column. This way, solids circulated through the fluidization system accumulated in one side of the measurement column for a given time period. Then, the solids circulating rate can be obtained from the measured time period of solids accumulation and solids packed volume by the following equation:
\[ G_s = \frac{V \rho_b}{A \Delta t} \quad (3.2) \]

where \( V \) is the volume of the half cylindrical column, \( \rho_b \) is the bulk density of the particle, \( A \) is the cross-sectional area of the riser and \( \Delta t \) is the time period of solids accumulation in that half cylindrical column.

### 3.2.3 Measurement of local solids holdup

In this study, local solids holdup is measured by two kinds of techniques: an intrusive optical fiber probe and a non-intrusive image calibration method with the application of high speed video camera.

#### Optical fiber probe

The PV6D optical fiber probe (The Institute of Processing Engineering, Chinese Academy of Science, Beijing, China), is a commonly intrusive technique that is used to measure the local solids holdup (Figure 3.7). The probe has an outer diameter of 3.8 mm including two sub-probes vertically aligned with a distance of 1.51 mm. Each sub-probe has an active tip area of 1 mm×1 mm and consists approximately 8000 light emitting and receiving quartz fibers with a diameter of 15 µm. These quartz fibers are arranged in alternating arrays.

With a light source, the light emitting fibers illuminated a certain volume of particles which reflected the light to the light receiving fibers. Through the processing of a photomultiplier, the reflected light intensity corresponding to the volumetric concentration within the illuminated volume is converted into voltage signals which are further amplified and fed into the PC. Using a prior accurate calibration equation, the relationship between the output voltage signal and the local solids holdup is built and the local solids holdup under different operating conditions can be achieved.
In the present study, the calibration procedure is performed in a downer calibration system developed by Zhang, et al. (1998). The calibration apparatus consists three parts: 1) feed control system; 2) solids holdup measurement system; 3) back pressure control system. A schematic is provided in Figure 3.8.

The falling solids fed by a vibrating solids feed are trapped by a couple of sling shot valves. The solids holdup is determined by weighing the trapped solids with the suspension density calculated from the solids weight and the volume of the trap section. With the application of a back pressure control system, the back pressure of the downer column is enhanced so as to slow down the particle velocity at the same time, which increases the solids holdup in the column. Solids holdup in the range of dilute to dense conditions can be achieved by adjusting the valve installed in the vibrating solids feeder and applying the back pressure control system. With the optical fiber probe applied to measure the light intensity reflected by the solids under each solids holdup condition, the voltage signal and the calculated solids holdup are correlated. In this way, a full calibration curve is generated. Figure 3.9 shows the calibration curve for spent FCC particles in the present study.
Figure 3.8 Schematic of the apparatus for solids holdup calibration of optical fiber probe
Figure 3.9 Solids holdup calibration curve of the optical fiber probe for the spent FCC particles

Image calibration method

The image calibration method is based on a fact that the information of an actual object conveyed by an image is expressed in grayscale. In the current study, in order to quantitatively analyze the image information of the FCC particles, a calibration process is needed to correlate the grayscale of the digital image and the solids holdup of FCC particles inside the rectangular CFB riser based on the consistency illuminance of the light source, which is verified in detail in Chapter 4.

The calibration apparatus with a height of 2.03 m is converted temporarily from the two section of the original riser so as to maintain the same illumination system for both calibration and the actual experiments (as shown in Figure 3.10). Moreover, to obtain stable and homogeneous fluidization with graded solids holdup for the calibration, a liquid-solid system is applied instead of the original gas-solid system. Therefore, a comparison becomes necessary to testify the influence of the refractive index of different medium (air and water) on the grayscale.
Blank tests are carried out first to compare image reflections of the gas and liquid phases, i.e. capturing images of the CFB column with only air and water respectively. As shown in Figure 3.11, the results turn out that the mean gray value of the image for water is 254.97, which is quite the similar to the value 254.98 for air (with a difference of 0.004%). This indicates that although there is a difference between the refractive index of air (1.00) and water (1.33), their image reflections have almost no difference. Note that the comparison here is between the images of the same object in the two different mediums, i.e. air and water, while the camera is always in the air. This is different from comparing images of the same object captured when the camera is immersed into the two
different mediums respectively, where the refractive index difference of the two mediums may play an important role. Therefore, the influence reflected by the difference refractive index of the two phases is negligible in the present study and it is reasonable to apply the calibration results obtained from the water-solid system in the air-solid system.

![Figure 3.11 Image similarity of the two different mediums](image)

After the blank tests, FCC particles with a mass of 400.5 g are used as the calibration materials. Water enters into the column from the entrance at the bottom and flows out through the exit at the top, where a screen mesh is installed to prevent the fluidized particles being carried out of the column. Through two pressure measurement ports with a vertical distance of 75mm, solids holdup in between can be obtained from the pressure difference. Different solids holdups can be achieved from changing the bed expansion, which is controlled by adjusting the water flow rate. For each solids holdup, the image grayscale between the two pressure measurement ports is calculated and a sequence of ten images is captured to improve the accuracy. Therefore, the corresponding image grayscale value is the mean value for the ten images. In this way, the relationship between graded solids holdup and corresponding mean grayscale is built.
Figure 3.12 Calibration curve between solids holdup and grayscale

Figure 3.12 presents the calibration curve of graded solids holdup and the mean gray value of respective digital images for FCC particles. The exponential correlation between solids holdup ($\varepsilon_s$) and grayscales (G) is obtained with an adjusted R square of 0.9972:

$$G = 28.0 + 228.3 \exp(-19.62 \varepsilon_s)$$  \hspace{1cm} (3.3)

The above equation is less sensitive when $\varepsilon_s$ is higher than 0.2, but the conditions encountered in this study is well below that.

This calibration experiment developed in the present study provides a very useful method to correlate the solids holdup of fluidized particles and their image information, the gray scale values. Thus, the calibration curve and equation will be used as the basis of image processing in the present and subsequent studies.

Comparing to the optical fiber probe, the image calibration method based on the high speed video camera is newly developed to obtain the local solids holdup from images captured by the high speed video camera, which belongs to a non-intrusive technique. Dividing an original image into different sub-images, the local solids holdup can be
converted by the mean grayscale of the corresponding sub-image. Therefore, with the relationship between the solids holdup and the grayscale achieved (Eq. 3.3), the local solids holdup can be obtained.

3.3 Operating and measurement conditions

The bed material is FCC particles of 67 μm (Sauter mean diameter) with particle density of 1877 kg/m³. Solids circulating rate, Gₛ, ranges from 50 to 150 kg/m²s, while the superficial gas velocity, Uₛ, ranges from 3.0 to 12.0 m/s.

The solids holdup are measured by the optical fiber probe at two axial levels H = 5.33 and 3.60 m along the riser height. For each axial level, there are nine radial positions, i.e. r/R = -0.98, -0.75, -0.50, -0.25, 0, 0.25, 0.50, 0.75, 0.98. Here, H is the height from the riser distributor and r/R is the dimensionless distance from the riser axis.

Based on the calibration equation (Eq.3.3), a non-intrusive method relying on the image calibration is developed to calculate the radial solids holdup values. Each image with a frame size of 485×255 is divided into 15 sub-images, which correspond to 15 radial positions, i.e. r/R = -0.94, -0.81, -0.69, -0.57, -0.44, -0.32, -0.2, 0, 0.2, 0.32, 0.44, 0.57, 0.69, 0.81, 0.94, in which r/R is still the dimensionless distance from the riser axis. Solids holdup of each position is calculated from the mean gray value of its corresponding sub-image. To guarantee the statistical significance, at least 100 images are obtained for each operating condition. Therefore, the solids holdup value is the mean value of these images (≥ 100) for each condition. The shooting positions are focused on the two axial levels: H = 5.33 and 3.60 m, which are the same as that of the optical fiber probe measurement.

3.4 Summary

In this study, besides the intrusive technique (the optical fiber probe that is used to study the hydrodynamic), a systematic non-intrusive method (image calibration method), is successfully developed by means of the high speed video camera in the rectangular CFB riser. This novel method correlates the solids holdup of fluidized particles and their image information, the grayscale values for the first time. As the whole research concentrates on the images, the calibration curve and equation becomes the basis of entire studies. An
important prerequisite for this newly developed method is the illuminance consistency of
the light source, which will be discussed specifically in Chapter 4. Moreover, to
guarantee the precision of the calibration experiments, two sections of the original riser
with a height of 2.03 m are temporarily converted to the calibration apparatus, which is
also an advantage of this method.

The image calibration method provides a new path to study the hydrodynamics and the
microscopic structure in the CFB, which deserves further application.

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Chapter 4

4 A novel method based on image processing to visualize clusters in a Rectangular Circulating Fluidized Bed Riser

A new method based on image processing has been developed to visualize clusters in a rectangular circulating fluidized bed (CFB) transparent Plexiglas riser at the fully developed region. A high speed video camera is adopted with FCC particles of 67 μm used as the bed material. In order to make sure day-to-day shooting images are reliable and comparable under the same light illumination during the whole shooting period, a reference plate is made first to verify the light illumination consistency. After the verification, the relationship between solids holdup and image grayscale is calibrated in the same riser with both calibration curve and equation obtained. With given solids holdup thresholds increasing from 0.01 and 0.1, clusters size clearly decreases while cluster solids holdup increases by transforming gray images into binary ones. The variation of cluster profiles with different thresholds also reveals that there is a solids holdup gradient inside the cluster with a lower value at the surface and a higher one in the core. The change in dense phase holdup or cluster population with operating conditions is indicated by the variation of the black area under given solids holdup thresholds, which compare well with the well-known fact reported by many previous studies: higher $G_s$ and lower $U_g$ are beneficial for clusters with higher solids holdup to form, while lower $G_s$ and higher $U_g$ induce clusters to breakup. This consistency proves that the image calibration method developed in the present study is effective and very useful.

4.1 Introduction

In gas-solid circulating fluidized beds (CFBs), the phenomenon that particles tend to aggregate together to form groups which have a relatively high particle concentration than the mean solids concentration, has been reported by many earlier researchers (Wilhel and Kwauk, 1948; Yerushalmi and Squires, 1975; Grace and Tuot, 1979; Li and Kwauk, 1980; Subbarao, 1986). Particle groups, first referred to as “clusters” in the so called “fast fluidization” realized in CFBs in the 1970s (Yerushalmi and Squires, 1975;
Grace and Tuot, 1979), have been studied comprehensively, starting from finding the evidence of their existence to attempting to observe their formations and movements. Later on, further studies have revealed that there are different types of clusters with different shapes and significantly varying sizes existing in the CFB riser. Takeuchi et al. (Takeuchi et al., 1991; 1996; 1998) noted that both relatively small and large chaotic dense packets existed and moved rapidly at two vertical heights along the riser. Besides, strands with parabolic shape pointing upward were relatively often observed. Li et al. (1991) visualized that cluster shapes are in general irregular but appear strands-like in the core region and spherical near the wall. Cluster sizes are also found highly variable. Rhodes et al. (1992) identified three flow forms: dilute, dense and swarm flow. The dense flow form was found least stable, agglomerating to produce swarm flow. Moreover, typical arch-shaped particle swarms with downward velocity were observed and size of vertical particle strands are often longer than 0.1m. Bi et al. (1993) identified four possible particle aggregation forms and illustrated their evolution and transformation through observation made in a two-dimensional circulating fluidized bed. With “internal” and “external” picturing systems, Kuroki and Horio (1994) were able to obtain “internal and external” images of clusters with Gs in the ranges of 0.2-16.5 and 0.016-0.60 kg/m²s respectively. The cluster shape changed frequently but its typical shape from the observation was a paraboloid heading downward and having a long skirt upward. In the dilute phase, particles from clusters were shed to the dilute phase continuously and were absorbed again by other clusters. The cluster sizes were rather uniform under a given operating condition but decreased with increased solid mass flux (Horio and Kuroki, 1994). The high-speed video observations from Matsuda et al. (1996) indicated that most particle swarms in the central region of the CFB riser are descending ones and the packing density of particle swarms was as high as that of a fixed bed. Van den Moortel et al. (1996; 1998) first used particle aggregates and void regions to characterize gas-solid flow structure and then reported that up-flowing particle clusters exhibited horseshoe shapes heading upward with thin downward tails, while the downward-moving cluster also exhibited a horseshoe shape but heading downwards with thin tails upward. The tails were formed by the motion of gas pockets on both sides. Shi et al. (2008) captured visual images and the micro-structure of various clusters. According to the distance between
particles and the shape and appearance position, clusters are classified into four categories. The understanding of clusters has been progressing with improvements to studying means and methods. However, due to the complication of microscopic gas-solid two phase flow in CFB, it is expected that further insights about the characteristics and hydrodynamics of clusters can be obtained. As there has been few common understandings on the definition and classification of clusters so far, to avoid confusion, the “clusters” used in this paper are a generalized conception, which refers to all forms of particle agglomeration.

Generally speaking, published experimental measurement techniques that were used to study the characteristics and structure of clusters in gas-solid systems can be mainly divided into two categories: intrusive probes (Horio et al., 1992; Manyele et al., 2002) and non-intrusive visualization systems (Rhodes et al., 1992; Shi et al., 2008) (also including some ‘inside bed imaging’ systems such as a high-speed video camera attached with a bore scope (Takeuchi et al., 1991; 1996; 1998) and a video camera connected with an optic fiber micrograph probe (Li et al., 1991; Zou et al., 1994)). The former is advantageous for using in dense regions and determining local flow properties such as solids holdup and particle velocity. The latter, however, are preferable due to their little disturbance to the flow. Visualization techniques were first devised as a method only providing qualitative indications and mapping the overall flow structures under dilute solids holdup conditions. However, with the development and improvement of modern video cameras and application of imaging process and analysis methods, those limitations are in the process of being overcome (Zou et al., 1994; Lim et al., 1996; Lackermeyer et al., 2001; Cocco et al., 2010; Xu and Zhu, 2011; 2012). Compared to complicated calibration procedures and undesirable physical flow disturbances of intrusive probes, visualization techniques are attracting more researchers in recent years. Visualization measurement techniques using video cameras to study clusters are listed in Table 4.1.

To summarize the previous cluster studies with video cameras, it is worthwhile to note that, firstly, most frame rates of the video camera setups were lower than 1000 fps with longer shutter times. In order to study the behavior and properties of clusters comprehensively, higher frame rates are required.
## Table 4.1 Clusters studies with visualization techniques in gas-solid flow

<table>
<thead>
<tr>
<th>Author</th>
<th>Measurement technique</th>
<th>Video camera setup</th>
<th>Particles</th>
<th>Particle properties</th>
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<tr>
<td></td>
<td></td>
<td>Frame rate (fps)</td>
<td>Shutter time (μs)</td>
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<tr>
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<td>High speed video system</td>
<td>400</td>
<td>200</td>
<td>FCC</td>
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<td>Li et al. (1991)</td>
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<td>FCC</td>
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<td>Rhodes et al. (1992)</td>
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<td>1000</td>
<td>n/a</td>
<td>Alumina particles</td>
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<td>Kuroki and Horio (1994)</td>
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<td>4000</td>
<td>FCC</td>
<td>61.3</td>
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<td>Horio and Kuroki (1994)</td>
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<td>10000</td>
<td>FCC</td>
<td>61.3</td>
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<td>n/a</td>
<td>FCC</td>
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<td>Matsuda et al. (1996)</td>
<td>High speed video system</td>
<td>2000, 3000</td>
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<td>Lin et al. (1996)</td>
<td>Video camera</td>
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<td>Van den Moortel and Tadjrit (1996)</td>
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<td>25</td>
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<td>n/a</td>
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<td>n/a</td>
<td>FCC</td>
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</table>

n/a: data not given in the paper.
Thus, the frame rate of 2000 fps were set in the current study. Secondly, almost all of the studies were conducted under lower solids circulation rates (< 80 kg/m²s) and superficial gas velocities (< 8.0 m/s). Taking into account the industrial applications of fluidized beds, cluster and flow structure visualization under higher operating conditions deserves further study. The present visualization technique with image processing method in this study has proved to be effective under high solids concentrations where G_s is at least up to 150 kg/m²s. Lastly, there was no discussion about relationships to correlate the image information (shown as various degrees of grayscale) and characteristics of clusters in the former image-based studies. However, in order to “extract” and process useful information from obtained images for a quantitative analysis, it is very necessary to build such a relationship before image processing methods are applied. As a result, a calibration method was introduced for the first time in the present paper.

As an image-based research work, the aim of the present study is to develop a systematic and integrative method to view clusters with certain solids holdups formed inside the rectangular CFB riser and to build a basis for deriving a comprehensive understanding of the micro-flow structure by processing and analyzing the images of clusters in the following studies.

4.2 Experimental

4.2.1 Circulating fluidized bed and operating conditions

The experiments were conducted in a cold-model rectangular CFB system that consists of a 7.6 m high riser with a rectangular cross section of 19 mm×114 mm and a 3.85 m height of 38 mm×203 mm downcomer with a 1.85 m cylindrical storage column of 203 mm i.d. on top, including two cyclones, a bag house filter, flapper valves on the cylindrical storage section for solids circulation rate measurement and a gas distributor at the bottom of the riser (Figure 4.1). A flip valve is used to control the solids flow rate. Air enters into the bottom of riser through the distributor, mixes with the particles fed from the downer and carries the particles up the riser into the first cyclone where solids are separated from the air. The separated particles flow down into the downcomer, from where they are fed into the riser again.
Figure 4.1 Schematic diagram of the rectangular circulating fluidized bed
Solids escaped from the first cyclone pass into the secondary cyclone for another separation, with the last gas-solids separation being carried out by a bag filter. Fine particles collected at the bottom of the secondary cyclone and the large capacity bag filter are also fed back to the downcomer. The bed material was FCC particles of 67 μm (Sauter mean diameter) with particle density 1877 kg/m³. Solids circulating rate, G_s, ranged from 50 to 150 kg/m²s, while the superficial gas velocity, U_g, ranged from 3.0 to 9.0 m/s.

**Figure 4.2 Visualization system**

4.2.2 Visualization system

The visualization system consists of a high speed video camera, a light source, real-time video monitoring and image storage and digital image programming analysis, as shown in Figure 4.2. In order to eliminate the entrance and exit effects, the shooting position is focused on the upper fully developed region at the 5.33 m height of the riser. The camera and the section of videoed column are covered by a black box to avoid the disturbance from external lightings. A 500 Watt quartz halogen bulb with irradiation of strong lights about 95000 lx is used as the experimental light source. A diffusion panel is applied to make the recorded area uniformly illuminated and eliminate undesirable shadows as well as intensity gradients. The panel also acts as an insulator to prevent overheating of the
wall of the CFB riser from the radiation of the lamp. Through a standard Firewire (IEEE-1394) interface, the software from Redlake, Motionscope 2.0.3 allows the shooting video to be monitored real-time and image sequences captured by the camera can be transferred to a computer and stored as well. Self-developed MATLAB programs enable the image process and frame-by-frame analysis later.

4.2.3 Description of the apparatus

The high speed video camera is the MotionScope M2 from Redlake. It allows frame rates of up to 16000 fps and a maximum resolution of 1280×1024 pixels at 500 fps leading to a record time of 4s for the built in memory. Its equipped sensor, MI-MV13, contains special self-calibrating circuitry that enables it to reduce its own column-wise fixed-pattern noise. The camera also has an IR cut-off optical filter to block infrared light from entering in the optical path so as to avoid its interference on the actual image. A Pentax C21228TH 12.5mm F1.8 manual lens was chosen to capture images of solids flow in the riser. A 500Watt quartz halogen bulb (4-5/8” T-3 lamp, L-16, The Designers Edge, USA) with a lifetime of 1500 hours was selected as the light source due to its high luminance over the complete spectrum and constant light emission during its lifetime (Ellenberger and Young, 2000), and also their advantage of possessing constant brightness for constant voltage. A digital illuminance meter or lux meter (LX-1330B, Easy Life Product, Hong Kong) is used to measure the illuminance before experiment to make sure every image was shot under the same luminance flux.

Another point worth mentioning is that for the resolution of the camera’s CMOS sensor, the bigger the frame size, the lower the frame rate. Therefore, considering the frame size and the illuminance of backup light, the frame speed of 2000 fps (frame per second) and 500 μs shutter time are chosen during the whole experiment. Output images are uncompressed full frames without any loss of original information, which guarantees the precision of later image processing. Thus a prominent advantage of the visualization system is that some valuable information, like flow patterns, shape and behavior of clusters, can be provided without any intrusion from recorded images. At every operating condition, at least 100 images are taken in order to guarantee the statistical significance of the observed results.
4.3 Results and Discussion

4.3.1 Light illumination consistency analysis

An image is the optical representation of an object illuminated by a radiating source. For digital images captured during the whole experiment time period, a critical concern is how to ensure all the experiments are operated under the same illumination conditions i.e. to confirm that day-to-day shooting images are consistent and comparable. From measurements of the avometer, the lamp voltage fluctuates between 114.4 and 116.3 volts with a difference of 1.7 %, which can be considered under constant voltage. According to the measurement of the lux meter during the experimental process, the light illuminance at the place of the camera lens fluctuated between 1970 and 2050 lx with a difference of 4.1 %, the variation of which is within a reasonable range as well. Beyond that, an outstanding feature of halogen lamps, lumen maintenance, ranges from 96-101 % on constant voltage lamps at 99 % life (Zubler and Mosby, 1959), and the output luminous flux at the end of its lifetime could be 90% of its original. Both measurement results and bulb characteristics show that the excellent stable illuminance of quartz halogen light bulbs is reliable to a great extent. However, qualitative analysis, as mentioned above, is not enough in order to prove that day-to-day shooting is comparable, so a reference plate was made to verify the accuracy quantitatively.

4.3.1.1 Reference Plate

The essence of a grayscale image is a 2-D array with one numerical value (between 0-255) at each pixel (Solomon and Breckon, 2011) and the gray value reflects the brightness of the scene at that point. Therefore, under the same illumination conditions, the gray value of the image of the shooting object only changes with its own brightness. On the other hand, the gray value of the object may change with the variation of illumination. To solve this problem, a reference plate is used as a “control” object to verify the light illuminance consistency. The reference plate is a 3mm thick transparent plastic plate glued with the same bed material, i.e. FCC particles (as shown in Figure 4.3). The particles are glued to purposely form unevenly solids distribution so that it reflects the real case.
4.3.1.2 Testification of light illuminance consistency results

Four bulbs of the same model are used in the testification. Among them, one (#1) had been used for roughly 800 hours with another (#2) roughly 400 hours and the other two (#3 and #4) were brand new before the experiments.

The gray values of the reference plate with two different positions under illumination of the four bulbs are given in Figure 4.4. The gray values of the four bulbs are nearly the
same with a maximum difference of 1.4 %. Similarly, when the reference plate is turned upside down, as shown in the lower row of Figure 4.4, the gray values are very close to each other with 1.2 % as their maximum difference. Comparing the two rows, it is obtained that, for each bulb, the gray values for both original images and upside-down ones are almost the same with a maximum difference of 0.8 % (bulb #2) and minimum 0.06 % (bulb #3). Also, the gray values of the same object has nothing to do with its angle position at the same illumination surface area under the same light source. Therefore, with respect to illuminance consistency, it can be confirmed that the comparison of shooting results from different bulbs with different usage times is reliable.

Since there is little change in the reference plate gray value for different bulbs under the same operating conditions, which makes the shooting results comparable when changing the bulb becomes unavoidable, the next concern is whether the radiated light flux is stable enough to make the shooting results acceptable for each single bulb. Experiments are then done to study how the gray value of the reference plate changes during each experiment time span for a single bulb in two consecutive days.

Figure 4.5 (a) and (b) show the variation of gray values for each bulb every 30 min (after using 30 min, 60 min, 90 min and 120 min) during one experiment set in two continuous days. The time when the video is first recorded is defined as 0 min. For the first day, the mean gray values of four bulbs during the 2-hour-experiment time are about 168.4, 168.7, 167.6 and 169.6, respectively (shown in Figure 4.5 (a)), while the values become 167.9, 167.8, 167.2, and 168.4 (shown in Figure 4.5(b)) correspondingly the following day. It is easy to observe that gray values of different usage times (30, 60 and 90 min) for each bulb in these two consecutive days fluctuate around their mean value. There is little change in gray values for each single bulb, the difference of which are 0.3% (#1), 0.5 % (#2), 0.2 % (#3) and 0.7 % (#4), respectively. Therefore, it is fair to say that images, whether shot in different usage times during one experiment set or in two consecutive days, are comparable under the illumination of a single bulb. Comparing (a) and (b), the same conclusion with Figure 4.4 can also be obtained that the comparability of images shot under illumination of different bulbs is testified.
Figure 4.5 Stability of the four bulbs with different time periods: (a) first day; (b) second day; (c) one week

Figure 4.5(c) shows the daily gray value variation of bulb #2 for a one-week period. The mean value for the whole week is 168.4 around which those daily values fluctuate. The standard deviation is 0.39, which shows that shooting results are very close to their mean values with little change. By now, it is qualitatively confirmed that under the illumination of bulbs with the same model, the light illumiance is consistent and image results shot day to day are comparable. These constant illumination testifications of the bulbs are the prerequisite for the whole experiment.

4.3.2 Relationship between grayscale and solids holdup

As mentioned in Section 4.3.1, information for an actual object conveyed by an image is expressed in its gray value (integers between 0-255). Therefore, to quantitatively study the actual objects, i.e. clusters from the view of images, a calibration process is needed to
relate the gray value of the digital image to the solids holdup of FCC particles inside the rectangular CFB riser. In order to obtain stable and homogeneous fluidization with graded solids holdup for the calibration, a liquid-solids system is introduced. Blank tests are carried out first to compare image reflections of gas and liquid phase, i.e. capturing images of CFB column with only air and water respectively.

As Figure 4.6 shows, the mean gray value of the image for water is 254.97 compared to 254.98 for air, which turns out nearly the same (with a difference of 0.004 %). This indicates that although there is a difference between the refractive index of air (1.00) and water (1.33), their image reflections have almost no difference (and can be exact the same when the two values are rounded to 255). Note that the image reflection of a medium here means capturing images of the objects which are inside the medium, while the camera are always in the air. This is different from the situation of capturing images inside different mediums where the camera is immersed into different mediums. Therefore, the influence reflected by the difference refractive index of the two phases is negligible in the present study and it is reasonable to apply the calibration results obtained from the water-solid system in the air-solid system. The similarity of the image
reflection of the two medium makes it possible to obtain the graded solids holdup with uniform particle distribution.

4.3.2.1 Calibration apparatus

In order to guarantee the calibration experiment sharing the same illumination system with the actual experiments, two sections of the original riser with a height of 2.03m are temporarily converted to the calibration apparatus. FCC particles with a mass of 400.5 g is used as fluidization materials and uniformly distributed in the water-solid system. Water enters into the entrance at the bottom and flows out through the exit at the top, where a screen mesh is installed to prevent the fluidized particles from being carried out of the column. Through two pressure measurement ports with a vertical distance of 75mm, solids holdup in between can be obtained from the pressure difference. On the other hand, different solids holdups can be achieved through changing the bed expansion, which is controlled by adjusting the water flow rate. In this way, the relationship between graded solids holdup and corresponding mean grayscale is built.

4.3.2.2 Calibration results

The calibration results are shown in Figure 4.7 which presents grayscales versus solids holdup for FCC particles. With the increase in solids holdup, the gray values of the respective images decrease exponentially. Due to the typical characteristics of fast fluidization, solids holdup ranging from 0 to 0.4 was calibrated. An exponential correlation between solids holdup ($\epsilon_s$) and gray scales (G) is obtained with an adjusted R square of 0.9972:

$$G = 28.0 + 228.3 \exp(-19.62\epsilon_s) \quad (4.1)$$

It is further noticed that the above equation becomes less sensitive for $\epsilon_s > 0.2$, but the conditions encountered in this study is well below that.

As quantitative hydrodynamic studies resorting to image processing are at the stage of exploration, this calibration experiment developed in the present study provides a very useful method to correlate the solids holdup of fluidized particles and their image
information, the gray scale values. Thus, the calibration curve and equation will be used as the basis of image processing in the present and subsequent studies.

![Graph showing the calibration curve between solids holdup and grayscale.](image)

**Figure 4.7 Calibration curve between solids holdup and grayscale**

### 4.3.3 Visualization of clusters under different operating conditions

As mentioned earlier, it is now widely accepted that cluster is a special existing form of particle groups, whose solids holdups are significantly higher and whose hydrodynamic behaviors are quite different from single particles. Knowledge of clusters has proven to be useful in predicting radial and axial gas-solids flow patterns and mixing phenomena, understanding of heat and mass transfer in risers and eliminating erosion in industrial units (Harris et al., 2002). Therefore, studies relating to clusters have potential industrial significance. Although a great deal of research have been performed on cluster characterization so far, problems relating to cluster definition, classification, formation and structure, are still far from fully resolved. Using the high speed video camera, the method developed in the current study is expected to provide a new pathway to address such issues.
To characterize the clusters in the gas-solids flow consisting of both dense and dilute phases, a suitable threshold solids holdup value needs to be identified to separate the two phases. In the present study, the grayscale in the image and the solids holdup is correlated by Eq. (4.1), so that a grayscale image can be regarded as a “solids holdup” image. Therefore, in the images obtained from the high speed video camera, a grayscale threshold, corresponding to the solids holdup threshold, is used to assign pixels with grays values higher than the threshold to the foreground and other pixels with values lower than the threshold to the background. With the gray image transformed into a binary image using this method, clusters can be clearly separated from its dilute surroundings. When different solids holdups are chosen as the thresholds to process the images, the clusters shape, size and solids holdup exhibit a transformation, as shown in Figure 4.8, where the black and white colors represent the dense and dilute phases respectively. With solids holdup thresholds increasing from 0.01 to 0.1, the area of dense phase is reduced. In other words, with cluster “layers” of different solids holdup “peeled off” with increasing solids holdup thresholds, cluster size reduces while its solids holdup increases.

(a) $U_g = 5.0 \text{ m/s}, G_s = 50 \text{ kg/m}^2\text{s}$
(b) $U_g = 5.0 \text{ m/s}, G_s = 100 \text{ kg/m}^2\text{s}$

(c) $U_g = 5.0 \text{ m/s}, G_s = 150 \text{ kg/m}^2\text{s}$

Figure 4.8 Binary images under different operating conditions with different solids holdup thresholds.
In addition, the variation of cluster profiles with different thresholds also reveals a solids holdup distribution inside the clusters i.e. the solids holdup gradually increase from lower values at the surface to higher values in the core. This observation suggests that a cluster is consist of particle layers with different solids holdups. Clusters with different shapes, sizes and solids holdups can be observed under different operating conditions as well.

Under a given solids holdup threshold, the percentage dense phase area can be calculated by dividing the total number of black pixels with the total pixel number of the whole binary image. Figure 4.9 plots the dense phase percentage against the solids holdup used as thresholds values, quantitatively linking the two parameters. Results in Figure 4.9 compare well with experimental observations reported in the literature (Xu and Zhu, 2010; 2011): taking a reasonable threshold value of 0.03 as the boundary, shown by the dash vertical line in Figure 4.9, the variation in the dense phase holdup or cluster population follow the general trend in gas-solids flow in a typical CFB riser. Consistent with the results of Xu and Zhu (2011), Figure 4.9 shows that black areas (cluster frequency) increase with increasing solids circulation rate ($G_s$) e.g., from 50 to 150 kg/m$^2$s under the same superficial gas velocity ($U_g$) of 5.0 m/s and decrease with increasing $U_g$ e.g., from 3.0 to 9.0 m/s under the same $G_s$ of 150 kg/m$^2$s. This also indirectly reflects the well-known fact that the average solids holdup inside the riser increases with increasing $G_s$ and decreases with increasing $U_g$. Furthermore, from the cluster point of view, the figure also indicates that clusters with higher solids holdup are easier to form with the increase of $G_s$. Considering that the clusters are in a dynamic equilibrium between formation and breakup, it can also be concluded that higher $G_s$ and lower $U_g$ are beneficial for the formation of clusters, while clusters are inclined to breakup under lower $G_s$ and higher $U_g$. These are all consistent with previous studies (Li et al., 1991; Rhodes et al., 1992; Bi et al., 1993; Kuroki and Horio, 1994; Horio and Kuroki, 1994; Matsuda et al., 1996; Van den Moortel et al., 1996; 1998; Shi et al., 2008) indicating that the method developed in this study is effective and useful.

Therefore, these visualization results provide a basis for future flow structure studies. As a quantitative expression of Figure 4.8, Figure 4.9 not only shows the influence of the operating conditions on the dense phase but also gives good information on solids holdup
distribution inside the cluster, which may be used to correlate with cluster size and holdup and the degree of particle clustering. Issues like these would be very interesting subjects for the future studies.

![Figure 4.9 Black area percentages versus solids holdup thresholds under different operating conditions](image)

**Figure 4.9** Black area percentages versus solids holdup thresholds under different operating conditions

### 4.4 Conclusions

By means of a high speed video camera, a systematic image-based method for the study of gas-solid two phase flow, including an image calibration between the grayscale of an image and the solids holdup, is successfully developed to quantify the cluster phenomenon in a transparent rectangular CFB riser. A 3 mm thick transparent plastic plate glued with FCC particles is used as a reference plate to ensure the consistent light illumination of the light source and thus the consistent measurement of the high speed camera.

A one-to-one correspondence between the solids holdup values inside the fluidized bed with FCC particles and their representative image grayscale values, is built for the first time using the image calibration method. Based on this correlation, the dense and dilute
phases inside the CFB riser are successfully separated by processing the images through choosing proper solids holdup thresholds to obtain cluster size and holdup. With increasing thresholds, cluster size clearly decreases while cluster solids holdup increases. By increasing the threshold, clusters can be “peeled off” into different “layers” to reveal solids holdup distribution inside the clusters: the solid holdup increases from lower values at the cluster surface to higher values in the core.

The variations of cluster population, as well as their size and holdup measured using this image calibration process compare well with the well-known fact reported by many previous studies. Such consistency shows that this image calibration method can be widely used in multiphase system flow.

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References


5 An alternative method for mapping solids holdup in CFB riser through image calibration

In this study, a newly developed image calibration method is compared with an optical fiber probe in the measurement of the solids holdup of FCC particles in a 7.6 m rectangular CFB riser. The image calibration method is based on experimentally correlating solids holdup of FCC particles in the CFB and the grayscale of the corresponding images obtained by a high speed video camera. Using this method, solids holdups along 15 radial positions are calculated under different operating conditions with $U_g$ and $G_s$ in the range of 3.0-12.0 m/s and 50-150 kg/m²s. The solids holdup distribution profiles obtained from the two methods in this study under identical operating conditions coincide with each other fairly well, reflecting the reliability of the image calibration method. Further comparison of the results of image calibration method from the current study with the measurement results of optical fiber probe from other researchers also show good agreement under the same operating condition. These comparisons clearly confirm the feasibility and accuracy of the image calibration method.

5.1 Introduction

Solids holdup is considered as one of the main parameters in characterizing the gas-solid two phase hydrodynamic flow structures in the riser of circulating fluidized bed (CFB). Since CFB technology has been used for a variety of industries from coal combustion, petroleum refineries to fine chemical production and material processes in the past few decades (Shaffer et al., 2013), extensive studies about this parameter highlight the importance of understanding the flow mechanism and development of fundamental theories and also provide key references in determining the accuracy of the computational fluid dynamics (CFD) models.

For solids holdup measurements, the commonly used method is to obtain the axial distribution of the pressure gradient, which is also reliable and easy to operate. However, this method cannot obtain the local solids holdup, especially the radial distribution.
Optical fiber probes have long been used by a number of researchers to measure the solids holdup (Oki et al., 1975; 1977; Patrose and Caram, 1982; Qin and Liu, 1982; Hartge et al., 1988; Kato et al., 1990; Herbert et al., 1994; Werther et al., 1996; Zhang et al., 1998; Issangya et al., 1999; Parssinen and Zhu, 2001a, 2001b; Liu et al., 2003a, 2003b). As a simple and relatively inexpensive technique, it is known to be beneficial in measuring the local solids holdup from dilute to dense conditions in both the gas and liquid riser systems. In addition, its immunity from interference of temperature, humidity, electrostatics and electromagnetic fields is another attractive advantage.

An external visualization technique can also be used to obtain solid holdup outside the riser. It is often operated in combination with narrow rectangular transparent risers due to the quite small depth to width ratio of the riser cross section so that the flow structure along the depth direction is relatively uniform (Xu and Zhu, 2010a). Because images can exhibit much clearer flow structures inside the bed, the external visualization method is more commonly used as an effective means to at least provide qualitative indications on flow patterns and map the overall flow structures. (Arena et al., 1989; Park et al., 2002; Pallares and Johnsson, 2006; Xu and Zhu, 2011). With the development and improvement of modern video cameras and application of imaging process and analysis methods, more and more quantitative details are provided by the visualization methods, such as solids holdup, cluster size and velocity and the cluster formation mechanism (Lackermeier, et al., 2001; Cocco et al., 2010; Casleton et al., 2010; Xu and Zhu, 2012; Shaffer et al., 2013; McMillan et al., 2013).

Based on the correlating of the image information (grayscale) and the solids holdup, an image calibration method developed in our earlier study (Yang and Zhu, 2013) can be applied to obtain the radial distribution of solids holdup, which is considered to be an alternative method to provide accurate and quantitative information about the flow structure. Therefore, the aims of the present study are to exhibit the radial distribution of the solids holdup obtained by the image calibration method at two axial heights along the riser and then to verify the feasibility and accuracy of this method by comparing the results with that of the commonly used optical fiber probe. Both the image calibration method and the optical fiber probe are adopted inside the same rectangular CFB riser.
under identical operating conditions to enable a direct comparison between the two measurement methods.

5.2 Experiment apparatus

5.2.1 Rectangular CFB apparatus

The rectangular CFB apparatus is shown in Figure 5.1. The height of the riser is 7.6 m with a cross section of 19 mm×114 mm. Above a 3.85 m high downcomer of 38 mm×203 mm in cross section, a 1.85 m cylindrical column of 203 mm i.d. is used as a storage vessel. The CFB system also includes two cyclones, a bag house filter and flapper valves near the top of the storage vessel for solids circulation rate measurement. The storage vessel between the two flapper valves is divided into two halves by a central vertical plate. By appropriately flipping over the top valve, particles are introduced to pass through the other half of the column where the bottom is sealed by the bottom valve. With the time period of solids accumulating at a certain height of the column known, the solids circulation rate can then be obtained. A flip valve at the bottom of the downcomer is used to control the solids flow rate. FCC particles of 67 μm (Sauter mean diameter) with particle density of 1877 kg/m³ is used as the bed material. The solids circulation rate \( G_s \) and superficial gas velocity \( U_g \) are in the range of 50-150 kg/m²s and 3.0-12.0 m/s respectively.

5.2.2 Optical fiber probe measurement system

An optical fiber probe system, PV6D (developed by The Institute of Process Engineering, Chinese Academy of Sciences) is used to measure the local solids holdup along the radial direction of the riser. The detailed information of the probe and its calibration steps were elaborated in the previous works (Zhang et al., 1998; Liu et al., 2003a, Xu, 2010b). Solids holdup are measured by the optical fiber probe at two axial levels, i.e. \( H = 5.33 \) and 3.60 m along the riser height, each having nine radial positions, i.e. \( r/R = -0.98, -0.75, -0.50, -0.25, 0, 0.25, 0.50, 0.75, 0.98 \). Here, \( H \) is the height from the riser distributor and \( r/R \) is the dimensionless distance from the riser axis.
Figure 5.1 Schematic diagram of the rectangular circulating fluidized bed
5.2.3 The visualization system and the image calibration method

The visualization system used to obtain the solids holdup images is shown in Figure 5.2. The system include a light source, a high speed video camera and the image processing device. More details for each part can be found in Yang and Zhu (2013).

An image calibration method has been proposed by Yang and Zhu (2013) to experimentally correlate solids holdups with grayscale of the corresponding images obtained by a high speed video camera. The regressed correlation is given as Eq. (5.1) below and the calibration curve with an adjusted R square of 0.9972 is shown in Figure 5.3.

\[ G = 28.0 + 228.3 \exp(-19.62\varepsilon_x) \]  

(5.1)

It is noticed that the above equation becomes less sensitive for \( \varepsilon_x > 0.2 \), but the conditions encountered in this study is well below that. Using the calibration equation (Eq.5.1), the grayscale of the image captured by the camera can be converted to solids holdup values. Therefore, solids holdup distribution along the radial direction can be expressed by the variation of corresponding grayscale values.
Figure 5.3 Calibration curve between solids holdup and grayscale

During the experiments, images with a resolutions of 1280×256 pixels are captured at a recording rate of 2000 fps and an exposure time of 500 µs. Each image is divided into 15 sub-images, corresponding to 15 radial positions, i.e. r/R = -0.94, -0.81, -0.69, -0.57, -0.44, -0.32, -0.2, 0, 0.2, 0.32, 0.44, 0.57, 0.69, 0.81, 0.94, where r/R is the dimensionless distance from the riser axis. Solids holdup at each position is calculated from the mean gray value of its corresponding sub-image. With this division, the radial distribution profiles of solids holdup can be obtained under different operating conditions. To guarantee the statistical significance, at least 100 images are extracted from the recorded video for each operating condition. The shooting positions are at two axial levels, 5.33 m and 3.60 m, the same as those for optical fiber probe measurements.

5.3 Results and discussion

5.3.1 Radial distribution of solids holdup based on the image calibration method

With the application of the image calibration method, the obtained radial distribution of solids holdup under different operating conditions are shown in Figures 5.4 and 5.5. For both axial measurement positions, the trend of the profiles are clear with higher solids...
holdup at the wall region and the lower solids holdup at the center region. It is also observed that the average solids holdup at H = 3.60 m are higher than that at H = 5.33 m under the same operating condition. These distributions are consistent with the findings of previous researchers, measured by the optical fiber probe (Xu and Zhu, 2010a, Parssinen, 2001a; 2001b; Yan and Zhu, 2004; Yan et al., 2005; 2008).

Using the image calibration method, Figures 5.4 and 5.5 also show the impact of operating conditions on the radial distribution of solids holdup for the two axial positions. It can be observed in Figure 5.4 that increasing $G_s$ increase the solids holdups at both the center and wall regions and leads to a less uniform profile. At the same time, higher $G_s$ generates an increased solids holdup gradient at the wall region due to the more pronounced wall effect, whist lower $G_s$ makes the solids holdup distribution more even with lower local solids holdups at each radial position. It is also worthwhile to note that under a certain $U_g$, the solids holdup radial distribution profiles of different $G_s$ show similar trends, which reflect the similarity of the flow structures. It has been noted that the radial distributions of solids holdup at the higher $U_g$ appear to be somewhat irregular. This may be due to the persistence of certain flow pattern developed at or near the distributor under higher gas velocity, “protected” by the narrow fluidized bed.

Figure 5.5 shows the influence of $U_g$ on the radial distribution of solids holdup from the measurements of the image calibration method. Increasing $U_g$ leads to a decreased solids holdup at both center and wall regions for a given $G_s$. Under the same operating conditions, the average solids holdup at the lower position of the riser are higher than that at the upper position. The parabolic shape of the solids holdup radial distribution profiles can also be observed through the image calibration method. Similar results are also reported by the optical fiber probe measurement from previous researches (Xu and Zhu, 2010a, Parssinen, 2001a; 2001b; Yan and Zhu, 2004; Yan et al., 2005; 2008).

Such similarities about the influence of the operating conditions on the solids holdup distribution along both the radial and axial direction between the image calibration method and the optical fiber probe indicate that this newly developed method is feasible and effective.
Figure 5.4 Radial distributions of solids holdup based on image calibration method under different solids circulation rates
5.3.2 Verification using the optical fiber probe

As mentioned earlier, the optical fiber probe is a commonly used method to obtain the local solids holdup. To verify the appropriateness of the image calibration method, both the optical fiber probe and the image calibration method are used in the present study in exactly the same riser under identical operating conditions, so as to enable a direct comparison between the image calibration method and the optical fiber probe.

Figure 5.6 shows the radial distribution of solids holdup under the same \( U_g \) from the two methods. It can be observed that an increase of \( G_s \) results in higher solids holdup at both the center and wall regions for both methods. Meanwhile, the obviously parabolic or “V”
shape distribution profile can be observed. Moreover, under the same operating condition, the average solids holdup at the lower axial position is higher than that at the upper position. These conclusions resemble the results in Section 5.3.1. It is also shown in Figure 5.6 that the radial distribution profiles of solids holdup obtained from the two methods show similar trends and are consistent with each other with a deviation of 13.5%. In other words, the image calibration method works as well as the optical fiber probe in measuring solids holdups.

Figure 5.6 Comparing the radial distribution of solids holdup between image calibration method and optical fiber probe under different solids circulation rates
Figure 5.7 Comparing the radial distribution of solids holdup between image calibration method and optical fiber probe under different superficial gas velocities

Figure 5.7 shows the radial distribution of the solids holdup under the same $G_s$ from the two methods. The common observation that the solids holdup at both center and wall regions decrease with the increase in $U_g$ can also be seen. Meanwhile, for both axial positions, the solids holdup profiles exhibit similar trends and show good consistency between the two measurement methods. The solids holdups measured by the image calibration method and the optical fiber probe under all conditions are plotted in Figure 5.8. The comparison shows excellent agreement between the solids holdups obtained
from the two methods, which clearly verifies the accuracy of the image calibration method.

![Comparison of solids holdup measurement between image calibration method and optical fiber probe](image)

**Figure 5.8 Comparing solids holdup measurement between image calibration method and optical fiber probe**

To further verify reliability of the image calibration method, comparison are also made between the obtained radial distribution profiles of solids holdup with the image calibration method in the present study and those obtained by using the optical fiber probe from previous researchers (Xu and Zhu, 2010a, 2010b). As shown in Figure 5.9 (a), (b) and (c), although $U_g$ is slightly different, the solids holdup distribution show similar shape and trend with only minor difference between the profiles. When the operating conditions are the same, as shown in Figure 5.9 (d), the two profiles are nearly identical.

Figure 5.10 shows the direct comparison of the measurement data from the two methods in Figure 5.9 (d). There is an excellent agreement between the two methods with a difference of solids holdup less than 10%. Therefore, it is concluded that the solids holdups obtained from the two methods in the rectangular CFB under the same operating conditions in the present study, are comparable and very close to each other. That is, the image calibration method is a good alternative method in measuring the solids holdup.
Figure 5.9 Comparing the radial solids holdup profiles between this study and previous researches

Figure 5.10 Comparing the measurements of the image calibration method between this study and those of the optical fiber probe in the previous research (corresponding to Figure 5.9 (d))
5.4 Conclusions

In this work, solids holdup of FCC particles with a Sauter mean diameter of 67 µm and a particle density of 1877 kg/m³ are measured by an alternative image calibration method and the optical fiber probe respectively. Both methods are taken in the riser of a rectangular CFB with a cross section of 0.019×0.114 m² and at two axial positions (5.33 and 3.60 m) under different operating conditions with $U_g$ and $G_s$ in the range of 3.0-12.0 m/s and 50-150 kg/m²s, respectively.

Using the image calibration method, the obtained radial distribution profiles of the solids holdup exhibit similar trends with that of previous research, which reflects the feasibility of the newly developed method. The direct comparing of solids holdup data obtained between the image calibration method and the optical fiber probe under identical operating conditions shows excellent agreement, which clearly verifies the accuracy of the image calibration method.

Further comparing between the image calibration method results from the current study and the measurement results of the optical fiber probe from other researchers also shows an excellent agreement under the same operating condition. These comparisons verify that the image calibration methods is a good alternative method in measuring the solids holdup in the rectangular riser.

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References


Chapter 6

6 Visualization of solids phase separation in a rectangular CFB riser using a novel image calibration method

The gas-solid two phase flow under different operating conditions are visualized in a 19 mm×114 mm narrow rectangular riser at the fully developed region through a high-speed digital image camera. Based on a calibration between image grayscale and solids holdup, the mean solids holdup under different operating conditions can be calculated from the mean grayscale of the images, the results of which is consistent with previous studies. By using different solids holdup as thresholds to transform the grayscale images into the binary images, the solids holdup distribution under different operating conditions can be clearly visualized. To quantify the solids phase separation, the term “relative dense phase area” is introduced as a parameter to characterize the variation of dense phase. A critical solids holdup value of \( \varepsilon_{sc} = 0.04 \) is chosen by carefully examining the variation profiles of the relative dense phase area with solids holdup thresholds, to demarcate the dilute and dense cluster phases. The cluster fraction is then obtained and ranges from 1 % to 59 % under the operating conditions of the present research. With images divided into three regions along the lateral direction, it is found that cluster fraction at the wall region is higher than that of the core and the middle regions. The cluster fraction is also found to increase with the mean solids holdup value.

6.1 Introduction

The hydrodynamic characteristics of the gas-solid flow in the riser of the circulating fluidized bed (CFB) play an important role in many industrial applications such as catalytic reactions, solid fuel combustion and gasification. Both experimental and modelling researches have been conducted extensively around the two-phase flow characterization of the riser. Studies carried out to obtain a better understanding of the gas-solid flow in CFBs dated back to the early 1970s. Pioneering work from Yerushalmi and Cankurt (1978) showed the observations of “demixing patterns” of fast fluidization in a two-dimensional bed, while a uniform and almost homogeneous structure was perceived by naked eye observation. High-speed movies revealed that the clusters and
densely packed strands continually break apart as new aggregates form. Subsequent studies showed that solids holdup is not uniform throughout the CFB riser and the gas-solid flow exhibited a core-annulus pattern characterised by a dilute rapidly rising core surrounded by a denser slowly falling annulus, which is termed as “core – annulus flow” (Rhodes, et al., 1989; Bai et al., 1995). Particle groups, so called clusters or streamers, were commonly found in the annulus region near the wall but also identified in the riser core region (Grace and Tuot, 1979; Li and Kwauk, 1980; Subbarao, 1986). With the development of intrusive and non-intrusive visualization methods, more and more studies of the gas-solid flow have been carried out focusing on more detailed information about the clusters, revealing that there are different types of clusters with different shapes and significantly varying sizes existing in the CFB riser (Takeuchi and Hirama, 1991; Takeuchi et. al., 1996; Takeuchi et. al., 1998; Li et al., 1991; Rhodes et al., 1992; Bi et al., 1993; Kuroki and Korio, 1994; Horio and Kuroki, 1994; Matsuda et al., 1996; Van den Moortel et al, 1996; Van den Moortel et al., 1998; Shi et al., 2008). Cluster is now widely accepted as a special existence of particles, whose hydrodynamic behaviors are quite different from that of single particles in the riser. (Note that the ‘clusters’ used in this paper are a generalized conception and refer to all forms of particle agglomeration.) It is such special existence of particles that makes the gas-solid two phase flow much more complex than that in dilute transport where there is no significant particles clustering. Particle clustering causes the significant alteration to the gas drag exerted on the particles and thus making the experimental understanding and modelling of the gas-solids two phase flow extremely difficult. Therefore, it is of eminent importance to fully characterize the clustering phenomenon. The current study presents an initial attempt to characterize the cluster.

Techniques employed to study the two-phase flow in the riser of the CFB have so far been classified into two major categories: intrusive probes (Horio et al., 1992; Manyele et al., 2002) and non-intrusive visualization methods (Rhodes et al., 1992; Shi et al., 2008). The former is advantageous for determining local flow properties such as solids holdup and particle velocity. The latter, however, is preferable due to their little or none disturbance to the flow. Initially, visualization methods were used only to provide qualitative indications and to map the overall flow structures under dilute solids holdup.
conditions. However, with the development and improvement of modern video cameras and application of imaging process and analysis methods, many researchers have applied digital visual techniques in experimental study of flow hydrodynamics under denser conditions (Zou et al., 1995; Lim et al., 1996; Lackermanier et al., 2001; Cocco et al., 2010; Xu and Zhu, 2011; Xu and Zhu, 2012). As the visualization methods have drawn more and more attentions in studying gas-solid two phase flow, it is expected that more quantitative hydrodynamic information can be provided by this type of method.

In the present paper, a newly developed image calibration method is introduced to correlate the image information (i.e. grayscale) and solids holdup firstly. Then, solids phase separation and analysis through the image calibration method are implemented under different operating conditions. One objective of this study is to use a high speed video camera to present the gas-solid phase visualization at the fully developed region to obtain a better understanding of the flowing behavior of FCC particles in the rectangular riser. Another objective is to use the image calibration method to quantitatively or at least semi-quantitatively analyze the hydrodynamics of the solids phase structure inside the riser as the basis for the microscopic studies.

6.2 Experimental

6.2.1 Rectangular CFB apparatus and operating conditions

The rectangular CFB used in this study consists of a 7.6 m high riser with a cross section of 19 mm×114 mm and a 3.85 m height downcomer of 38 mm×203 mm with a 1.85 m cylindrical storage column of a 203 mm i.d. on top, including two cyclones, a bag house filter, flapper valves on the cylindrical storage section for solids circulation rate measurement and a gas distributor at the bottom of the riser. A flip valve at the bottom of the downcomer is used to control the solids flow rate. A schematic diagram of the apparatus is shown in Figure 6.1. The bed material is FCC particles of 67 μm (Sauter mean diameter) with particle density of 1877 kg/m³. Solids circulation rate, Gs, ranges from 50 to 150 kg/m²s, while the superficial gas velocity, Ugs, ranges from 3.0 to 12.0 m/s.
Figure 6.1 Schematic diagram of the rectangular circulating fluidized bed
6.2.2 Visualization system

The visualization system consists of a MotionScope M2 high speed video camera (The Redlake, USA), a 500Watt quartz halogen bulb (4-5/8” T-3 lamp, L-16, The Designers Edge, USA) with a lifetime of 1500 hours as the light source, a desktop for real-time video monitoring and image storage and a laptop for digital image programming analysis, as shown in Figure 6.2. The shooting position is focused on the upper fully developed region at the height of 5.33 m of the riser.

The camera allows frame rates up to 16000 frame per second (fps) and a maximum resolution of 1280×1024 pixels at 500 fps leading to a record time of 4s for the built in memory. Its equipped sensor, MI-MV13, contains special self-calibrating circuitry that enables it to reduce its own column-wise fixed-pattern noise. It also has an IR cut-off optical filter to block infrared light from entering in the optical path so as to avoid its interference on the actual image. A Pentax C21228TH 12.5mm F1.8 manual lens is chosen to capture images of solids flow in the riser. During the whole experimental time span, the camera with the lens and the section of videoed column are covered by a black box to avoid the disturbances from external lightings. The 500Watt quartz halogen bulb is selected as the light source because of its high luminance over the complete spectrum and
constant light emission during its lifetime (Ellenberger et al., 2000). Also, as an outstanding feature of halogen bulbs, their lumen maintenance, ranges from 96-101 % on constant voltage lamps at 99 % life (Zubler and Mosby, 1959), and the output luminous flux at the end of its lifetime could be 90% of its original. A diffusion panel is installed in front of the lamp to make the recorded area uniformly illuminated and eliminate undesirable shadows as well as intensity gradients. The panel also acts as an insulator to prevent overheating of the wall of the CFB riser from the radiation of the lamp. Through a standard Firewire (IEEE-1394) interface, the software from Redlake, Motionscope 2.0.3 allows the shooting video to be monitored real-time and image sequences captured by the camera to be transferred to a computer. Self-developed MATLAB programs enable the image process and frame-by-frame analysis.

A digital illuminance meter or lux meter (LX-1330B, Easy Life Product, Hong Kong) is used to measure the illuminance before, mid-way and after each experiment to make sure that every image is shot under the same luminance flux. From the video camera settings, it is known that for the resolution of the camera’s CMOS sensor, the higher the resolution, the lower the frame rate. Therefore, considering the frame size and the illuminance of backup light, the frame speed of 2000 fps with a resolution of 1280×256 pixels and 500 μs shutter time are chosen for the whole experiment. Output images are uncompressed full frames without any loss of original information, which guarantees the precision of later image processing. With these settings, valuable information, like variation of solids phase, shape and behavior of clusters, can be provided from the original recorded images. In order to guarantee the statistical significance of the observed results, at least 100 images are extracted from the video to obtain cluster information.

6.3 Results and discussion

6.3.1 Calibration between image grayscale and solids holdup

The information of an actual object conveyed by an image obtained through the high speed video camera in the present study is expressed in grayscale. Therefore, to quantitatively study solids phase structure from their images, it is necessary to conduct a
calibration experiment to correlate the grayscale of the digital image and the solids holdup of FCC particles inside the CFB riser.

Two sections of the original riser with a height of 2.03 m are temporarily converted to the calibration apparatus to “host” a liquid-solid particulate fluidized bed. A liquid-solid system is used because it can achieve stable and homogeneous fluidization with uniform solids holdup for the calibration experiment. Blank test with air or water only show that the influence reflected by the difference refractive index of the air and water is negligible in the present study so that it is reasonable to apply the calibration results obtained from the water-solid system in the air-solid system.

Figure 6.3 Calibration curve between solids holdup and grayscale

With 400.5 g FCC particles used as the bed materials, calibration tests are carried out by capturing images with changing solids holdup in the liquid-solids fluidized bed by gradually increasing the bed expansion. Then, the relationship between solids holdups and the corresponding grayscale is built to generate the calibration curve. Details of the calibration procedure are presented in Yang and Zhu (2013). The calibration curve between solids holdup ($\varepsilon_s$) and grayscales (G) is shown in Figure 6.3 and is also given by the following correlation with an adjusted R square of 0.9972:

![Exponential Fit: $y=28.0+228.3 \exp(-19.62x)$ $R^2=0.99722$](image)
\[ G = 28.0 + 228.3 \exp(-19.62 \varepsilon) \quad (6.1) \]

It is noticed that the above equation becomes less sensitive when \( \varepsilon \) is higher than 0.2, but the conditions encountered in this study is well below that. This calibration curve and equation will be used as the basis of image processing in the present and subsequent studies.

### 6.3.2 Variation of mean solids holdup with operating conditions

The image calibration method allows the solids holdup and image grayscale mutually transformable. Therefore, mean solids holdup at a given operating condition in the fully developed region can be obtained from the mean grayscale of the captured images. As mentioned earlier, at least 100 images were used under each operating condition to ensure statistical significance.

Figure 6.4 shows the mean solids holdup obtained by the image calibration method in the fully developed region in the riser. As shown in Figure 6.4 (a), when the superficial gas velocity (\( U_g \)) increases from 3.0 to 9.0 m/s, the mean solids holdup decreases under each circulation rate (\( G_s \)). However, when \( U_g \) is increased from 9.0 to 12.0 m/s, the mean solids holdups only decreases slightly or remain relatively constant. This can be explained by that when \( U_g \) is lower than 9.0 m/s, clusters are prone to break up by the increasing gas drag force with the increasing \( U_g \). Therefore, particles become more dispersed and particle velocities are increased, which leads to the decrease of the mean solids holdup. While under higher \( U_g \) (>9.0 m/s), with lower cluster fraction, the breakage effect of the gas becomes less obviously, which results in the relatively constant mean solids holdup.

Figure 6.4 (b) further shows the effect of \( G_s \) on the mean solids holdup, which is relatively small compared to the effect of \( U_g \). The mean solids holdup increases with the increase of \( G_s \) under certain \( U_g \). These results are consistent with the previous study (Xu and Zhu, 2010). The slight variation of the mean solids holdup at \( U_g = 3.0 \) m/s when the \( G_s \) is increased from 100 to 150 kg/m²s may be related to both the gas carrying capability
and the equilibrium state of the breakup and coalescence of the clusters under lower $U_g$ at the fully developed region.

**Figure 6.4** Mean solids holdup obtained by the image calibration method at the fully developed region in the riser.
6.3.3 Visualization of solids phase distribution

Figure 6.5 (a) and (b) show the original grayscale images under typical dense and dilute operating conditions. The denser phase (with lower grayscale) show darker color. By transforming the original image into Hue, Saturation and Value (HSV) image, different grayscales are expressed in different colors, as shown by the color bar in Figure 6.5 (c) and (d). As the image grayscale and the solids holdup has been correlated by Eq. (6.1), the solids phase with different solids holdup can be observed more easily in Figure 6.5 (c) and (d), which essentially show the solids holdup distribution over the riser section. As expected, relatively higher solids holdup areas or dense phases are exhibited more under lower \( U_g \) and higher \( G_s \) (\( U_g = 3.0 \text{ m/s}, G_s = 100 \text{ kg/m}^2\text{s} \)), while lower solids holdup areas or dilute phases are exhibited more under higher \( U_g \) and lower \( G_s \) (\( U_g = 9.0 \text{ m/s}, G_s = 50 \text{ kg/m}^2\text{s} \)).

Figure 6.5 Grayscale distributions under typical dense and dilute operating conditions
(a) Dense operating condition \((U_g=3.0 \text{ m/s}, G_s=100 \text{ kg/m}^2\text{s})\)

(b) Dilute operating condition \((U_g=9.0 \text{ m/s}, G_s=50 \text{ kg/m}^2\text{s})\)

Figure 6.6 Binary image variations with different solids holdup thresholds
One key characteristics of gas-solid fluidization is the two phase phenomenon; with the dilute phase having only a small fraction of solid particles and the dense phase having significantly solid particles. To quantitatively analyze the phase distribution, a grayscale image is best to be transformed into a binary image with a given threshold. The transformation can be accomplished by the following expression, relating the original grayscale image $I(x, y)$ to the transformed binary image $b(x, y)$ using a threshold of $T$ (Solomon and Breckon, 2011):

$$b(x, y) = \begin{cases} 1, & \text{if } I(x, y) > T \\ 0, & \text{otherwise} \end{cases}$$ (6.2)

When different solids holdups are chosen as the thresholds of separating the dense and dilute phases to process the images, the variation of dense phase under two typical dense and dilute operating conditions are shown in Figure 6.6, where the black and white colors represent the dense and dilute phases, respectively. With solids holdup thresholds increasing from 0.005 to 0.1, the area of dense phase is reduced. In addition, under a same threshold value, there are more solids phase with higher solids holdup under dense operating condition with lower $U_g$ and higher $G_s$ (Figure 6.6 (a)) than that under dilute operating condition with higher $U_g$ and lower $G_s$ (Figure 6.6 (b)).

To describe the change of the dense phase in Figure 6.6, a term “relative dense phase area” is introduced here. The area percentage is calculated by dividing the total number of black pixels with the total pixels number of the whole image. Figure 6.7 gives examples of the variation of the relative dense phase area with different thresholds under the two typical dense and dilute operating conditions. As the threshold is the phase holdup value that separates the dilute and dense phases, the increase of the threshold will decrease the fraction of the dense phase and therefore the relative dense phase area. These are clearly shown in Figure 6.7 for both conditions. The corresponding example images under certain thresholds are exhibited at the same time.

Figure 6.8 shows the variation of relative dense phase area with different solids holdup thresholds under many operating conditions in the present study.
(a) Dense operating condition \((U_g=3.0 \text{ m/s}, G_s=100 \text{ kg/m}^2\text{s})\)

(b) Dilute operating condition \((U_g=9.0 \text{ m/s}, G_s=50 \text{ kg/m}^2\text{s})\)

**Figure 6.7 Relative dense phase area vs. solids holdup thresholds**

When \(G_s\) is increased under a same \(U_g\), more particles are circulated and aggregated in the riser, which increases the dense phase fraction. This can be reflected by the increase
of the relative dense phase area with the increase of $G_s$, as shown in Figure 6.8 (a). On the other hand, when $U_g$ is increased under a same $G_s$, particles are inclined to be scattered with more particles carried upwards more quickly in the riser by the increasing gas carrying capacity, which makes the solids phase in the riser more dilute. Therefore, the dense phase fraction is decreased and the obtained relative dense phase area is decreased as well, as shown in Figure 6.8 (b). In addition, from the large changes of the profiles of relative dense phase area with the increase of $U_g$, it can be concluded that $U_g$ plays a more important role on the relative dense phase area, comparing to that of $G_s$.

(a) Variation with solids circulation rate
6.3.4 Solids phase separation

As shown in Figure 6.5, there are dilute and dense (or cluster) phases inside the CFB riser and there exists obvious difference in solids holdup between the two phases. Clusters existing in the dense form have significantly higher solids holdup than the surroundings, even though they may form and break quickly and continuously due to the gas-particle and particle-particle interactions (Manyele et al., 2002). To characterize the clusters in the gas-solids flow consisting of both dense and dilute phases, a suitable threshold solids holdup value needs to be identified to separate the two phases. If a critical solids holdup $\varepsilon_{sc}$ is chosen to demarcate the dilute and the cluster phase, there should be a sharp change in the change of relative dense phase area when a solids holdup threshold “passes through” the critical value, $\varepsilon_{sc}$, as seen in Figure 6.9, where the relative dense phase fraction is plotted against the solids holdup threshold.

Figure 6.8 Variation of relative dense phase area with solids holdup thresholds

(b) Variation with superficial gas velocity
Based on the analysis above, to locate the maximum change point for the variation profile of relative dense phase area with the different thresholds, the first derivative is applied to obtain the critical value in Figure 6.9. Now, the variation profile of relative dense phase area and its corresponding first derivative with solids holdup thresholds under the dense operating condition are plotted together in the Figure 6.9. As expected, a sharp change in the former profile leads to a minimum point in the first derivative at $\varepsilon_s = 0.04$. This is set as the critical solids holdup $\varepsilon_{sc}$ to separate dilute phase and the clusters.

### 6.3.5 Cluster distribution

With the set critical solids holdup at 0.04, the variation of cluster fraction under different operating conditions can be calculated based on the images obtained from the high speed video camera. This critical threshold solids holdup therefore essentially provides a separation phase holdup that demarcate the dilute and dense phases. As expected, the cluster fraction (the relative dense phase area percentage at $\varepsilon_s = 0.04$) increases with $G_s$ and decreases with $U_g$, as shown in Figure 6.10. This is consistent with the variation of mean solids holdup shown in Figure 6.4 (a) and also verifies the proposed explanation.
that when $U_g$ is lower than 9.0 m/s, clusters are prone to break up by the increasing gas drag force with the increasing $U_g$, which results in more dispersed particles with increased velocities. Therefore, the cluster fraction decreases. While under higher $U_g$ (> 9.0 m/s), with lower cluster fraction, the breakage effect of the gas becomes less obviously, which results in the relatively constant cluster fraction. It is also shown that the cluster fraction spans over a large range from 1 % to 59 % under the operating conditions of the current study.

![Figure 6.10 Variation of dense phase fraction with operating conditions](image)

Figure 6.10 Variation of dense phase fraction with operating conditions

To examine the cluster distribution in the lateral direction, the images captured by the high speed video camera were divided into three regions laterally: the core region, $r/R \in (0-0.58)$, the middle region, $r/R \in (0.58-0.82)$, and the wall region, $r/R \in (0.82-1)$, along the lateral direction, where $r/R$ is the dimensionless distance from the riser axis.

Figure 6.11 examines the change of the cluster fraction of the three regions along the lateral direction at the $G_s$ of 100 kg/ m²s under different $U_g$. While the cluster fraction show a trend of sharp decrease first, it becomes relative constant at higher $U_g$. It is clearly shown that the cluster fraction in the core region is significantly higher than those in the middle and the wall region under lower $U_g$. This is because clusters are more prone to
form in the wall region than that in the core and middle region, due to the low local gas velocity in the wall region and the non-slip condition at the wall. At a lower \(U_g\) (3 m/s) the cluster fraction reaches nearly 95 %, indicating the fraction of continuous particle sheet as reported by Bi et al. (1993). Even in the core region, the cluster fraction is as high as 40 % at \(U_g\) of 3 m/s, suggesting very significant particle aggregation, a characteristics of a higher density operation (Parssinen and Zhu, 2001).

With increasing \(U_g\), the cluster holdup decreases quickly in all three regions, and remains below 20 % beyond \(U_g = 8\) m/s. It is interesting to see a reverse trend at higher \(U_g\), with the higher cluster fraction in the core region than that in the other two regions. We believe this may not be a typical phenomenon, which may be caused by the persistence of certain flow pattern developed at or near the distributor under higher gas velocity, “protected” by the narrow fluidized bed (Zhu et al., 2012).

However, the values of cluster fraction depend inherently on the value of critical solids holdup which demarcate the two phases. Figure 6.12 shows the variation of the cluster fractions with different operating conditions using two different critical values.
As shown in the figure, the cluster fraction ranges from 11% to 59% when the critical solids holdup is selected as 0.04. When a value of 0.08 is selected, however, the cluster fraction ranges from 0.7% to 17%. In other words, the cluster fraction also depends on the definition of minimum solids holdup inside a cluster and as a matter of fact decrease with the solids holdup inside the clusters. More details on these matters will be the subject of a further study to be reported elsewhere (in Chapter 7). Figure 6.12 also plots the mean solids holdup inside the riser over the measured section, along with the cluster fractions. The cluster fraction, regardless of the demarcating critical solids holdup, is shown follow the same trend as the mean solids holdup.

### 6.4 Conclusions

The visualization of the solids phase separation in the CFB, by a high-speed video camera in combination with the image calibration method, is conducted in the fully developed region in a narrow rectangular CFB riser with a 19 mm×114 mm cross section and a 7.6 m height.

Using an image calibration method, the cross sectional solids holdup under different operating conditions can be calculated from the mean grayscale of the images. The results...
are consistent with the previous studies. The transformation from grayscale images into binary images using various solids holdup thresholds allows the solids holdup distribution to be clearly visualized along the lateral direction under different operating conditions in the fully developed region. At the same time, a term “relative dense phase area” is introduced to quantify the distribution of dilute and dense phases.

A critical solids holdup value of $\varepsilon_{sc} = 0.04$ is chosen to demarcate the dilute and cluster phases, by finding the minimum first derivative of the variation profile of relative dense phase area with solids holdup thresholds. It is found that cluster fraction is in the range from 1 % to 59 % under the operating conditions in the present research. With images divided into three regions along the lateral direction: the core, the middle and the wall regions, cluster fraction is higher at the wall region than that of the core and middle regions, indicating that clusters are prone to form in the wall region than the other two. In addition, it is found that the cluster fraction depends on the cluster critical solids holdup. With different value selected, the cluster fraction is different.

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**References**


Chapter 7

7 Cluster identification in a rectangular circulating fluidized bed using image processing

With close examination of the solids holdup distribution in the riser from the Hue, Saturation and Value (HSV) image, the dense (or cluster) phase is regarded as a “compound” of core clusters with the highest solids holdup and intermediate dispersed particles, which is in the processing of coalescence or breakup, with higher solids holdup than the dilute phase. Based on this analysis, a threshold selection method is introduced by maximizing the inter-class variance between the two classes representing the background and foreground. A systematic cluster identification process is presented by applying the threshold selection method first to obtain a critical solids holdup ($\varepsilon_{sc}$) discriminating the dense and dilute phases. Then the method is applied in the dense region under each operating conditions to select the cluster threshold solids holdup ($\varepsilon_{sct}$) so that core clusters can be identified under different operating conditions. Applying this process, the clusters with different shapes and sizes with a certain geometrical shape and a relatively clear boundary can be visualized clearly and identified accurately.

7.1 Introduction

The existence of clusters in the circulating fluidized beds (CFBs) has been widely accepted by many studies since the concept of “clusters” was introduced by early researchers (Yerushalmi and Squires, 1975; Grace and Tuot, 1979). Further arguments indicate that the presence of clusters is also responsible for high gas-solid slip velocity and the core-annulus flow development (Rhodes, et al., 1989; Horio and Kuroki, 1994; Bai et al., 1995). With the progressing of cluster studies, it is found that particle clustering causes the significant alteration to the gas drag exerted on the particles and thus making the experimental understanding and modelling of the gas-solids two phase flow extremely difficult. Besides, the clustering mechanisms under dense and dilute operating conditions, which related to the cluster structures, are still unclear. Therefore, more investigations are needed before further insights about the characteristics and hydrodynamics of clusters obtained.
Obtaining more quantitative knowledge about the nature of clusters is based on a clearly and accurately identification of clusters, which relates to the applied measurement techniques. Generally speaking, intrusive probes and visualization methods are two major measurement techniques that are used to study the characteristics and structure of clusters in gas-solid systems. From the reported studies so far, both intrusive probes and visualization methods can be used to identify the clusters. The intrusive probes are one-point measurement methods, which can provide information at various time scales but limited spatial variation. The visualization method, on the other hand, can practically provide information at any point within the measurement zone. The specialties of the two kinds of methods leads to their own criterion to identify the clusters.

For a number of reported experimental studies which identify clusters using the intrusive probes, cluster information are obtained from the local instantaneous probe signals (Soong et al., 1993; Tuzla et al., 1998; Sharma et al., 2000; Manyele et al., 2002; Xu and Zhu, 2011, 2012). Based on a suggested criterion, a cluster would be identified if the local instantaneous solids holdup is significantly greater than the mean solids holdup, i.e. $\bar{\varepsilon} + n\sigma$. One of the major discussion on cluster identification for the following studies is concentrated on how to select the value of $n$. Manyele et al. (2002) conducted a sensitivity analysis to determine the value and found it was in the range of 1.0-1.4. Xu and Zhu (2011) adopted the sensitivity analysis, and determined the value of to be 2.

Comparing to intrusive probes, a particular advantage of the image processing method is the exact geometrical determination of the measuring area which is needed for the calculation of velocities and sizes of clusters. However, there are less studies for cluster identification with visualization methods. Burkhardt and Bredebusch (1996) and Lackermeier et al. (2001) calculated a threshold to identify clusters from the histograms of gray values for each pixel of obtained images over time. Based on the comparable relationship between grayscale and solids holdup, they set the threshold to the gray value which leads to the same value of the cluster volume (or area) fraction as was obtained from corresponding fiber optical measurements. Xu and Zhu (2012) also applied image processing to characterize the cluster size and velocity. The threshold is set to the mean gray value of the whole image. Mondal et al. (2013) used the similar criterion as that of
Soong et al. (1995) to choose a threshold grayscale to convert the original image into binary image so that the clusters can be clearly separated from its surroundings. The grayscale value of the clusters $\delta$ is higher than the local average grayscale, i.e. $\delta = \bar{\delta} + k\sigma_\delta$, where $\sigma_\delta$ is the standard deviation of the local grayscale intensity. By visual inspection and the comparison to the original image, the $k$ value was chosen as 1.

While it is all agreed that the solids holdup of clusters is significantly greater than that of its surroundings, the criteria to separate cluster from its surroundings are still not clear and the selection of the threshold solids holdup are still more a trial and error than systematic. Therefore, the major object of current study is to provide a systematic method to identify the clusters by means of image processing, which provides an initial attempt and also a new path to quantitatively characterize clusters. Due to the lack of common understandings on the definition and classification of different particle group forms so far, the “clusters” used in this paper are a generalized conception and refer to all forms of core particle agglomeration which can exist relatively stable under a certain operating condition.

### 7.2 Experimental

#### 7.2.1 CFB apparatus

FCC particles of 67 $\mu$m (Sauter mean diameter) with particle density of 1877 kg/m$^3$ are used as bed material in a 7.6 m high narrow rectangular CFB riser with a cross section of 19 mm×114 mm, as shown in Figure 7.1. A 3.85 m high downcomer has a cross section of 38 mm×203 mm, above which a 1.85 m cylindrical column of 203 mm i.d. is installed and used as a storage vessel. Two flapper valves on the storage vessel are used for solids circulation rate measurement. Two cyclones, a bag house filter are also included in the CFB system. A flip valve at the bottom of the downcomer is used to control the solids flow rate. More details of the CFB system can be found in Yang and Zhu (2013). The solids circulation rate $G_s$ and superficial gas velocity $U_g$ are in the range of 50-150 kg/m$^2$s and 3.0-9.0 m/s respectively.
Figure 7.1 Schematic diagram of the rectangular circulating fluidized bed
7.2.2 Visualization system

Cluster images are obtained from the visualization system developed in the present study. The system consists of three major parts: light source, high speed video camera and image analyzing and processing unit (see Figure 7.2).

A 500Watt quartz halogen bulb (4-5/8’’ T-3 lamp, L-16, The Designers Edge, USA) with a lifetime of 1500 hours and the illuminance about 95000 lx is selected as the light source. The high speed video camera is the MotionScope M2 from Readlake, which allows frame rates of up to 16000 fps (frame per second) and a maximum resolution of 1280×1024 pixels at 500 fps leading to a record time of 4s for the built in memory. A Pentax C21228TH 12.5mm F1.8 manual lens is chosen to capture images of solids flow in the riser. During the whole experimental time span, the camera with the lens is covered by a black box to get rid of the restriction of external light and other disturbances. A desktop is used for real-time video monitoring and image storage and a laptop for digital image programming analysis. Self-developed MATLAB programs enable the original images to be transformed into binary images and to be processed further. Images are taken at a frame speed of 2000 frame per second (fps) with a shutter time of 500 μs. Output images are uncompressed full frames without any loss of original information.
which guarantees the precision of later image processing. The video recording area was focused on the upper fully developed region. At least 100 images are extracted from the video under each operating condition to ensure the statistical significance of the observed results. More details of the visualization system can be found in Yang and Zhu (2013).

7.3 Results and discussion

7.3.1 Solids holdup examination inside the CFB

According to the previous studies (Bi et al., 1993; Xu and Zhu, 2011), all kinds of clusters with different forms are in a dynamic equilibrium state of coalescence and breakup and particles travels between different kinds of clusters and between wall and center regions in the bed due to different forces and interactions. In this study, the solids holdup distribution in the riser are examined further to demonstrate the microscopic structure.

![Figure 7.3 Flow structure exhibition (U_g = 3.0 m/s, G_v = 100 kg/m^2s)](image)

Figure 7.3 Flow structure exhibition (U_g = 3.0 m/s, G_v = 100 kg/m^2s)
As shown in Figure 7.3(a), region 1 belongs to the dilute phase, while clusters 2, 3 and 4 with different sizes and shapes belong to the dense phase. By transforming the original image into Hue, Saturation and Value (HSV) image Figure 7.3(b), different grayscales (or solids holdup, due to the correlation between the grayscales and solids holdups developed in our previous works (Yang and Zhu, 2013)) are expressed in different colors (as shown by the color bar in Figure 7.3(b)). The dilute phase is expressed in red and purple colors, as shown in local enlarged Figure 7.3(c), while the dense phase including clusters 2, 3 and 4 are exhibited in light blue and green colors in the local enlarged Figure 7.3(d), (e) and (f). For the three kinds of clusters with size from small to very large and shape from sphere to stripe, they all consist of a core with color of green surrounded by dispersed particles with color of light blue. The difference of color shows that the core clusters have the highest solids holdup, while the intermediate dispersed particles have higher solids holdup than the dilute phase. Therefore, the dense (or cluster) phase where the cluster formed are considered as a “compound” of the stable (i.e. at the equilibrium state) existed core clusters with the highest solids holdup and intermediate dispersed particles, which are in the processing of coalescence or breakup, with higher solids holdup than the dilute phase.

7.3.2 Cluster threshold solids holdup

Based on the solids holdup examination above, a threshold is needed to identify the core clusters from its surroundings of dispersed particles. In the current study, a systematic cluster identification process is presented by adopting a threshold selection method from grayscale histograms (Otsu, 1979) to obtain the cluster threshold so as to identify the clusters from their surroundings. The method is based on a straightforward analysis which finds a threshold to minimize the within-class variance (intra-class variance) of the thresholded black and white pixels (i.e. the two classes). In other words, this method results in the least overlap between the two groups represented by the foreground and background pixels. It can be proved that minimizing the intra-class variance is the same as maximizing the inter-class variance. In the image processing, it can be expressed as:

\[
V = \omega_f \omega_b (\mu_f - \mu_b)^2
\]  

(7.1)
\[
\omega_f = \frac{N_f}{W} \\
\omega_b = \frac{N_b}{W}
\]

(7.2)  
(7.3)

where \(V\) is the inter-class variance; \(\omega_f\) is the pixel number percentage (or probability) of the foreground; \(\omega_b\) is the pixel number percentage (or probability) of the background; \(\mu_f\) is the mean grayscale of the foreground; \(\mu_b\) is the mean grayscale of the background; \(N_f\) is the total pixel number of the foreground; \(N_b\) is the total pixel number of the background; \(W\) is the total pixel number of an image.

As examined in Section 7.3.1, there are dense (cluster) phase including core clusters and intermediate dispersed particles, and dilute phase inside the riser. Therefore, to identify the clusters from their surroundings, the threshold selection method is applied first to obtain a critical solids holdup (\(\varepsilon_{sc}\)) discriminating the dense and dilute phases and then applied in the dense region under each operating conditions to select the cluster threshold solids holdup (\(\varepsilon_{sct}\)). As the grayscale has already been correlated to the solids holdup by the calibration equation (Yang and Zhu, 2013), the identification process can also be regarded as to apply the threshold selection method on those pixels with solids holdup higher than the critical solids holdup (\(\varepsilon_{sc}\)) which used to separate the dense and dilute phase under a certain operating condition. In this way, clusters with higher solids holdup can be identified from the dense background by the obtained \(\varepsilon_{sct}\) value. The process are reflected by the histogram in Figure 7.4 and 7.5.

Figure 7.4 shows the histogram of the grayscale under a certain operating condition, e.g. \(U_g = 3.0\) m/s; \(G_s = 100\) kg/m\(^2\)s. As shown in the figure, the gray value of 92 corresponding to the critical solids holdup (\(\varepsilon_{sc}\)) is at the trough between the two peak values 82 and 117; the gray value of 134 corresponding to the cluster threshold solids holdup (\(\varepsilon_{sct}\)) is at the trough between the two peak values 117 and 152. The gray value of 92 and 134 are thresholds obtained by maximizing the inter-class variance according to structure of dense phase mentioned in 7.3.1.
Figure 7.4 Histogram of grayscale

Figure 7.5 The critical solids holdup ($\varepsilon_{sc}$) and the cluster threshold solids holdup ($\varepsilon_{sct}$)
Figure 7.5 shows the histogram of the solids holdup under $U_g = 3.0 \text{ m/s}$ and $G_s = 100 \text{ kg/m}^2\text{s}$. The values of $\varepsilon_{sc}$ and $\varepsilon_{sct}$ are 0.039 and 0.065, respectively. It is shown that the two values are at the trough of the histogram. The value of $\varepsilon_{sct}$ is significantly higher than that of $\varepsilon_{sc}$, reflecting that the solids holdup inside the cluster is higher than the solids that of its dense surroundings.

Under the processing of the critical solids holdup ($\varepsilon_{sc}$) and the cluster threshold solids holdup ($\varepsilon_{sct}$), the change of the flow structure are exhibited in Figure 7.6. Figure 7.6(a) shows the original flow structure. As mentioned earlier, it consists of dense (cluster) phase including core clusters and intermediate dispersed particles, and dilute phase. Under the processing of the $\varepsilon_{sc}$, the dilute phase is discriminated and transformed into black color. In this way, the dense (cluster) phase including core clusters and the dispersed particles is shown more clearly (see Figure 7.6(b)). Clusters with different shapes and solids holdups can be identified by further processing with the cluster threshold solids holdup ($\varepsilon_{sct}$), as shown in Figure 7.6(c).

![Image exhibition of flow structure under $\varepsilon_{sc}$ and $\varepsilon_{sct}$](image)

**Figure 7.6 Image exhibition of flow structure under $\varepsilon_{sc}$ and $\varepsilon_{sct}$**

### 7.3.3 Visualization of core clusters using the cluster threshold solids holdup

Core clusters with different shapes and sizes can be identified by applying the threshold selection method to transform the original image into the binary image. The process is exhibited in Figure 7.7. With the critical solids holdup ($\varepsilon_{sc}$), the dilute phase in Figure 7.7(a) is successfully discriminated, as exhibited in the black color in the binary image of Figure 7.7(b). However, core clusters with higher solids holdup are still not clear in the dense phase especially at the wall region. With the cluster threshold solids holdup ($\varepsilon_{sct}$),
the core clusters with a certain geometrical shape and a relatively clear boundary can be
discriminated from its surroundings even at the wall region, as exhibited in Figure 7.7(c).

![Figure 7.7 Variation of cluster fraction with superficial gas velocity](image)

**Figure 7.7 Variation of cluster fraction with superficial gas velocity**

Figure 7.8 shows the obtained cluster threshold solids holdup under different operating
conditions in this study. The cluster threshold solids holdup \( (\varepsilon_{\text{sc}}) \) decreases with the
increase of superficial gas velocity \( (U_g) \) and increases with the increase of the solids
circulation rate \( (G_s) \). With self-developed MATLAB program, clusters are identified from
frame-by-frame analysis.

![Figure 7.8 Cluster threshold solids holdup under different operating conditions](image)

**Figure 7.8 Cluster threshold solids holdup under different operating conditions**

Based on the obtained cluster threshold solids holdup, clusters under different operating
conditions can be obtained by changing the original image into binary images. Examples
are exhibited in Figure 7.9. In contrast to original image shown in Figure 7.9(a), (d) and (g), the cluster can now be identified as a bright structure with a certain geometrical shape and a relatively clear boundary to the background (as shown in Figure 7.9(c), (f) and (i)) with the dense phase visualized in Figure 7.9(b), (c) and (h) at the same time. This is a remarkable result and can be regarded as a unique characteristic for the image processing method based on the high speed video system, because it makes the cluster selection more precisely and systematically, which ensures the accuracy of the following studies like cluster size and velocity determination.

![Image of clusters under different operating conditions](image)

**Figure 7.9 Examples of clusters under different operating conditions**

### 7.4 Conclusions

Based on the examination of the solids holdup distribution in the riser, the dense phase (or cluster) phase is regarded to include a stable existed core (or core cluster) with highest solids holdup and dispersed particles, which is in the processing of coalescence or breakup, with higher solids holdup than the dilute phase. A threshold selection method is introduced by maximizing the inter-class variance between the two classes representing the background and foreground. The threshold selection method is adopted first to
process the original grayscale image to obtain a critical solids holdup ($\varepsilon_{sc}$) discriminating the dense and dilute phases. Then it is applied in the dense region under each operating conditions to select the cluster threshold solids holdup ($\varepsilon_{sc_t}$) so that core clusters can be identified. Applying this process, the clusters with different shapes and sizes with a certain geometrical shape and a relatively clear boundary can be visualized clearly and identified more accurately.

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**Nomenclature**

- $k$: Parameter for determine cluster separation, -
- $n$: Number of standard deviation above the mean value, -
- $G_s$: Solids circulation rate, kg/m$^2$s
- $N_b$: Total pixel number of the background, -
- $N_f$: Total pixel number of the foreground, -
- $U_g$: Superficial gas velocity, m/s
- $V$: Inter-class variance, -
- $W$: Total pixel number of an image, -

**Greek Letters**

- $\delta$: Grayscale value of clusters, -
- $\bar{\delta}$: Local average grayscale, -
- $\varepsilon_{sl}$: Local instantaneous solids holdup, -
\( \varepsilon_{sc} \) Critical solids holdup, -

\( \bar{\varepsilon}_{sc} \) Mean solids holdup, -

\( \varepsilon_{sct} \) Cluster threshold solids holdup, -

\( \mu_b \) Mean grayscale of the background, -

\( \mu_f \) Mean grayscale of the foreground, -

\( \sigma \) Times of standard deviation above the mean value, -

\( \sigma \_l \) The standard deviation of the local grayscale, -

\( \omega_b \) Pixel number percentage (or probability) of the background, -

\( \omega_f \) Pixel number percentage (or probability) of the foreground, -

References


Chapter 8

8 Determination of cluster size and velocity by means of image processing in a rectangular circulating fluidized bed

With images obtained from a high speed video camera, cluster size and velocity are determined inside a 7.6 m narrow rectangular CFB riser by means of image processing at the fully developed region. The cluster fraction is calculated by dividing the total number of pixels belongs to the core cluster with the total number of pixels in the entire image. The variation of cluster fraction with operating conditions are also discussed. A cluster equivalent diameter (d_e) is determined by the area of the cluster in the binary image. At the same time, the solids holdup inside the clusters can also be determined by converting the grayscale of the cluster from the original image to the solids holdup. Moreover, cluster vertical velocity can be determined by the shift of clusters between sequential binary images. Typical dense (U_g = 3.0 m/s; G_s = 100 kg/m²s) and dilute (U_g = 9.0 m/s; G_s = 50 kg/m²s) operating conditions are selected to compare the variation of the cluster size and velocity.

8.1 Introduction

Cluster solids holdup, size and velocity are considered as the main parameters of characterizing the hydrodynamic microscopic flow structure. A large number of parabolic strands were observed in the core region with vertical velocity twice faster than the superficial gas velocity mostly and four times at most (Takeuchi and Hirama, 1991; Takeuchi et al., 1996; Takeuchi et al., 1998). Li et al. (1991) visualized that cluster shapes were in general irregular but appear strands-like in the core region and spherical near the wall. Cluster sizes were found highly variable. Rhodes et al. (1992) identified three flow forms: dilute, dense and swarm flow. The dense flow form was found least stable, agglomerating to produce swarm flow. Moreover, typical arch-shaped particle swarms with downward velocity in the range of 0.3-0.4 m/s were observed and size of vertical particle strands were often longer than 0.1m. Bi et al (1993) identified four possible particle aggregation forms with different shapes and sizes and illustrated their
evolution and transformation through observation through a two-dimensional circulating fluidized bed. With “internal” and “external” picturing systems, Kuroki and Horio (1994) found that the cluster shape changed frequently but its typical shape from the observation was a paraboloid heading downward and having a long skirt upward. In the dilute phase, particles from clusters were shed to the dilute phase continuously and were absorbed again by other clusters. The cluster sizes were rather uniform under a given operating condition but decreased with increased solid mass flux (Horio and Kuroki, 1994). The high-speed video observations from Matsuda et al (1996) indicated that most particle swarms in the central region of the CFB riser are descending ones with velocity in the range of 0-0.8 m/s and the packing density of particle swarms was as high as that of a fixed bed. Van den Moortel et al (1996; 1998) first used particle aggregates and void regions to characterize gas-solid flow structure and then reported that up-flowing particle clusters exhibited horseshoe shapes heading upward with thin downward tails, while the downward-moving cluster also exhibited a horseshoe shape but heading downwards with thin tails upward. The tails were formed by the motion of gas pockets on both sides. Shi et al (2008) captured visual images and the micro-structure of various clusters. According to the distance between particles and the shape and appearance position, clusters are classified into four categories. McMillan et al (2013) found that the frequency of seeing the clusters was more predominant in the core. Large clusters dominated the wall region while smaller ones were more prevalent in the core region.

Although many experimental studies including both intrusive (Brereton and Grace, 1993; Zhou et al., 1994; Li et al., 1995; Pandey et al., 2004; Xu and Zhu, 2010) and non-intrusive methods mentioned above have revealed that clusters varies in shapes, sizes and velocities, studies about the cluster characteristics are still far from enough. Based on three guidelines to identify the clusters, cluster characteristics including solids holdup in cluster, occurrence frequency, duration time and time fraction for cluster existence were obtained using a capacitance probe technique (Soong et al., 1993; 1995; Tuzla et al., 1998; Sharma et al., 2000). Manyele et al. (2002) reported their investigation of the aggregate properties in a high-flux and high-density riser using a fiber optic probe. The aggregate frequency, time fraction, existence time, average solids concentration and cluster vertical dimension were established using sensitivity analysis. They also revealed
the dependence of the aggregate properties on the operating conditions. Xu and Zhu (2011; 2012) also adopted the sensitivity analysis and studied the cluster characteristics including cluster time fraction, cluster mean existence time, cluster frequency and cluster size and velocity as well. Lackermeier et al. (2001) studied the particle aggregates properties by applying high-speed video technique in combination with the laser sheet technique. By adding the image sequences, cluster image is obtained with cluster size and velocity calculated.

Comparing to the intrusive techniques, visualization techniques were first utilized as a non-intrusive method only providing qualitative indications and mapping the overall flow structures. However, with the development and improvement of modern video cameras and application of imaging process and analysis methods, more and more quantitative information are provided by this kind of non-intrusive methods (Zou et al., 1994; Lim et al., 1996; Lackermeier et al., 2001; Cocco et al., 2010; Xu and Zhu, 2011; 2012). With clusters identified by a threshold selection method from grayscale histograms (Otsu, 1979) in the previous studies (Chapter 7), cluster solids holdup, size and velocity are determined by the image arithmetic and logical operations in combination with the developed calibration equation (Yang and Zhu, 2013) in this study. This provides a new path to quantitatively characterize clusters from the image processing point of view aiming to give some guidance in understanding the dominate effects and mechanisms which govern the cluster formation inside the CFB. Due to the lack of common understandings on the definition and classification of different particle group forms, the ‘clusters’ used in this paper are a generalized conception and refer to all forms of particle agglomeration which can exist relatively stable under a certain operating condition.

8.2 Experimental

8.2.1 CFB apparatus

The narrow rectangular CFB apparatus is shown in Figure 8.1. The height of riser is 7.6 m with a cross section of 19 mm×114 mm. Above a 3.85 m high downcomer of 38 mm×203 mm, a 1.85 m cylindrical column of 203 mm i.d. is used as a storage vessel.
Figure 8.1 Schematic diagram of the rectangular circulating fluidized bed
The CFB system also include two cyclones, a bag house filter, flapper valves on the storage vessel for solids circulation rate measurement and a gas distributor at the bottom of the riser. A flip valve at the bottom of the downcomer is used to control the solids flow rate. More details of the CFB system can be found in Yang and Zhu (2013). FCC particles of 67 $\mu$m (Sauter mean diameter) with particle density of 1877 kg/m$^3$ is used as the bed material. The solids circulation rate $G_s$ and superficial gas velocity $U_g$ are in the range of 50-150 kg/m$^2$s and 3.0-9.0 m/s, respectively.

### 8.2.2 Visualization system

The visualization system developed in the present study consists of three major parts: light source, high speed video camera and image analyzing and processing system (see Figure 8.2).

![Figure 8.2 Visualization system](image)

**Light source**

A 500Watt quartz halogen bulb (4-5/8” T-3 lamp, L-16, The Designers Edge, USA) with a lifetime of 1500 hours and the illuminance about 95000 lx is selected as the light source. The reason for the selection is that halogen bulb have higher luminance and
possess constant brightness for constant voltage (Ellenberger et al., 2000). Also, as an outstanding feature of halogen bulbs, their lumen maintenance, ranges from 96-101 % on constant voltage lamps at 99 % life (Zubler and Mosby, 1959), and the output luminous flux at the end of its lifetime could be 90 % of its original. A diffusion panel is applied to make the recorded area uniformly illuminated and eliminated undesirable shadows as well as intensity gradients. The panel also acts as an insulator to prevent overheating of the wall of the CFB riser from the radiation of the lamp.

**High speed video camera**

The high speed video camera is the MotionScope M2 from Readlake. The camera allows frame rates of up to 16000 fps (frame per second) and a maximum resolution of 1280×1024 pixels at 500 fps leading to a record time of 4s for the built in memory. Its equipped sensor, MI-MV13, contains special self-calibrating circuitry that enables it to reduce its own column-wise fixed-pattern noise. It also has an IR cut-off optical filter to block infrared light from entering in the optical path so as to avoid its interference on the actual image. A Pentax C21228TH 12.5mm F1.8 manual lens is chosen to capture images of solids flow in the riser. During the whole experimental time span, the camera with the lens is covered by a black box to get rid of the restriction of external light and other disturbances.

**Image analyzing and processing**

A desktop is used for real-time video monitoring and image storage and a laptop for digital image programming analysis. Through a standard Firewire (IEEE-1394) interface, the software from Redlake, Motionscope 2.0.3 allows the video shooting to be monitored in real-time and image sequences captured by the camera can be transferred to the desktop and stored as well. Self-developed MATLAB programs enable the original images to be transformed into binary images so as to obtain the cluster equivalent diameter. The image arithmetic and logical operations enable the solids holdup inside the cluster and cluster velocity to be determined.
8.2.3 Visualization operating conditions

A digital illuminance meter or lux meter (LX-1330B, Easy Life Product, Hong Kong) is used to measure the illuminance before each experiment to make sure every image shot under the same luminance flux. From the video camera set, it is known that for the resolution of the camera’s CMOS sensor, the higher the resolution, the lower the frame rate. Therefore, considering the frame size, speed and the illuminance of backup light, the frame speed of 2000 fps with a resolution of 1280×256 pixels and 500 μs shutter time are chosen during the whole experiment. Output images are uncompressed full frames without any loss of original information, which guarantees the accuracy of later image processing. With these settings, the valuable information, like flow patterns, shape and behavior of clusters, can be provided without any intrusion from the original recorded images. The video recording area focuses on the upper fully developed region, the height of which is 5.33 m. At least 100 images are extracted from the video under each operating condition to ensure the statistical significance of the observed results.

8.3 Results and Discussion

8.3.1 Cluster fraction under different operating conditions

With clusters identified by the cluster threshold solids holdup, the variation of the cluster fractions with superficial gas velocity \( U_g \) under a certain solids circulation rate (100 kg/m²s) is shown in Figure 8.3. It is shown that the variation of cluster fraction decreases with the increasing of the \( U_g \). This indicates that the higher \( U_g \) increase the breakage of the cluster, which leads to the decrease of the mean solids holdup \( \bar{\varepsilon}_s \) and the corresponding cluster threshold solids holdup \( \varepsilon_{sc} \).

The variation of the cluster fraction with the solids circulation rate \( G_s \) is shown in Figure 8.4. The cluster fraction increases with the increasing of \( G_s \), meaning the higher solids flux is beneficial for the cluster formation, which in turn leads to higher \( \bar{\varepsilon}_s \) and \( \varepsilon_{sc} \). In addition, both Figure 8.3 and 8.4 show that the cluster threshold solids holdup \( \varepsilon_{sc} \) is much higher than the mean solids holdup \( \bar{\varepsilon}_s \), which consists with the common agreement.
Figure 8.3 Variation of cluster fraction with superficial gas velocity

Figure 8.4 Variation of cluster fraction with solids circulation rate
8.3.2 Determination of cluster size

Previous researchers reported that the clusters have irregular shapes and highly variable sizes (Li et al., 1991; Horio and Kuroki, 1994). The observations in the present study verifies this fact. Therefore, the equivalent diameter ($d_e$) is introduced to characterize the cluster sizes. The determination of cluster equivalent diameter is demonstrated in Figure 8.5. The original image was transformed into the binary image by the $\varepsilon_{\text{sect}}$ with cluster exhibited in the white color (Figure 8.5 (b)). The area of the cluster can be calculated by the number of pixels occupied by the cluster image. The cluster equivalent diameter can be determined by the cluster image area with the pre-calibrated scale of pixel ($s = 1.905 \times 10^{-4}$ m/pixel in the current study), as shown in Eq. (8.1).

$$d_e = 2s \sqrt{\frac{N}{\pi}} \quad (8.1)$$

where $N$ is the pixel number occupied by the cluster image.

Figure 8.5 Demonstration of cluster size determination based on image processing

In addition, the solids holdup inside the clusters can be obtained by the image arithmetic operation in combination with the calibration equation of correlating the grayscale and the solids holdup (Yang and Zhu, 2013). That is, the original image Figure 8.5(a) is dot-multiplied by the binary image (b), which generates image (c). Then, the average grayscale of image (c), i.e. the cluster average grayscale can be obtained by the
MATLAB program, which further transferred into the cluster solids holdup by the calibration equation.

To ensure the accuracy, the cluster size and solids holdup are average values of an image sequence, as shown in Figure 8.5(d)-(f). It is worthwhile to mention that the cluster solids holdup variation in a certain image sequence is found less than ± 0.5%, which can be considered as constant. Moreover, as it is proved that the variation of the cluster equivalent diameter is less than 5% in the image sequences, the change of the cluster form is negligible during its moving up through the observation area.

The relationship between the solids holdup inside the cluster and the equivalent size under the typical dense \((U_\text{g}= 3.0 \text{ m/s}; G_s=100 \text{ kg/m}^2\text{s})\) and dilute \((U_\text{g}= 9.0 \text{ m/s}; G_s=50 \text{ kg/m}^2\text{s})\) operating conditions are shown in Figure 8.6. There is a clearly solids holdup difference between clusters formed under the two operating conditions. Clusters formed under the dense operating condition have higher solids holdup with an average value \((\bar{\epsilon}_c)\) of 0.072 and larger population in small sizes with an average value \((\bar{d}_c)\) of 13.6 mm. On the other hand, clusters formed under the dilute operating condition have lower solids holdup with an average value \((\bar{\epsilon}_c)\) 0.033 and larger population in larger sizes with an

\[
\begin{array}{cc}
U_\text{g}(\text{m/s}) / G_\text{s}(\text{kg/m}^2\text{s}) & \\
3.0 / 100 & \bar{\epsilon}_c = 0.072 \\
9.0 / 50 & \bar{\epsilon}_c = 0.033 \\
\end{array}
\]

Figure 8.6 Cluster equivalent sizes under the two different operating conditions

The relationship between the solids holdup inside the cluster and the equivalent size under the typical dense \((U_\text{g}= 3.0 \text{ m/s}; G_s=100 \text{ kg/m}^2\text{s})\) and dilute \((U_\text{g}= 9.0 \text{ m/s}; G_s=50 \text{ kg/m}^2\text{s})\) operating conditions are shown in Figure 8.6. There is a clearly solids holdup difference between clusters formed under the two operating conditions. Clusters formed under the dense operating condition have higher solids holdup with an average value \((\bar{\epsilon}_c)\) of 0.072 and larger population in small sizes with an average value \((\bar{d}_c)\) of 6.5 mm. On the other hand, clusters formed under the dilute operating condition have lower solids holdup with an average value \((\bar{\epsilon}_c)\) 0.033 and larger population in larger sizes with an
average value ($\bar{d}_c$) of 13.6 mm. Under the dense operating condition, the higher solids population results in the higher solids holdup, which makes the drag force from the gas reduce and the inter-particle forces increase. Therefore, it is easier for clusters with higher solids holdup and smaller size existing stably. However, under the dilute condition, the larger clusters are mainly formed at the lower part of the bed. During their traveling to the upper part, although they break and release some particles, they can also draw the particles in the vicinity according to the wake theory (Fujima et al., 1991; Bi et al., 1993; Horio and Kuroki, 1994). In this way, they can maintain their larger sizes at the video recording area in the fully developed region.

### 8.3.3 Determination of cluster vertical velocity

The cluster velocity is determined between the two dynamic images in an image sequence. The procedure is described in Figure 8.7. Two original cluster images with a certain time interval (e.g. 500 µs) are transformed into the binary images (from Figure 8.7(a) to (c) and (b) to (d) respectively). Then the logical operation “XOR” is performed between the two binary images, which detects the movement of clusters between the two frames, as shown in Figure 8.7(e). At the same time, the centroids of the cluster at the two positions can be obtained by self-developed MATLAB program. As the change of the cluster form is negligible and there is no relative movement between the fixed video camera and the video targets i.e. clusters, also, the cluster solids holdup in a certain image sequence is constant, the centroid can be used to characterize the cluster position effectively. From the obtained centroid in an image sequence, it is found that the horizontal movement of the cluster is only 1-2 pixels during the chosen time span (2000 µs), which causes about the difference of $\pm$ 0.2 m/s in the horizontal velocity, as shown in Figure 8.7(e) with the two coordinates of the cluster (266.05, 172.93) and (265.05, 122.50). Therefore, based on the precision consideration, only the velocity in the vertical direction is used to characterize the cluster vertical movement speed in the current study.
The relationship between cluster vertical velocity and the cluster solids holdup under the typical dense ($U_g = 3.0 \text{ m/s}; G_s = 100 \text{ kg/m}^2\text{s}$) and dilute ($U_g = 9.0 \text{ m/s}; G_s = 50 \text{ kg/m}^2\text{s}$) operating conditions are shown in Figure 8.8. As shown in the figure, although the cluster solids holdup between the two conditions are clearly different, the difference between the cluster vertical velocities ($V_c$) is less. Under the dense operating condition, the average cluster vertical velocity ($\bar{V}_c$) is 3.0 m/s comparing to that of 2.5 m/s under the dilute operating condition. Figure 8.9 shows the relationship between $V_c$ and $d_c$, it seems that the cluster vertical velocity decreases with the increasing cluster equivalent diameter under the both operating conditions. When the $V_c$ is normalized by the superficial gas velocity ($U_g$), as shown in Figure 8.10, the relative velocity ($V_c/U_g$) decreases obviously with the cluster equivalent diameter ($d_c$) under the two typical operating conditions. In addition, the relative velocity is observed below 1 under the dilute operating condition.
Figure 8.8 Cluster vertical velocity under the two different operating conditions

Figure 8.9 Relationship between the cluster vertical velocity and the clusters equivalent diameter
8.4 Conclusions

With the obtained $\varepsilon_{\text{sc}}$ values, the cluster fraction can be calculated by dividing the total number of pixels belongs to the core cluster with the total pixels number of the entire image. The results show that the cluster fraction increases with the increasing $G_s$ and decreases with the increasing $U_g$.

By transforming the original image into the binary image with $\varepsilon_{\text{sc}}$ value, the cluster equivalent diameter ($d_c$) can be determined by the area of the cluster. At the same time, with the image arithmetic operation between the original and the binary images, the grayscale of core cluster can be obtained and therefore the solids holdup inside the cluster can be determined by the correlation equation obtained in our previous works. Moreover, by transforming two dynamic cluster images in an image sequence into the binary images, the centroids of the two dynamic cluster image can be obtained. With the time interval between the two dynamic images already known, the cluster vertical velocity can be calculated. It is found that clusters with higher solids holdup and smaller size are prone to form at the dense operating condition ($U_g = 3.0$ m/s; $G_s = 100$ kg/m$^2$s), while cluster with lower solids holdup and relative larger size are incline to form at the dilute
operating condition \((U_g = 9.0 \text{ m/s}; G_s = 50 \text{ kg/m}^2\text{s})\). The average solids holdup inside the clusters, the average equivalent cluster size and the average cluster vertical velocity are 0.072, 6.5 mm and 3.0 m/s under the dense operating condition, while the corresponding values are 0.033, 13.6 mm and 2.5 m/s for that of dilute operating condition.

**Acknowledgements**

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**Nomenclature**

- \(d_c\) The cluster equivalent diameter, mm
- \(\bar{d}_c\) Average cluster equivalent diameter, mm
- \(N\) Pixel number occupied by the cluster in the image, -
- \(s\) Scale constant \((1.905 \times 10^{-4})\), m/pixel
- \(G_s\) Solids circulation rate, kg/m\(^2\)s
- \(U_g\) Superficial gas velocity, m/s
- \(V_c\) Cluster vertical velocity, m/s
- \(\bar{V}_c\) Average cluster vertical velocity, m/s

**Greek Letters**

- \(\delta\) Grayscale value of clusters, -
- \(\bar{\delta}\) Local average grayscale, -
- \(\bar{\varepsilon}_s\) Cross-sectional solids holdup in the bed, -
- \(\varepsilon_{sct}\) Cluster threshold solids holdup, -
References


Chapter 9

9 Conclusions and Recommendations

As a newly developed method, the calibration method in this study provides a new path to study the micro-flow structure. Based on the obtained results so far, conclusions for the present study and recommendations for the further work are addressed as following:

9.1 Conclusions

By means of a high speed video camera, the systematic image calibration method, is successfully developed, based on a well-designed calibration experiment correlating the solids holdup of FCC particles and the grayscale of the images so as to quantify the cluster phenomenon in a transparent rectangular CFB riser. To ensure the consistent light illumination of the light source and thus the consistent measurement of the high speed camera, a 3 mm thick transparent plastic plate glued with FCC particles is used as a reference plate.

Using the image calibration method, the one-to-one correspondence between the solids holdup values inside the fluidized bed with FCC particles and their representative image grayscale values, is built for the first time. Based on this correlation, the dense and dilute phases inside the CFB riser are successfully separated by processing the images through choosing proper solids holdup thresholds to obtain cluster size and holdup. With increasing thresholds, cluster size clearly decreases while cluster solids holdup increases. By increasing the threshold, clusters can be “peeled off” into different “layers” to reveal solids holdup distribution inside the clusters: the solid holdup increases from lower values at the cluster surface to higher values in the core. The variations of cluster population, as well as their size and holdup measured using this image calibration method compare well with the well-known fact reported by many previous studies. Such consistency shows that this image calibration method can be widely used in multiphase system flow.
The radial distribution profiles of the solids holdup obtained by the image calibration method exhibit similar trends with that of previous researchers, which reflects the feasibility of the newly developed method. The direct comparison of solids holdup data obtained from the image calibration method with the optical fiber probe under identical operating conditions shows excellent agreement, which clearly verifies the accuracy of the image calibration method. Further comparison between the image calibration method results from the current study with the measurement results of the optical fiber probe from other researchers also shows an excellent agreement under the same operating conditions. These comparisons verify that the image calibration method is a good alternative method in measuring the solids holdup in the rectangular riser.

Using the image calibration method, the cross sectional solids holdup under different operating conditions can be calculated from the mean grayscale of the images. The results are consistent with the previous studies. The transformation from grayscale images into binary images using various solids holdup thresholds allows the solids holdup distribution to be clearly visualized along the lateral direction under different operating conditions in the fully developed region. To quantify the distribution of dilute and dense phases, a term “relative dense phase area” is introduced. A critical solids holdup value of $\varepsilon_{sc} = 0.04$ is chosen to demarcate the dilute and cluster phases, by finding the minimum first derivative of the variation profile of relative dense phase area with solids holdup thresholds. It is found that cluster fraction is in the range from 1% to 59% under the operating conditions in the present research. With images divided into three regions along the lateral direction: the core, the middle and the wall regions, cluster fraction is higher at the wall region than that of the core and middle regions, indicating that clusters are prone to form in the wall region than the other two. In addition, it is found that the cluster fraction depends on the cluster critical solids holdup. With different value selected, the cluster fraction is different.

With close examination of the solids holdup distribution in the Hue, Saturation, Value (HSV) image, the dense phase (or cluster) phase is regarded to include a stable existed core and dispersed particles in the processing of coalescence or breakup. A threshold selection method is adopted to identify the clusters by maximizing the inter-class
variance between the foreground and background pixels. With the selection method, a systematic cluster identification process is proposed to obtain the cluster threshold solids holdup ($\varepsilon_{sc}$) so that the clusters can be identified under different operating conditions. With the obtained $\varepsilon_{sc}$ values, the cluster fraction can be calculated by dividing the total number of pixels belongs to the cluster with the total pixels number of the entire image. It shows that the cluster fraction increases with the increasing $G_s$ and decreases with the increasing $U_g$.

By transforming the original image into the binary image with $\varepsilon_{sc}$ value, the cluster equivalent diameter ($d_e$) can be determined by the area of the cluster. At the same time, with the image arithmetic operation between the original and the binary images, the grayscale of core cluster can be obtained and therefore the solids holdup inside the cluster can be determined by the correlation equation obtained Yang and Zhu, (2013). Moreover, by transforming two dynamic cluster images in an image sequence into the binary images, the centroids of the two dynamic cluster image can be obtained. With the time interval between the two dynamic images already known, the cluster vertical velocity can be calculated. It is found that clusters with higher solids holdup and smaller size are formed at the dense operating condition ($U_g = 3.0$ m/s; $G_s = 100$ kg/m$^2$s), while cluster with lower solids holdup and relative larger size are formed at the dilute operating condition ($U_g = 9.0$ m/s; $G_s = 50$ kg/m$^2$s). The average solids holdup inside the clusters, the equivalent cluster size and the cluster vertical velocity are 0.072, 6.5 mm and 3.0 m/s under the dense operating condition, while the corresponding values are 0.033, 13.6 mm and 2.5 m/s for that of dilute operating condition.

### 9.2 Recommendations

The present dissertation provides a new path to quantitatively study the microscopic flow structures in a rectangular CFB riser. The relationship between the solids holdup of the FCC particles and the grayscale of the images is correlated for the first time. Therefore, there are more rooms for this method to be applied.
Cluster size and velocity are only determined under two typical operating conditions. More operating conditions are needed to study the variation of cluster size and velocity so as to classify the clusters under wider operating range.

The circulating capacity for current study is less than 200 kg/m²s. Higher circulation rate could be the subject for the future study.

The current study focuses on the fully developed region of the riser, where the particle dispersion and aggregation are relatively stable. Future work can be extended to the entire riser to elucidate flow development and original formation of clusters.

With the well-designed calibration experiment apparatus, other kind of particles can be calculated to study their microscopic flow structures. For example, particles in classification of Geldart B groups can be used.

As the image calibration method is used in the circulating fluidized bed in the present study, the bubbling bed and turbulent bed could be choices to be applied with this novel method.

This study is mainly experimental work. With more cluster information provided by the image calibration method, the data of clusters can be used for empirical and mathematical modelling purpose in different areas.
Appendices

Appendix A1 Results analysis for the calibration experiment between the solids holdup and the grayscale

The calibration apparatus to obtain the calibration equation, Eq. (A1.1) which correlates the exponential relationship between the solids holdup and the corresponding grayscale of FCC particles effectively (with an adjusted R square of 0.9972) is well-designed.

\[ G = 28.0 + 228.3 \exp(-19.62 \varepsilon_s) \]  \hspace{1cm} (A1.1)

It is noticed that the above equation becomes less sensitive when \( \varepsilon_s \) is higher than 0.2, but the conditions encountered in this study is well below that.

As shown in Figure A1.1, to ensure the calibration experiment sharing the same illumination system with the actual experiments, the calibration apparatus is converted from the original CFB riser. As the whole system is liquid-solid system, to ensure the accuracy of solids holdup (\( \varepsilon_s \)) and grayscale (\( G \)) measurements, it is suggested that the \( \varepsilon_s \) value should be obtained from the measured water level difference between the two glass tubes (i.e. pressure difference) instead of calculation from the bed height due to the following problems intrinsically linked to the bed height calculation method. The reasons are listed in the following:

Firstly, the bed height calculation relies on the clear discrimination of the bed height by the visual measurement, which makes the mass of the bed material become a key influence factor. As shown in the local enlarged figure in Figure A1.1, there is a distance of 9.2 cm from the distributor to the lower boundary of the shooting area, therefore, when there is less fluidized particles (e.g. \( M = 75.2 \) g), with a static bed height (see level A) lower than the lower boundary of the shooting area, the grayscale corresponding to the higher solids holdups cannot be obtained because the image of the dense phase cannot be obtained, while the solids holdups for the dilute phase can be calculated relatively accurate; When the mass of fluidized particles is increased (e.g. \( M = 114.3 \) g), the static bed height (see level B) is in the range of the shooting area, relatively high solids holdups...
and the corresponding grayscale can be calculated accurately, while lower solids holdup values cannot be obtained due to the obscured boundary in the dilute phase; When there is more fluidized particles (e.g. \( M = 400.5 \) g), the static bed height see level C) is higher than the upper boundary of the shooting area, higher solids holdups and the corresponding grayscale in the dense phase can be calculated accurately, while lower solids holdup values under very dilute conditions cannot be obtained due to the obscured boundary. The relationships between grayscale and solids holdup for three different masses of fluidized FCC particles are shown in Figure A1.2. It is obvious that the three curves corresponding to different masses are different from each other.

Secondly, using bed height to calculate solids holdup assumes a stable and homogenous distribution of the bed materials. However, when the bed is expanded very high, the solids holdup gradient along the axial direction of the riser becomes more obviously. Thus, error can be introduced more or less when to equal the solids holdup value calculated from the whole bed height to the value at the shooting area.

Lastly, with the increase in the water flux, the boundary between the particles and water becomes more and more unstable and obscured. Therefore, it is harder and harder to identify the bed height. The unreadable bed height is another source of errors.

Comparing to the bed height calculating method, the pressure measurement from the water level difference through two glass tubes between the two pressure ports covering the range of the shooting area has more accuracy. With enough fluidized material (i.e. \( M = 400.5 \) g), the solids holdups ranging from the dilute to dense conditions can be obtained. As shown in Figure A1.2, focusing on the curve from pressure measurement, it has good agreement with the that of the smaller mass (75.2 g) at the dilute phase (i.e. lower solids holdup) and that of bigger mass (114.3 g and 400.5 g) at the dense phase (i.e. higher solids holdup) respectively. This verifies the error analysis above and shows better accuracy of the pressure measurement method and reliability of the obtained calibration curve at the same time.
Figure A1.1 Calibration apparatus and local enlarged demonstration for results analysis
Figure A1.2 Results comparison between the pressure measurement and the bed height reading methods

Appendix A2 An example of error bars for the grayscales of the reference plate in the testification of light illuminance consistency

To ensure the accuracy of grayscale and the solids holdup measurement by the newly developed image calibration method, preliminary measurements and analyses of standard error were taken for measurement over one week period under the illumination of the bulb that was used during the whole experiment. Ten measurements were taken for each day measurements. Figure A2.1 shows the error bar of the grayscale measurements with corresponding error bar of solids holdup measurements shown in Figure A2.2.

The results confirm the consistency of the accurate measurements.
Figure A2.1 Error bars for grayscale measurement

Figure A2.2 Error bars for solids holdup measurement
Appendix B1 Raw data of radial distribution of solids holdup based on the image calibration method under different operating conditions

For H=5.33 m:

<table>
<thead>
<tr>
<th>Radial position (r/R)</th>
<th>Operating conditions U_g (m/s) / G_s (kg/m²s)</th>
<th>3.0 / 50</th>
<th>3.0 / 100</th>
<th>3.0 / 150</th>
<th>5.0 / 50</th>
<th>5.0 / 100</th>
</tr>
</thead>
<tbody>
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<th>7.0 / 100</th>
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### Operating conditions $U_g$ (m/s) / $G_s$ (kg/m$^2$s)

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### Operating conditions $U_g$ (m/s) / $G_s$ (kg/m$^2$s)

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Appendix B2 Raw data of mean solids holdup obtained by the image calibration method under different operating conditions

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Appendix B3 Raw data of relative dense phase area with different solid holdup thresholds under different operating conditions

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Appendix B4 Raw data of cluster thresh solid holdup under different operating conditions

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Appendix C1 MATLAB program used to obtain cluster holdup, size, velocity

```matlab
clear all, close all
clc

files=dir('*.bmp');
m=numel(files);

for i=1:m
    I=imread(files(i).name);
    B=rgb2gray(I);
    im_thresh = [171.6734694];
    A=B<im_thresh;
    figure,imshow(A);
    h = imrect;
    position = wait(h);
    BW = createMask(h);
```
n=size(im_thresh,2);
area_vector=zeros(1,n);
centroid_vector = zeros(n,2);
gray_avg_vector = zeros(1,n);
holdup_avg_vector = zeros(1,n);

for j = 1:n

[gray_avg,holdup_avg,area,centroid]=obtainarea_centroid_gray_holdup(m,B,im_thresh(1,j),BW);
if(isempty(centroid))
    break
else
    area_vector(1,j)=area;
    centroid_vector (j,:)=centroid;
    gray_avg_vector(1,j)=gray_avg;
    holdup_avg_vector(1,j)=holdup_avg;
end

end
cluster_diameter=sqrt(area_vector./3.14).*(1.905*10^-4).*2;
k={area_vector,cluster_diameter,gray_avg_vector,holdup_avg_vector,centroid_vector(:,1),centroid_vector(:,2)};

strRange1=[‘A’ num2str(i+1) ‘:A’ num2str(i+1)];
strRange2=[‘B’ num2str(i+1) ‘:G’ num2str(i+1)];
len=length(files(i).name);
xlswrite(‘Cluster_size_holdup_velocity1.xls’,str2double(files(i).name(1:len-4)),’Sheet1’,strRange1);
xlswrite(‘Cluster_size_holdup_velocity1.xls’,k,’Sheet1’,strRange2);
end

function [gray_avg,holdup_avg,area,centroid]=obtainarea_centroid_gray_holdup(m,B,thresh,BW)
figure(m+1),subplot(131),imshow(B);
title(’Input image’);
bgw1=B<thresh;
bgw1=bgw1&BW;
cc = bwconncomp(bwI);
s = regionprops(cc,'Area', 'centroid');
[maxarea idx]=max([s.Area]);
bwI = ismember(labelmatrix(cc), idx);
figure(m+1),subplot(132),imshow(bwI);
title('Processed image');
area = sum(bwI(:));
centroids = cat(1, s.Centroid);
centroid=centroids(idx,:);
I0=B.*(uint8(bwI));
figure(m+1),subplot(133),imshow(I0);
title('Combined gray image');
gray_sum=(sum(sum(I0)));
gray_avg=gray_sum/area;
holdup_avg = (-1/19.61703)*log((gray_avg-27.98413)/228.25898));
# Curriculum Vitae

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**Post-secondary Education and Degrees:**  
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