Chapter 5

Imaging Of 2-Dimensional Fluidized Beds with Optical Fiber Probes

5.1 Introduction

In Gas-Solid fluidized-beds bubble formation begins randomly near the distributor when the minimum bubbling velocity is attained. During their ascent, the bubbles tend to grow in size due to a variety of reasons, such as gas through flow, expansion because of favorable pressure differential and coalescence with other bubbles. Hence, an array of bubbles of different size and shapes are found rising randomly in the bed instead of bubbles of a specified size at any particular location within the bed. Thus bubble growth in a freely bubbling bed is a stochastic phenomenon. The true bubble size distribution is almost never known or at the best rarely known. In this work an attempt is made to determine bubble size distribution, probable bubble shape and bubble frequency across any plane of a Gas-solid fluidized bed using optical fiber based imaging techniques. It is expected that this investigation would result in a more precise knowledge and understanding of the hydrodynamic feature of freely bubbling beds, which would eventually lead to the development of better design of combustors and industrial reactors.

In his seminal work Werther (1973), developed the methodology of processing the signals obtained from miniature capacitance probes inserted in bubbling Gas-solid fluidized beds, considering uniform rise velocity of bubbles. His work relates the distribution of measured chord lengths to the size distribution of bubbles and provides techniques for transforming the chord length distribution into the bubble diameter distribution.

Clark et al. (1988) measured bubble chord length distribution using a stem static probe (static pressure probe) and also developed an algorithm to obtain distribution of chord lengths from information of bubble shape and bubble size distribution. They called this algorithm ‘forward transformation’. Further these investigators also developed ‘backward transformation’ algorithm for generating bubble size distribution from given distribution of chord lengths. Due consideration was given to the fact that the probes need not necessarily
intersect the bubble at its largest vertical dimension and therefore could measure chord lengths relatively smaller than the largest vertical bubble dimension. These investigators also considered uniform bubble rise velocity.

However, in a subsequent work Turton and Clark (1989) obtained bubble size distribution using backward transformation technique, by considering varying bubble rise velocities and from a knowledge of bubble shape and the interrelationship between the bubble size and rise velocity. This technique was however susceptible to instability when too many intervals in discrete bubble sizes are used. Later Clark et al. (1996) solved the problem of instability associated with backward numerical transformation by introducing the direct transformation of the probe time signals into the bubble-size distribution by means of nonparametric estimation technique known as the Parzen’s window (Parzen, 1962).

Lim et al. (1990) combined digital image analysis technique with geometrical probability to convert distribution of chord lengths to that of bubble size distribution. Mainland et al. (1995) developed an optical probe suitable for high temperature operation and proposed a method to determine the bubble properties such as bubble frequency, local bubble residence time, bubble velocity, chord length, characteristic bubble size and visible bubble flow. Using the Parzen window as an estimator of the probability density functions, Santana et al. (2000) proposed a method for transforming chord length distribution to local bubble-size distribution knowing the direction of velocity. Recently Sobrino et al. (2009) using optical probes obtained bubble size distributions based on maximum entropy principle.

In literature the use of non intrusive probing of bubbles is restricted to photographic, cine graphic, X-ray and Gamma ray techniques. Optical probing techniques are usually intrusive and in spite of being versatile, they too suffer from the same deficiencies that are found in all other intrusive probing techniques, wherein the presence of the probe itself alters the hydrodynamic pattern in the system. The net output thus remains at best tentative in nature. Non intrusive optical probes are difficult to function with beds of circular cross section because the curvature of the bed would interfere with the measurements. However, such interference is not expected in rectangular two dimensional Gas-solid fluidized beds. Therefore, it is possible to use non intrusive optical probing of bubbling phenomena in 2-D
fluidized beds and obtain bubble size distribution using the techniques available in literature for signal processing.

In this work, an assembly of non-intrusive type optical fiber probes was fabricated using laser as a light source to fetch information of bubble chord lengths in terms of time signals. Techniques were also developed for processing (translating) the signals obtained from the probes and thereby determining the hydrodynamic properties, bubble size distribution and bubble frequency in rectangular two dimensional Gas-solid fluidized beds from the distribution of chord lengths obtained experimentally.

5.2 **EXPERIMENTAL**

5.2.1 **Experimental set-up**

The experimental set – up consisted of the rectangular 2-dimensional fluidized bed that was tightly sandwiched between two specially designed 10 mm thick acrylic sheets having length 0.75m and width 0.15m. The acrylic sheets had a matrix of 5 mm holes drilled on it at a pitch of 10 mm covering almost its entire surface. These sheets were used to mount the laser light source on one side and the optical fiber probe on the opposite side as shown in Fig 5.1. The holes in both the sheets were so aligned that when clamped to the 2-dimensional bed if the light source was introduced in any particular hole then in the exactly opposite hole the optical probe could be introduced to record the intensity of the light as shown in Fig 5.2. The assembly had the possibility of introducing a number of light sources and receiving fiber probes in different planes of the bed.

The low power LASER (GaAlAs) having 825nm monochromatic wavelength was used as a light source and mounted on the front side of the assembly. The parameters of the light source are given in Table 5.1. Fiber optic cables were mounted on the rear side of the assembly.

Proper care was taken to maintain perfect alignment between light source and receiver, in order to avoid any losses of light. Scientech Technologies Pvt. Ltd., Indore, supplied these optical fiber cables. The major specifications of the optical fiber cable are presented in
Table 5.2. Each fiber cable length was 1.5m and had negligible losses associated with them as specified in Table 5.2 in terms of cable attenuation and reference attenuation parameters. The optical fibers carried optical light induced on it to the phototransistor AN-3005 (sensor). The optical receiver AN-3005 converted optical signal (information) into the electrical signal (information). The major specifications of AN–3005 are listed in Table 5.3.

Fig. 5.1 Schematic view of the arrangement of laser source and optical fiber probes used for optical imaging

<table>
<thead>
<tr>
<th>Table 5.1 Optical light source parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
</tr>
<tr>
<td>Optical Output Power</td>
</tr>
<tr>
<td>Threshold Current</td>
</tr>
<tr>
<td>LD operating Voltage</td>
</tr>
<tr>
<td>Slope Efficiency</td>
</tr>
<tr>
<td>Lasing wavelength</td>
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</table>
Fig. 5.2 Side view of the arrangement of laser source and optical fiber probes used for optical imaging

Table 5.2 Fiber cable mechanical/optical parameter

<table>
<thead>
<tr>
<th>specification</th>
<th>Symbol</th>
<th>Min</th>
<th>Max</th>
<th>Unit</th>
<th>Condition</th>
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<tr>
<td>Cable Attenuation</td>
<td>$\alpha_s$</td>
<td>0.15</td>
<td>0.27</td>
<td>dB/m</td>
<td>825 $\mu$m LASER, 50m length</td>
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<tr>
<td>Reference Attenuation</td>
<td>$\alpha_r$</td>
<td>0.12</td>
<td>0.23</td>
<td>dB/m</td>
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<tr>
<td>Numerical Aperture</td>
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<td>0.46</td>
<td>0.49</td>
<td>--</td>
<td>&gt; 2 meter</td>
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<tr>
<td>Diameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core &amp; Cladding</td>
<td>$D_c$</td>
<td>0.94</td>
<td>1.06</td>
<td>mm</td>
<td>Simplex Cable</td>
</tr>
<tr>
<td>Jacket</td>
<td>$D_j$</td>
<td>2.13</td>
<td>2.27</td>
<td>mm</td>
<td></td>
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<tr>
<td>Propagation Delay</td>
<td>l/v</td>
<td>5.0</td>
<td>--</td>
<td>ns/m</td>
<td>--</td>
</tr>
<tr>
<td>Constant</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refractive Index</td>
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<td>--</td>
<td>--</td>
<td>--</td>
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<tr>
<td>Cladding</td>
<td></td>
<td>1.417</td>
<td>--</td>
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Table 5.3 Optoreceiver Parameter

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<th>Symbol</th>
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<th>Typical</th>
<th>Max</th>
<th>Unit</th>
<th>Condition</th>
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<td>Emitter to Collector Breakdown BV ECO</td>
<td>7.0</td>
<td>--</td>
<td></td>
<td>Volt</td>
<td>IF = 100 μA, Ec = 0</td>
</tr>
<tr>
<td>Collector to Emitter Breakdown BVCEO</td>
<td>30.0</td>
<td>--</td>
<td>--</td>
<td>Volt</td>
<td>IF = 1 mA, Ec = 0</td>
</tr>
<tr>
<td>Collector to Emitter Leakage ICEO</td>
<td>--</td>
<td>--</td>
<td>100</td>
<td>mA</td>
<td>VCE = 25 V, Ec = 0</td>
</tr>
<tr>
<td>Turn-On Time TON</td>
<td>--</td>
<td>45</td>
<td>--</td>
<td>Ms</td>
<td>IF = 10 mA, VCC = 5 V, RL = 750</td>
</tr>
<tr>
<td>Turn-Off Time TOPF</td>
<td>--</td>
<td>250</td>
<td>--</td>
<td>Ms</td>
<td>IF = 10 mA, VCC = 5 V, RL = 750</td>
</tr>
</tbody>
</table>

The output of the AN-3005 was fed to the Analogue to Digital Converter (ADC), via unit gain amplifier designed using operational amplifier LM 308. The output of the ADC was digital data that was fed to the data acquisition system via micro-controller 89C51 using synchronous serial communication at 9600-baud rate. The circuit arrangement and its PCB layout are shown in the Fig. 5.3 and 5.4.
Designing the circuit with Analogue to Digital Converter, gave information about the intensity of optical power that passed through fluidized bed column at any particular sensing location. From the intensity of power the significant information pertaining to amount of solid present in the bubble (solid wake) and voidage distribution in the emulsion phase could be inferred.

In total eight laser sources were mounted on the assembly such that light emitted from laser was focused on the centre of the width of the fluidized bed column at fixed vertical locations of 0.03 m, 0.06 m, 0.09 m, 0.12 m, 0.15 m, 0.18 m, 0.21 m, 0.24 m from the distributor. The complete arrangement of equipment mounted with sensors and data acquisition system is shown in Fig. 5.5. The fluidization setup was tested under empty conditions and also with only gas flow in the column to ensure that there was no loss of intensity of optical power in absence of solids due to any maladjustment.

5.2.2 Initial experiments

Initial fluidization experiments were performed in a 0.01 m thick fluidized bed using 450 μm size resin particle system with a static bed height of 0.29 m. From the data obtained the bubble occurrence was noted when light passed through the fluidized bed column from one
side to other. In view of the 8 bit ADC used in the circuit there exist possibilities of 256 different variations of light intensity to be recorded. Therefore, a plot of signal occurrence versus power intensity variation could be developed as shown in Fig. 5.6. The nature of these plots were exponential decay type, at high occurrence the power intensity was very low while at low occurrence the power intensity was high. High power intensities could be correlated with the passage of the bubble while low intensities of light recorded could be due to a multitude of reasons such as light penetration through the emulsion phase, diffraction, passage through transient cavities in the bed, system noise etc.

![Fig. 5.5 Schematic view of the experimental set-up along with data acquisition system used for optical imaging](image)

Considering a specific case for data obtained with \((U_0 - U_{mf}) = 0.048\text{m/s} \text{ and } U_{mf}/U_{inf} = 1.18\) from the optical fiber probes located at distances of 0.06 m, 0.09 m, 0.12 m and 0.15 m from the distributor. It is seen from the Fig. 5.6 that with an increase in sensor location from 0.06 m to 0.15 m, no significant change in the profile was observed except that the maximum light intensity at occurrence was less at 0.15 m location.

It is amply clear from the figures that nothing significant could be discerned from them and at the best it provides only some qualitative idea about the behavior of the bed. After a thorough review of the scheme of things it was realized that there was lacuna with the
circuit itself, because the conversion time required by ADC severely limited the number of data fetched per second that was only around 15 samples/s.

Investigations in Chapter 4 revealed that the bubble rise velocity \( (U_{tr}) \) ranges from 0.28 m/s to 0.39 m/s. If we consider that the bubble rise velocity is 0.28 m/s it can easily be figured out that with a data-fetching rate of 15 samples per second a bubble having size smaller than 0.0186 m has a possibility to escape detection by the sensor. It could also happen in certain cases that due to the slow rate of fetching erroneous sizes would be reported if the sensor encounters two different bubbles in two consequent measurements. The third possibility is that the bubble could be detected but nothing conclusive could be discerned out of it. In view of these anomalies and to overcome the limitations in the data

![Image](image.png)
fetching rate a new circuit was designed so as to substantially enhance the data-fetching rate.

5.2.3 Circuit modification

The objective of the circuit modification was to enhance the data-fetching rate so as to enhance the resolution of the system. The major circuit change involved was in replacing the ADC and in using the phototransistor AN-3005 as a comparator in a switching circuit. AN-3005 was configured as an emitter followed with 8.2 K emitter resistor. The output of the phototransistor was given to the OP-Amp based comparator circuit.

The comparator compares the output voltage level from the phototransistor and switches between only two levels the $+V_{sat}$ and $-V_{sat}$ level. Signal from the comparator passes to the diode IN 4001 that will conduct only when the output of the OP-Amp is $+V_{sat}$ level. For $-V_{sat}$ level, the diode is reversed biased and will give no output signal. The output of the diode IN 4001 was given to the 5.1 volt Zener diode voltage regulator. The output voltage across the 5.1 volt Zener diode was switched between +5 V to 0 V only. This output terminal was connected to microcontroller 89C2051 used for data acquisition. The detailed circuit diagram is shown in Fig.5.7(a,b).

![Fig. 5.7(a) Modified circuit diagram](image-url)
Fig. 5.7(b) Circuit diagram of optical to electrical convertor block

The output sensor and interfacing circuit produces ‘0’ volt (or ‘0’ logic) on the corresponding line on a port of micro-controller when light does not pass through the bed; and produces ‘+5’ volt (or ‘1’ logic) on corresponding line on port of micro-controller, when light completely passes through the bed. The output of this operational amplifier is fed to the microcontroller 89C2051 on its port. The microcontroller was programmed to fetch the output at the rate of 200 samples/s and transmit data to Visual Basic based data acquisition system using RS 232 serial bus communication system. Asynchronous mode of transmission with 9600 baud rate was utilized to transmit the data from microcontroller to data acquisition system. Data acquisition system stored these data in Microsoft Access files, which were utilized later for further analysis.

5.3 DATA MODULATION AND ANALYSIS

5.3.1 Data acquisition and filtering

The data acquisition system was designed and programmed to acquire digital data from optical sensors at the rate of 200 samples/sec. A standard operating procedure was evolved to acquire data for each set of parametric variation of the fluidized bed system. Data acquisition software was designed using the MATLAB platform to fetch the data, starting from the initiation of the process of acquisition and ending with the termination of the
process. There was provision for varying the time of acquisition however, the processing speed was a limiting factor.

For each experimental run, data acquisition was initiated only after the fluidization behavior had stabilized. With experience it was realized that a time span of two to three minutes of operation was sufficient to stabilize the fluidization behavior, however the data acquisition system was never initiated before 5 to 8 minutes of operation. The data acquisition system was run for a period of 250 seconds i.e. each sensor for each experimental run acquired 50,000 data samples.

The data that was obtained in binary form was filtered to eliminate the noise in the data. The presence of noise could be due to physical reasons such as wake circulation in the bubbles, transient cavities formed in the emulsion phase, raining of particles within the bubbles and also due to circuit malfunctioning.

![Original Data String](image1)

![Filtered Data String](image2)

**Fig. 5.8 Approximation algorithm method for data filtering**

The basis of filtering was to remove short spikes of ‘0’ from a long string of ‘1’ and vice versa using the ‘approximation algorithm method’ wherein up to three sequential spikes in a long string was filtered as shown in Fig.5.8. The necessity of such filtering could be justified from the fact that at a data fetch rate of 200 samples/s each sample value corresponds to only 5 milliseconds, this yields a bubble size of 1.25 mm, for a single spike
CHAPTER 5: IMAGING OF 2-DIMENSIONAL FLUIDIZED BEDS WITH OPTICAL FIBER PROBES

at an average bubble rise velocity of 0.25 m/s. Existence of such small sized bubble is highly unlikely in the fluidized bed.

5.3.2 Bubble frequency determination and analysis

Bubble frequency is an important parameter that gives an idea of hydrodynamic parameters such as bubble volume and bubble size. When measured simultaneously at two or more locations of the bed one also gets a reasonable idea about the processes of bubble coalescence and bubble breakage occurring between the measured locations. The bubble frequency \( f \) is obtained by dividing the number of data samples \( n \) reporting bubble occurrence (i.e. number of '1') by the total time span of the measurements in seconds.

\[
f = \frac{n}{t}
\]  

(5.1)

In this study the bubble frequency was determined using optical sensors located at distances of 0.03 m, 0.06 m, 0.09 m, 0.12 m, 0.15 m, 0.18 m, 0.21 m and 0.24 m vertically from the distributor. The data obtained from these sensors were recorded simultaneously, filtered and analyzed. The influence of various fluidized bed parameters and operational parameters on bubble frequency was investigated. It was observed that under all set of conditions the bubble frequency increases with the fluidization velocity. However, after traversing a certain distance up the bed, bubbles tend to coalesce and due to this reason, in the upper regions of the bed a decline in frequency is sometimes observed.

Bubble frequencies are influenced by a number of processes that include primary processes that contribute to bubble formation at the distributor and its growth during rise in the bed and the secondary processes that contribute to bubble coalescence, bubble splitting etc. Both the primary and secondary processes are influenced by a number of variables, the effects of such variables are listed below.

5.3.2.1 Effect of fluidization velocity

Bubble frequency like bubble size increases with an increase in excess gas velocity. Bubble frequency in general increases with height above the distributor although in many cases it tends to decrease in the upper realm of the bed. Fig. 5.9 shows the variation of bubble
frequency with sensor location for 460 μm glass-beads, in a 0.01 m thick bed having static bed height of 0.35 m, at different excess gas velocities. Two effects get established from the figure, one is that of \((U_o - U_{mf})\) on bubble frequency and the other being the height above distributor on the bubble frequency. Increase in \((U_o - U_{mf})\), increases the gas rate in the bubble phase which leads to an increase in the frequency of the bubble. With increasing height above the distributor, bubble frequency tends to decline due to the effects of bubble coalescence in bed. The effect of bubble coalescence leading to slug formation is more pronounced in case of 780 μm resin particle system in a 0.005 m thick bed having static bed height of 0.35 m, at different excess gas velocities as seen in Fig. 5.10 (a), where, bubble frequency increases with fluidization velocity up to 0.06 m sensor location and thereafter a sharp decline in bubble frequency is observed from 0.09 m height onwards.

![Fig. 5.9 Bubble frequency vs sensor location at varying excess gas velocities (\(U_o-U_{mf}\))](image)

\[\text{460 μm glass-beads, } t = 0.01 \text{m, } H_s = 0.35 \text{m}\]

**5.3.2.2 Effect of bed thickness**

Usually bed diameters are obtained as a consequence of the design process, however in slender fluidized beds with large size particles the bed thickness can exert considerable influence on the fluidization behavior. To assess the influence of bed thickness on bubbling
Chapter 5: Imaging of 2-Dimensional Fluidized Beds with Optical Fiber Probes

Fig. 5.10 (a) Bubble frequency vs sensor location at varying excess gas velocities $(U_o-U_{mf})$ (780 μm resin, $t = 0.005$ m, $H_s = 0.35$ m)

Fig. 5.10 (b) Bubble frequency vs sensor location at varying excess gas velocities $(U_o-U_{mf})$ (780 μm resin, $t = 0.015$ m, $H_s = 0.35$ m)
rates, 780 µm sized resin particles were used as the test case in bed sizes of 0.005 m and 0.015 m with static bed height of 0.35 m and with excess gas velocities ranging from 0.032 m/s to 0.32 m/s for 0.005 m thick beds and 0.011 m/s to 0.11 m/s in 0.015 m thick beds.

Fig. 5.10 shows the change in bubble frequency with sensor location at different excess gas velocities for the case of 780 µm resin in beds having thickness 0.005 m and 0.015 m respectively. It was found that in 0.005 m thick bed there was a sharp increase in bubbling rates in the region close to the distributor and thereafter a progressive decline in the bubble frequencies. The peak bubble frequencies ranged from 2 to 3 s⁻¹ and was observed at a height of 0.06 m above the distributor.

This behavior indicates the possibility of slug formation that was common with this particle-bed system, due to intense particle wall effect. While in the 0.015 m bed the peak bubble frequencies were relatively on the lower side and the location was close to mid elevation (central region of the column) of the bed. The decline in bubble frequencies were observed only at large excess gas velocities at the upper region of the bed. This is attributed to the presence of the freeboard region at that location.

5.3.2.3 Effect of static bed height

The effect of static bed height on bubble frequency was studied with 450 µm resin particle system in 0.015 m thick bed at different excess gas velocities as shown in Fig. 5.11 (a, b, c). A sharp decline in the bubble frequency observed in Fig. 5.11 (a and b) at excess velocities of 0.011 to 0.11 m/s is attributed to the existence of freeboard region in the bed. With deep beds Fig. 5.11(c) such freeboard regions were not observed at the measuring points.

Fig. 5.12(a, b) shows the effect of static bed height on bubble frequency in 0.005m thick bed filled with 350 µm sand at varying excess gas velocities. The static bed heights were found to have a pronounced effect on bubble frequency. Lower the static bed height more is the bubble frequency. Increase in static bed height increases the bubble residence time that lowers the bubble frequency rate.
Chapter 5: Imaging Of 2-Dimensional Fluidized Beds with Optical Fiber Probes

Fig. 5.11 (a) Bubble frequency vs sensor location at varying excess gas velocities 
\( (U_\text{g} - U_{\text{mf}}) \) (450 µm resin, \( t = 0.015 \text{m}, H_s = 0.21 \text{m})

Fig. 5.11 (b) Bubble frequency vs sensor location at varying excess gas velocities 
\( (U_\text{g} - U_{\text{mf}}) \) (450 µm resin, \( t = 0.015 \text{m}, H_s = 0.25 \text{m})

169
Chapter 5: Imaging Of 2-Dimensional Fluidized Beds with Optical Fiber Probes

Fig. 5.11(c) Bubble frequency vs sensor location at varying excess gas velocities 
\((U_0-U_{mf})\) (450 \(\mu\)m resin, \(t = 0.015\)m, \(H_s = 0.35\)m)

Fig. 5.12 (a) Bubble frequency vs sensor location at varying excess gas velocities 
\((U_0-U_{mf})\) (350 \(\mu\)m sand, \(t = 0.005\)m, \(H_s = 0.21\)m)
S.2.3.4 Effect of particle size

The effect of particle size on bubble frequency is not established. Hence, this aspect was investigated by obtaining data of bubble frequency at varying particle sizes for the case of sand, mustard and resin particles. With sand particles in 0.01 m thick beds at excess gas velocities of 0.032 m/s the bubble frequency for 250 μm sand was lower than the larger sized 350 μm sand as seen in Fig 5.13 (a), (b) and (c). It appears that the larger voidage of the 350 μm particles assist the bubble formation under these conditions. Doubling the excess gas velocities not only doubles the bubbling rate but also brings the bubbling rates of 250 μm sand very close to that of 350 μm sand indicating that the inertial effects dominate the bubble formation process. Similar behavior was also observed at (Uo-Umf) of 0.144 m/s but, at upper regions of the bed the bubble frequency with 250 μm was more.
Chapter 5: Imaging of 2-Dimensional Fluidized Beds with Optical Fiber Probes

(a) \( t = 0.01 \text{m}, \ (U_o - U_mf) = 0.032 \text{ m/s} \)

(b) \( t = 0.01 \text{m}, \ (U_o - U_mf) = 0.064 \text{ m/s} \)
With resin particles in 0.01 m bed having static bed height of 0.35 m and at excess gas velocities of 0.128 m/s and 0.192 m/s, it is observed from Fig. 5.14 (a) and (b) that the bubble frequency shows identical pattern with all the three particle sizes, sharply increasing up to a short distance from the distributor and thereafter declining. This behavior appears to be more out of some local disturbance etc. rather than a general trend. With the large diameter mustard particles the bubble frequencies are obviously low for excess gas velocities ranging from 0.048 m/s to 0.128 m/s in 0.005 m thick beds having static bed height of 0.35 m. In all the three cases seen in Fig 5.15 (a), (b) and (c), it is observed that 1002 µm particle shows much larger bubble frequencies than the 2084 µm mustard particle, which doesn’t appear to fluidize with ease in either of the three cases and often leads to the formation of rectangular slugs.
Fig. 5.14 Bubble frequency vs sensor location at varying particle sizes 
(220 μm, 450 μm, 780 μm resin)
Chapter 5: Imaging of 2-Dimensional Fluidized Beds with Optical Fiber Probes

(a) \( t = 0.005 \text{m}, \ (U_o-U_{mf}) = 0.048 \text{ m/s} \)

(b) \( t = 0.01 \text{m}, \ (U_o-U_{mf}) = 0.08 \text{ m/s} \)
5.3.3 Bubble size distribution

The optical imaging technique in addition to its utilization for determination of bubble frequency could also be used as a tool to obtain information on bubble sizes and their distribution at the various sensor locations. This was achieved by identifying the string transitions from ‘0’ to ‘1’ and ‘1’ to ‘0’ from the data obtained at each sensor location. The strings of ‘1’ appearing in the data set were segregated, their lengths counted and then tagged by assigning labels, $\Phi_1, \Phi_2, \Phi_3, \ldots, \Phi_n$ sequentially to all the ‘n’ number of strings of ‘1’ in the data set. It may be noted that equal string lengths were not sorted out at this stage. Thereafter the string lengths were converted to chord lengths using Equation (5.2) with knowledge of the bubble rise velocity.

$$Y_i(cm) = \frac{\phi(sample) \times U_{hr}(cm/\sec)}{\text{sampling rate}}$$ (5.2)

where $\phi$ is the string size, $U_{hr}$ is the bubble rise velocity in cm/s and the sampling rate is 200/s.

Fig. 5.15 Bubble frequency vs sensor location at varying particle sizes (1002 µm, 2084 µm mustard)
In Equation (5.2) instead of using a constant value of bubble rise velocity \( U_{br} \) for all the parametric variations of fluidization explored in this study, representative values of experimental bubble rise velocities obtained under more or less similar conditions from digital image analysis (Chapter 4) were used to compute the chord lengths. Table 5.4 illustrates the procedure of computation of chord lengths at any sensor location using appropriate values of \( U_{br} \).

**Table 5.4 Distribution of chord length at a specific sensor location \( (U_{br} = 24 \text{ cm/s}) \)**

<table>
<thead>
<tr>
<th>S.No</th>
<th>String definition</th>
<th>Count of data samples / string of I</th>
<th>Chord Length (cm) ( \text{Count} \times U_{br} / \text{sampling rate} )</th>
<th>Chord Identifier</th>
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<tbody>
<tr>
<td>1</td>
<td>( \Phi_1 )</td>
<td>22</td>
<td>2.64</td>
<td>( Y_1 )</td>
</tr>
<tr>
<td>2</td>
<td>( \Phi_2 )</td>
<td>40</td>
<td>4.80</td>
<td>( Y_2 )</td>
</tr>
<tr>
<td>3</td>
<td>( \Phi_3 )</td>
<td>38</td>
<td>4.56</td>
<td>( Y_3 )</td>
</tr>
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<td>( \Phi_4 )</td>
<td>15</td>
<td>1.80</td>
<td>( Y_4 )</td>
</tr>
<tr>
<td>5</td>
<td>( \Phi_5 )</td>
<td>26</td>
<td>3.12</td>
<td>( Y_5 )</td>
</tr>
<tr>
<td>6</td>
<td>( \Phi_6 )</td>
<td>17</td>
<td>2.04</td>
<td>( Y_6 )</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>N</td>
<td>( \Phi_n )</td>
<td>28</td>
<td>3.36</td>
<td>( Y_n )</td>
</tr>
</tbody>
</table>

The largest value of chord length obtained for each data set was taken as the ‘Maximum vertical size’ attainable by a bubble \( (Y_{max}) \) in that set. Although the laser emitters and sensors were located on axis symmetric plane, the bubbles also have a tendency to rise through the centre of the unit but due to random bubble motion, the light signal need not always intersect the bubble at its centre. Hence, the chord lengths obtained for any specific data set using Equation (5.2) is a measure of the length of any portion of the bubble that is crossing the sensor plane as shown in Fig. 5.16. It is very much likely that a vertical distance smaller than the maximum vertical bubble dimension could also be measured. Similarly, in case the bubble tilts while crossing the sensor a bubble size much greater than actual bubble size would be recorded. It is for this reason that measured distance is called ‘chord length’ or ‘pierced length’ in case, the probe physically penetrates the flow field. To obtain the probability distribution function (PDF), the chord length distribution data, obtained for various set of conditions at different sensor location, were normalized using Equation (5.3).
Chapter 5: Imaging Of 2-Dimensional Fluidized Beds with Optical Fiber Probes

Fig. 5.16 Chord length variation based on measurement locations

\[
W(Y_i < Y < Y_{\text{max}}) = \frac{\text{Number of observations of chord length between } Y_i \text{ and } Y_{i+1}}{\text{Total number of observations}} \quad (5.3)
\]

\(Y_{\text{max}}\) was selected based on the total data range. In this study 20 cm size bubbles were the maximum size that were observed hence, \(Y_{\text{max}}\) was taken as 20 cm. This maximum value was split into sub ranges so as to get chord lengths in the interval of 1 cm up to a final value of 20 cm.

The probability bubble distribution function thus obtained was used to develop histograms with respect to chord length and various design and operational parameters. These 3-D plots gave a clear idea of the influence of variation in fluidization parameters on the bubble size distribution. The effects of various parameters are elucidated below:

5.3.3.1 Effect of excess gas velocity

It is well known that increase in excess gas velocities always contribute to an increase in bubbling rate as well as bubble sizes. For the case of 450 \(\mu\)m resin in 0.015 m thick bed having static bed height of 0.25 m, the data obtained at sensor location of 0.12 m above the
distributor is presented in Fig. 5.17. In this figure the Probability bubble distribution function (Bubble PDF), which is a measure of the frequency of bubbles of a given size is plotted versus chord length and the excess gas velocity ($U_0 - U_{mf}$).

Fig. 5.17 clearly shows that with an increase in the excess gas velocities from 0.033 m/s to 0.077 m/s there is an increase in the size of bubbles as well as a change in the pattern of chord size distributions. At excess gas velocities of 0.033 m/s it is found that the 6 cm and 4 cm size chord lengths are dominant and they together account for almost 44% of the bubbles. With an increase of the excess gas velocities, considerable rearrangement of the bubble sizes are observed due to the processes of coalescence, splitting and growth. At an excess gas velocity of 0.055 m/s the frequency of bubble sizes having chord lengths ranging from 3 cm to 8 cm are almost constant. Further increasing ($U_0 - U_{mf}$) to 0.066 m/s the distribution changes considerably with tendency of the formation of larger sized bubbles at the cost of smaller sized bubbles hinting at greater extent of bubble coalescence. When ($U_0 - U_{mf}$) is 0.077 m/s the tendency of the growth of larger bubbles at cost of smaller bubbles is more prominent, there is an emergence of very large bubbles at this velocity that widens the whole distribution.

Fig. 5.17 Probability bubble distribution function vs chord length and excess gas velocities ($U_0 - U_{mf}$) (450 μm resin, $t = 0.015$m, $H = 0.25$m, sensor location = 0.12m)
The unique changes in the pattern of chord length distribution noted for this specific system are the following:

- There is almost an exponential decay of the 4 cm chord length with an increase in the excess gas velocities.
- There is a definite increase in the 9 cm chord length with an increase in the excess gas velocities.

In another case, a bed 0.01 m thick filled with 350 μm sand up to static bed height of 0.25 m was fluidized at excess gas velocities ranging from 0.048 m/s to 0.112 m/s. The results obtained at 0.15 m sensor location are recorded in Fig. 5.18. At an excess gas velocity of 0.048 m/s, it was found that the 3 cm and 4 cm sized chord lengths were dominant accounting for 82% of the bubbles while 5 cm chord lengths accounted for the remaining 18% bubbles. As the excess gas velocity was increased to 0.064 m/s, the distribution widened and bubbles having chord length greater than 5 cm emerged. Simultaneous to this there was a decline in the 3 cm chord length bubbles indicating that the process of bubble coalescence was active.

When excess gas velocity was further increased to 0.08 m/s, consolidation of bubble sizes were observed with the restoration of the 3 cm size bubbles and substantial decline in the frequency of the 4 cm sized bubbles. There was enhancement in the frequency of 5cm and 7cm bubbles. Further increase in the excess gas velocity to 0.096 m/s again showed a decline of the 3 cm sized bubbles. In this case the 3 cm and 4 cm sized bubbles have identical frequencies of about 35% each. There was also emergence of large bubbles of around 10 cm size. This itself indicates that the bubble coalescence and breakage was quite active at this velocity. On further increase of (U_{0}-U_{mf}) to 0.112 m/s, it appears that the distribution reaches a sort of equilibrium. The 3 cm, 4 cm and 5 cm sized chord length have nearly 21 to 24 % frequency each, while the 6 cm chord length has 18% frequency. The remaining frequency is distributed between 7 to 9 cm sized chord lengths. In this case an oscillatory behavior was observed in 3 cm to 5 cm sized chord lengths and the presence of very large sized bubbles were missing. As it is the sand system is known to be susceptible to bubble splitting (Toei et al.,1969).
5.3.3.2 Effect of sensor location

It is well known that the bubble sizes increase with height from the distributor as observed in Chapter 4 section 4.4.2.1, but answer to the question ‘How the bubble size distribution changes with height?’ is still largely unknown. Hence, an attempt was made to address this question. Three representative cases are discussed below. In each of these cases the measurement of chord lengths at different sensor locations were done simultaneously while the overall system was under steady state conditions.

Case 1 deals with a bed of 0.01 m thickness filled with glass beads having 256 μm size, having static bed height of 0.21 m. The bed was fluidized with excess gas velocity of 0.112 m/s and the results of chord length variation are shown in Fig. 5.19. It is observed that as the distance from the distributor increases the chord length distribution widens. At 0.09 m above the distributor 3 cm sized chord length is dominant closely followed by 4 cm sized chord length. The occurrence of 8 cm sized chord length is just about 2% while that of larger sized bubbles is rather scarce.
Moving to 0.12 m bed location we find that the 3 cm chord length is still dominant but an overall increase in bubble size is observed. The 3 cm sized bubble also grown but the growth of the 4 cm bubble is prominent because the 5 cm size chord length has caught up with the 4 cm sized chord length. In subsequent frames at 0.15 m height it was found that the 4 cm bubble frequency is identical with the 3 cm bubble frequency but there is reduction in the 3 cm size distribution while there is an enhancement of the 4 cm size distribution. At 0.18 m distance an orderly pattern of distribution emerges, there is a wide range of bubble sizes observed and almost uniform gradient of distribution is seen. This order dissolves at 0.21 m height from distributor. There is a large shift towards the large sized bubbles although slug formation is unlikely under these conditions.

**Fig. 5.19** Probability bubble distribution function vs chord length and sensor locations

(256 μm glass-beads, \(t = 0.01\) m, \(H_s = 0.21\) m, \((U_0 - U_{inf}) = 0.112\) m/s)

**Case II** describes the behavior of 780 μm resin in a column having bed thickness of 0.005 m. The static bed height was kept 0.25 m and the excess gas velocity was 0.08 m/s. Wide chord size distribution was observed even at just 0.09 m distance from the distributor as seen in Fig 5.20. It was surprising to find that the frequency of 3 cm, 4 cm and 9 cm sized chord lengths were identical. The results at sensor located at 0.12 m shows more uniform distribution with peak chord length of 6 cm. This is perhaps due to splitting of large sized unstable bubbles. At 0.15 m distance from the distributor there is again greater extent of
randomness in the distribution caused by an overall widening of the distribution due to presence of larger sized bubbles, increase in the frequency of larger sized bubbles, decline in the frequency of bubbles in the range of 3 – 6 cm sized chord lengths.

At 0.18 m distance from the distributor very large sized bubbles (> 15 cm) start appearing that cause a decline of the frequencies of smaller sized bubbles indicating the possibility of bubble coalescence. The sensor at 0.21 m height senses the presence of the largest sized bubbles in the distribution. From the figure it is apparent that the processes that lead to the formation of large bubbles at 0.18 m height get further consolidated at 0.21 m height. It is interesting to observe that the least change in frequency was observed with the 4 cm sized bubbles in the entire span of bed height. The frequency of the 6 cm sized chord length shows a Gaussian nature over the height of the bed (all sensor locations).

**Fig. 5.20 Probability bubble distribution function vs chord length and sensor locations**

(780 μm resin, t = 0.005m, Hc = 0.25m, (U0-Umf) = 0.08 m/s)

**Case III** considers 0.005 m thick bed filled with 250 μm size sand up to 0.21 m static bed height fluidized at an excess gas velocity (U0-Umf) of 0.192 m/s. The histogram of chord size distributions obtained at the sensors located at 0.09, 0.12, 0.15, 0.18, 0.21 m are shown in Fig. 5.21. In this case the distribution of chord lengths at 0.09 m and 0.12 m heights are quite close. At 0.15 m from the distributor major rearrangements are observed. The sharp
increase in the frequency of the 4cm chord length is indicative of bubble splitting occurring in the bed leading to formation of smaller sized bubbles.

At 0.18 m location from the distributor the bubble size distribution suddenly widens with larger sized bubbles coming into existence. This sudden increase in chord lengths indicate that bubble coalescence is dominant. This inference is augmented by the measurements taken at the sensor located at 0.21 m, where it was found that bubbles of chord lengths up to 20 cm are present and the frequencies of bubbles of large chord lengths being nearly the same.

This part of the investigation gave a glimpse of the complex dynamics active at each sensor level and the pattern of chord length distribution evolving in space.

**5.3.3.3 Effect of static bed height**

The influence of static bed height is reported for three different cases as detailed below:
Case 1 considers 256 μm glass-beads in a 0.005 m thick bed, fluidized at excess gas velocity of 0.16 m/s with measurement made at a sensor located at height of 0.18 m above the distributor. Effect of static bed heights 0.21 m, 0.25 m and 0.29 m were investigated. One striking feature that is observed is that as the static bed height increases, the bubble size distribution narrows down. The reason for this behavior is that the weight of the particle increases with increase in static bed height which mounts more pressure on the roof of the bubbles and bubble gets suppressed (Geldart (1972). As a consequence of narrowing down of the distribution the bubble size frequency tends to increase.

The distribution patterns obtained at 0.25 m and 0.29 m are almost identical with the exception that 11 cm sized chord length does not exist when the static bed height is 0.29 m. The dominant chord lengths are that of 3 cm and 5 cm closely followed by the chord length of 4 cm in the 0.25 m and 0.29 m bed. It is surprising that in spite of the very slender thickness of the bed very large size bubbles were not found, except in the case of 0.21 m static bed height.

Fig. 5.22 Probability bubble distribution function vs chord length and static bed heights (H_s) (256 μm glass-beads, t = 0.005m, sensor location = 0.18m, (U_e-U_inl) = 0.192 m/s)
Case II also deals with 256 µm glass-beads but in 0.01 m thick beds fluidized at 0.096 m/s excess gas velocities and the result obtained at the sensor located at 0.21 m is presented in Fig. 5.23. In this case again it was observed that the bubble size distribution tends to shrink with an increase in static bed height. Thus widest bubble size distribution is observed in 0.21 m static bed height and narrowest is observed at 0.29 m bed height with the 0.25 m height being intermediate. The 3 cm and 4 cm sized chord lengths are dominant at all the 3 cases. However, the frequencies of these sizes increase with an increase in static bed heights. This trend of increase in frequency of a particular size with static bed height is observed only with 3 cm to 5 cm chord length. For chord lengths greater than 5 cm the distribution tends to become random, that indicates splitting, coalescence and growth induced by change in static bed height (or indirectly due to change in pressure) is active.

![Fig. 5.23 Probability bubble distribution function vs chord length and static bed heights (H_s) (256 µm glass-beads, t = 0.01m, sensor location = 0.21m, (U_0-U_{ml}) = 0.096 m/s)](#)

Case III considers mustard particles of 1002 µm size fluidized in a bed having thickness of 0.005m. As in previous cases, three different static bed heights 0.21 m, 0.25 m and 0.29 m were considered. Mustard is a low-density, large size particle that shows tendency of slugging. Comparing the bubble size distribution patterns obtained for the three different static bed heights, at the sensor located at 0.21 m height, for a bed fluidized with an excess gas velocity of 0.224 m/s, it was observed that the distribution patterns obtained for static
beds of 0.21 m and 0.25 m are quite similar to each other but they are relatively wide distributions as seen in Fig. 5.24.

![Graph showing probability bubble distribution function vs chord length and static bed heights](image)

**Fig. 5.24 Probability bubble distribution function vs chord length and static bed heights** ($H_s$) (1002 μm mustard, $t = 0.005$m, sensor location = 0.21$m$, $(U_0-U_{mf}) = 0.224$ m/s)

It is interesting to observe that with 0.29 m bed heights, there is a dominance of 3 cm and 5 cm chord length which together accounts for more than 67% of the bubbles. The distribution though wide is discrete with disappearance of bubble sizes of 7 cm, 9 cm, and 11 cm from the bed with 0.29 m static bed height. It appears that for this specific static bed height, bubble splitting is the predominant feature. It is otherwise inexplicable why certain chord lengths were missing from the distribution. It is also interesting to know that the 4 cm size chord length remains nearly constant with all the three static bed heights. The same behavior is observed with the frequency of the 10 cm chord length which also remains nearly constant for the three static bed heights.

**5.3.3.4 Effect of bed thickness**

The thickness of a two-dimensional fluidized bed is expected to exert considerable influence on the bubble size distribution. Thin / slender beds are expected to have wider
size distribution than thick beds, because in thin beds the primary bubble growth is expected to be predominantly in the axial direction as measured in our experimental technique. Thus, for 350 μm sand fluidized with an excess gas velocity of 0.06 m/s in a bed with static bed height of 0.29 m, the bubble distribution profile is shown in Fig. 5.25, measured by the sensor located at 0.15 m height above the distributor.

![Fig. 5.25 Probability bubble distribution function vs chord length and bed thickness](image)

In the 0.005 m thick beds the distribution of bubble sizes is quite wide which narrows down for 0.01 m thick bed and further shrinks for 0.015 m sized beds. It was observed that with 0.005 m sized bed, the chord lengths of 3 to 8 cm have comparable frequencies. Increasing the bed thickness to 0.01 m, this parity in chord length distribution is gone. In the 0.01 m thick bed the 2 cm and 3 cm size chord lengths are dominant followed by 3 cm and 4 cm sized chord length, while the 5 and 6 cm sized chord length have identical frequencies. In the 0.015 m thick bed, the 3 cm and 4 cm sized chord lengths are dominant. In the bed having 0.015 m thickness, it appears that the distribution patterns observed result from the primary bubble size distribution at the distributor during formation, instead of the secondary processes causing the distribution that is observed.
Under identical experimental conditions but with chord lengths measured at 0.18 m above the distributor the distribution nature is shown in Fig. 5.26. Comparing Fig. 5.25 with Fig 5.26, both measured simultaneously, it was observed that the distributions are quite close. The major differences observed were the increase in the 5 cm chord length in the 0.005 m thick bed, disappearance of the 7 cm sized chord length and appearance of 8 cm size chord length in the 0.01 m thick bed, and decline in the 4 cm chord length in the 0.015 m thick bed.

Considering 250 μm sand fluidized at an excess gas velocity of 0.048 m/s in beds having static bed height of 0.29 m the bubble chord length distribution obtained at the sensor located at 0.15 m is shown in Fig. 5.27 and under identical conditions the chord length distribution at 0.18 m is shown in Fig. 5.28. The wideness of the distribution in 0.005 m thick bed is larger in comparison with the other beds. It is also interesting to note from Fig. 5.27 at 0.15 m location that the relative frequency of the 3 cm size chord length progressively increases step by step over the three bed sizes. Similar is the trend with the 4 cm sized chord length. But, the 5 cm and 6 cm chord length shows a reverse trend and there is a decline in bubble of these sizes with an increase in bed thickness. Measurements made
Fig. 5.27 Probability bubble distribution function vs chord length and bed thickness
(t) (250 μm sand, sensor location = 0.15m, H_s = 0.29m, (U_0-U_{mf}) = 0.048 m/s)

Fig. 5.28 Probability bubble distribution function vs chord length and bed thickness
(t) (250 μm sand, sensor location = 0.18m, H_s = 0.29m, (U_0-U_{mf}) = 0.048 m/s)
at 0.18 m height above the distributor show an increase in the frequency of the longer chord lengths as expected.

Therefore, one comes to the conclusion that bubble size distributions are narrow when bed thicknesses are large. Obtaining the bubble size distribution in a fluidized bed is considered to be a valuable tool to understand the general nature of fluidization and this information could be used effectively for designing beds with narrow bubble size distributions.

5.4 **Bubble Shape Analysis**

5.4.1 *Generation of standard PDF by heuristic analysis*

When bubbles form at the bottom of the bed, just above the distributor, they are spherical in nature. As the bubble moves upward, different forces act on it, resulting in a change of the bubble shape. Images of the bubbles in fluidized beds of different thicknesses obtained in the previous Chapter indicated, that for all the particle systems as well as for all parametric variations, most of the bubbles were ellipsoidal (either prolate or oblate) in shape, followed by spherical cap bubbles as reported in Table 4.5. Further it was observed that the bubble aspect ratio ($d_y/d_x$) usually varied in the range of 0.3 to 2.0. Taking these as guidelines a methodology was evolved to estimate the bubble shape and size that was likely to represent all the bubbles for a given set of parametric conditions in the fluidized bed. The advantage of having one bubble as the representative of a family of bubbles in terms of shape and size is profound in the design of fluidized bed reactors and other fluidized bed equipment.

Consider a spherical bubble which has aspect ratio of 1 since $d_y = d_x$. If the aspect ratio is varied by changing the value of $d_y/d_x$ from 1 to 2 with an increment of 0.1 one gets a family of *prolate* bubbles with 10 different variations of $d_y/d_x$. Likewise reducing the value of $d_y/d_x$ from 1.0 to 0.3 again in decrements of 0.1, one gets a family of *oblate* bubbles having 8 different variations. Thus with step size of 0.1, increment or decrement, 18 variations in shape are observed while traversing from aspect ratio 0.3 to 2.
Further, realizing that due to the presence of a wake, bubbles in a fluidized bed are never spherically symmetric i.e. bubble cross sections are not circular, but are dimpled at the base like an orange. Since a wake cuts the bubble surface at the base it was thought appropriate to generate different bubble shapes by cutting each of the 18 different shaped bubbles from the base with an increment of 0.1 of the original vertical distance. In this fashion each bubble could be sliced nine times thereby generating a matrix of 18 X 10 bubbles i.e. totally 180 different bubble shapes as shown in Fig. 5.29. It was obvious from the beginning that numerous shapes generated are very unlikely to exist, but in view of the non-existence of any established theory of bubble shapes it was difficult to judge which shapes to retain and which to reject. Hence, all the 180 shapes were retained for comparison with the experimentally generated PDF.

Experimental PDF’s of chord lengths were generated differently in comparison with the previous case. The experimental chord length distribution data, obtained for various set of conditions at different sensor location, were normalized using Equation 5.2. The largest value of chord length obtained for each data set was taken as the ‘Maximum vertical size’ attainable by a bubble ($Y_{\text{max}}$) in that set. $Y_{\text{max}}$ was chosen as the basis and the data was segregated in ten sets of chord lengths ranging from 0 to 0.1$Y_{\text{max}}$, 0.1 $Y_{\text{max}}$ to 0.2 $Y_{\text{max}}$, 0.2 to 0.3 $Y_{\text{max}}$, .. till 0.9-1.0 $Y_{\text{max}}$ as illustrated in Table 5.5.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Chord length range</th>
<th>No. of chord lengths in range (representative values)</th>
<th>String identifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0* $Y_{\text{max}}$ to 0.1* $Y_{\text{max}}$</td>
<td>8</td>
<td>$y_1$</td>
</tr>
<tr>
<td>2</td>
<td>0.1* $Y_{\text{max}}$ to 0.2* $Y_{\text{max}}$</td>
<td>4</td>
<td>$y_2$</td>
</tr>
<tr>
<td>3</td>
<td>0.2* $Y_{\text{max}}$ to 0.3* $Y_{\text{max}}$</td>
<td>10</td>
<td>$y_3$</td>
</tr>
<tr>
<td>4</td>
<td>0.3* $Y_{\text{max}}$ to 0.4* $Y_{\text{max}}$</td>
<td>15</td>
<td>$y_4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.8* $Y_{\text{max}}$ to 0.9* $Y_{\text{max}}$</td>
<td>12</td>
<td>$y_9$</td>
</tr>
<tr>
<td>10</td>
<td>0.9* $Y_{\text{max}}$ to 1.0* $Y_{\text{max}}$</td>
<td>20</td>
<td>$y_{10}$</td>
</tr>
</tbody>
</table>
The shape of the bubbles were obtained by comparing the experimentally obtained PDF values for each data set, at each sensor with the PDF of each of the 180 different bubble shapes generated by the arguments given above. To generate theoretical PDF of the 180 bubble shapes each of the 180 bubbles was sliced vertically along the horizontal plane into 10,000 slices. Each of these vertical slices was the ‘chord lengths’. This large number of vertical slicing takes a severe toll of computational power and memory. Moreover, it takes large amount of time to generate the theoretical PDF. Attempts to generate PDF with lesser number of vertical slices (1000, 5000, 6000, 8000) all resulted in failure due to poor resolution as well as lack of stability. Turton and Clark (1989) also observed similar behavior in their attempt to obtain theoretical PDF of single bubble.

The maximum vertical distance for each bubble was arbitrarily taken as 10z. This distance was split into ten equal parts (on the same line of normalization of $Y_{max}$ for the experimental results of bubbles). The number of occurrence of chord lengths in each of these ten groups were identified. These results were then normalized with the total number of chord lengths (10,000) as shown in Table 5.6. In this manner PDF histograms were obtained for each of the 180 bubbles.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Category</th>
<th>No. of occurrence</th>
<th>Normalized value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 to $z$</td>
<td>$O_1$</td>
<td>$O_1/10000 = N_1$</td>
</tr>
<tr>
<td>2</td>
<td>$z$ to 2$z$</td>
<td>$O_2$</td>
<td>$O_2/10000 = N_2$</td>
</tr>
<tr>
<td>3</td>
<td>2$z$ to 3$z$</td>
<td>$O_3$</td>
<td>$O_3/10000 = N_3$</td>
</tr>
<tr>
<td>4</td>
<td>3$z$ to 4$z$</td>
<td>$O_4$</td>
<td>$O_4/10000 = N_4$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>10</td>
<td>9$z$ to 10$z$</td>
<td>$O_{10}$</td>
<td>$O_{10}/10000 = N_{10}$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>10,000</td>
<td></td>
</tr>
</tbody>
</table>

The shape and the corresponding histograms of all the 180 bubbles generated by the above mentioned process are presented in Fig.5.29. Note should be taken of the fact that in this exercise of obtaining PDF of each bubble the unit of horizontal distance was always unity.
Fig. 5.29 Plausible 180 bubble shapes
Fig. 5.29 Plausible 180 bubble shapes
5.4.2 Shape identification by comparison of experimental and theoretical PDF

Comparing the PDF of the experimental chord lengths with the PDF of the 180 plausible bubble shapes an idea of the bubble shape was inferred. The least square method was adopted for these comparisons. The root mean square error of each normalized segment was determined as shown below. The shape of the bubble that returned least error value when compared with the experimental results, and whose PDF histograms matched the experimental PDF histogram was chosen as the shape of the representative bubble.

\[ E = \sqrt{\sum_{i=1}^{n} (y_i - N_i)^2} \]  

Where \( E \) is the root mean square error, suffix \( i \) is the indicator of bubbles that varies from 1 to 180 and \( 'i' \) is the number of segments of the measured and evaluated chord lengths. Expanding equation (5.4) we get,

\[ E_1 = \sqrt{(y_1 - N_1)^2 + (y_2 - N_2)^2 + ... + (y_{10} - N_{10})^2} \]

\[ E_2 = \sqrt{(y_1 - N_1)^2 + (y_2 - N_2)^2 + ... + (y_{10} - N_{10})^2} \]

\[ ... \]

\[ E_{180} = \sqrt{(y_1 - N_1)^2 + (y_2 - N_2)^2 + ... + (y_{10} - N_{10})^2} \]  \( (5.5) \)

Once the bubble shape was identified, the chord length \( R_{\text{max}} \) was used to restore its dimensions. Algorithms of the above analysis are given in Appendix B.

5.4.3 Results and discussion

5.4.3.1 Bubble shapes in glass bead system: effect of fluidization velocity

Case I \( (U_o-U_{mf}) = 0.044 \text{ m/s} \)

Experiments were performed in a 0.015 m thick bed, filled with 256 \( \mu \text{m} \) glass-beads up to static bed height of 0.21 m. The sensor was located at a height of 0.15 m above the distributor. The bed was fluidized at excess gas velocities ranging from 0.044 m/s to 0.11 m/s. The PDF of the experimental chord lengths for 256 \( \mu \text{m} \) glass-beads in the 0.015 m
thick bed for excess gas velocity values of 0.044 m/s was generated based on the maximum string size obtained in the bed, at the excess gas velocity of 0.044 m/s, which was found to be 118. This resulted in system $Y_{\text{max}}$ of 23.4 using bubble rise velocity of 0.39 m/s.

The longest string size measured at the specified sensor location was 56 while the bubble rise velocity at that location was 0.38 m/s. This yields $Y$ of 10.64 cm, thus the range of the experimental chord length obtained at the specified sensor location for the bed thickness - particle size- velocity combination was up to 0.5 $Y_{\text{max}}$.

Comparing the PDF's of the experimental chord length distributions with the PDF's generated for the 180 bubble shapes, it was found that the best fit by the least square method returned an error of 18.8% for the bubble shape as shown in Fig. 5.30. However, in spite of the mathematical match, little physical similarity existed between the two PDF's. While the experimental PDF consisted of 5 ranges of distributed chord lengths i.e. up to 0.5 $Y_{\text{max}}$, the bubble PDF consisted of 8 range of distributed chord lengths up to 0.8 $R_{\text{max}}$. In view of this difference the bubble shape and its PDF were not considered to be the representative shape of the 'family of bubbles' obtained in the experimental run.

Hence, comparison was again made between the experimental PDF and the PDF of the remaining 179 bubble shapes. In this case the best mathematical fit was obtained for the bubble whose PDF histogram and shape are shown in Fig. 5.31. Comparing the PDF's of the experimental data set with that obtained for the matching bubble it was found that a high degree of parity exists between these two PDF's and both have nearly the same range of distributed chord lengths. The error obtained in this case was 19.8%.

Further, to confirm the efficacy of the results, once again comparison was done between the PDF's of the remaining 178 bubble shapes with the PDF of the experimental data. In this case the best fit returned an error of 21.67%. The bubble PDF also did not match with experimental PDF physically as it consisted only four range of distributed chord lengths as shown in Fig. 5.32. This result confirmed that the ellipsoidal shaped bubble of Fig. 5.31 could be considered as the representative of the 'family of bubbles' obtained experimentally. It was in a way the 'face of the race of bubbles'.
Chapter 5: Imaging Of 2-Dimensional Fluidized Beds with Optical Fiber Probes

Fig. 5.30 to 5.32 Comparison of experimental and generated PDF and bubble shape
(256 µm glass-beads, t = 0.015 m, Hs = 0.21 m, sensor location = 0.15 m, (U0 - Umr) = 0.044 m/s)
Case II \((U_o-U_{mf}) = 0.066 \text{ m/s}\); considering variation in sensor location

Increasing the excess gas velocity to 0.066 m/s under otherwise identical conditions (256 μm glass-beads, \(t = 0.015\text{m}, \ H_s =0.21\text{m}, \ \text{sensor location} = 0.15\text{m}\)) resulted in an experimental chord length distribution PDF as shown in Fig. 5.33. The maximum string size for this case in the bed was 103, while the bubble rise velocity at that specific location was 0.39 m/s that resulted in \(Y_{\text{max}}\) of 20.08 cm. At the sensor location the longest string size measured was 46 and the bubble rise velocity was 0.38 m/s resulting in \(Y\) of 8.74 cm, hence for the excess gas velocity of 0.066 m/s too, the range of the experimental chord length was up to 0.5 \(Y_{\text{max}}\).

When the PDF of experimental chord lengths was compared with the PDF’s obtained for the 180 bubble shapes, it was found that the best fit obtained by the least square method returned an error of 32%, but it did not have parity with the experimental PDF. Hence eliminating that particular shape the experimental chord length PDF’s were again compared with the PDF’s of the remaining 179 bubbles. In this case the fit was obtained with an error of 32.4% and there was good parity between the experimental PDF with the PDF of the bubble shape as seen in Fig. 5.34.

Further a third match was also attempted with 178 bubbles eliminating the best two fits and it was found that in the third case also the parity between experimental PDF and matched bubble PDF was good Fig. (5.35). The least square error was marginally larger being 33.1%. The second match was the most representative shape of the bubble in view of the close parity between the experimental PDF and the PDF of bubble shape.

Measurements at sensor location of 0.18 m under otherwise identical conditions yielded the longest string size of 43. With the bubble rise velocity of 0.38 m/s it results in \(Y\) of 8.2 cm. Hence, in this case also the range of experimental chord length was up to 0.5\(Y_{\text{max}}\). The resulting PDF of experimental chord length were very similar to that obtained at the sensor location 0.15 m as reported in Fig. 5.33. This was expected in view of only a small change in the height of the sensor.

Comparing the PDF of the experimental chord lengths with the PDF’s of the 180 bubble shapes. Once again yielded results almost identical to that obtained in Fig. 5.33 to Fig. 5.35. The best fit by the least square method did not have parity with the experimental
Fig. 5.33 (E = 32%)  
Fig. 5.34 (E = 32.43%)  
Fig. 5.35 (E = 33.1%)  
Fig. 5.33 to 5.35 Comparison of experimental and generated PDF and bubble shape  
(256 μm glass beads, t = 0.015 m, H_{in} = 0.21 m, sensor location = 0.15 m, \(U_0 - U_{mr}\) = 0.06 m/s)
Fig. 5.36 to 5.38 Comparison of experimental and generated PDF and bubble shape.

(256 μm glass-beads, t = 0.015m, H_L=0.21m, sensor location = 0.18m, (U_0-U_mf) = 0.066 m/s)
PDF. However, the next best fit which had a marginal increase in error gave an overall good match with the experimental PDF so did the third best fit as seen in Fig. 5.36 to 5.38. Thus the efficacy of this technique was established over the range of variation in sensor location.

**Case III  \( (U_0-U_{mf}) = 0.11 \text{ m/s} \)**

PDF of chord lengths were generated based on the experimental data for \( (U_0-U_{mf}) = 0.11 \) m/s for the glass bead system under otherwise identical conditions. The maximum string size obtained in the bed was 113 that resulted in \( Y_{\text{max}} \) of 22.08 cm, using bubble rise velocity of 0.39 m/s. The longest string size measured at the sensor location was 45 while the bubble rise velocity at that location was 0.38 m/s returning \( Y \) of 8.55 cm. Thus the range of the experimental chord length obtained at the sensor location was only up to 0.4 \( Y_{\text{max}} \).

![Graphs and images](https://example.com/graphs.png)

**Fig. 5.39 (E = 23.22%)**  
**Fig. 5.40 (E = 23.82%)**

**Fig. 5.39 and 5.40 Comparison of experimental and generated PDF and bubble shape**  
(256 \( \mu \)m glass-beads, \( t = 0.015 \text{m}, H_s = 0.21 \text{m}, \) sensor location = 0.15m, \( (U_0-U_{mf}) = 0.11 \text{ m/s} \))
Comparing the experimental PDF with the bubble PDF's using least square method gave best fit having error of 23.22% for a bubble shape whose PDF did not have parity with the experimental PDF hence, it was unacceptable as the representative bubble shape (Fig. 5.39). The match was tried again after eliminating this shape from the list of bubbles and once again a bubble shape was obtained whose PDF did not have good parity with the experimental PDF the range of $R_{\text{max}}$ was 0.5 while experimentally range of $Y_{\text{max}}$ was only 0.4. Thereafter the process was again repeated to match the experimental PDF with 178 remaining bubbles, it was found that even in the third time there was lack of parity, but the distributed chord length in the fifth range was lower than in the previous case hence, this PDF more or less resembled the PDF of experimental data (Fig. 5.40). Therefore this shape was chosen as the representative shape of the bubble. The difference in error was marginal in all three cases being 23.22% for best fit, 23.7% for the second best fit and 23.8% for the chosen third best fit.

5.4.3.2 Bubble shapes in resin system: effect of fluidization velocity

Case I $(U_o-U_{mf}) = 0.064 \text{ m/s}$

Experiments were performed in a 0.01 m thick bed, filled with 220 $\mu$m resin up to static bed height of 0.29 m. The sensor was located at a height of 0.21 m above the distributor. The bed was fluidized at excess gas velocities ranging from 0.064 m/s to 0.16 m/s. When $(U_o-U_{mf})$ was 0.064 m/s the maximum string size obtained in the bed was 81. This resulted in $Y_{\text{max}}$ of 15.7 cm since the bubble rise velocity was 0.39 m/s. The maximum string size measured at sensor location of 0.21 m was 38 while the bubble rise velocity at that location was 0.38 m/s returning $Y$ of 7.22 cm. Thus the range of the experimental chord length obtained at the specified sensor location for the bed thickness – particle size- velocity combination was up to 0.5 $Y_{\text{max}}$.

Comparing the PDF of the experimental data set with the PDF of the chord length distribution of 180 bubbles, it was found that the best fit by the least square method returned an error of 33.6% for the PDF of the bubble shape as reported in Fig. 5.41. It can be seen from the figure that parity was missing between the two histograms of the PDF’s, hence attempt was made to match the experimental PDF with the PDF’s of the remaining 179 bubbles. Unlike the previous cases of glass-bead system, the attempts to match PDF’s with other bubble chord lengths were not successful as can be made out from Fig. 5.42.
Subsequent trials also did not yield bubble shapes whose PDF of chord length distributions showed any resemblance of parity with the PDF of the experimental data set, although the errors were not very different from each other being 33.6% for best fit followed by 33.97% and 34.7% for the subsequent fits. Therefore, it appears that in this case the spherical cap bubble shown in Fig 5.41 that gave the least error of 33.6% is representative of the experimental data.

**Case II** \((U_0-U_{mf}) = 0.112 \text{ m/s}\)

Experimental data obtained under otherwise identical conditions but at excess gas velocity of 0.112 m/s, generated a PDF based on \(Y_{\text{max}}\) of 21.25 cm based on the maximum string size of 109 obtained in the bed with corresponding bubble rise velocity of 0.39 m/s. The longest string size measured at the sensor location of 21 cm was 53 while the bubble rise velocity at that location was 0.38 m/s, hence \(Y\) of 10.07 cm was obtained. Therefore, the range of the experimental chord lengths obtained at the specified sensor location was up to 0.5 \(Y_{\text{max}}\).

![Fig. 5.41 (E = 33.67%)](image1)

![Fig. 5.42 (E = 33.97%)](image2)

**Fig. 5.41 and 5.42 Comparison of experimental and generated PDF and bubble shape**

(220 µm resin, \(t = 0.01\text{m}, H_s = 0.29\text{m}, \text{sensor location} = 0.21\text{m}, (U_0-U_{mf}) = 0.064 \text{ m/s})
Comparing the chord length distribution PDF of the experimental data with the PDF's generated for the 180 bubble shapes, it was found that the best fit obtained by the least square method returned an error of 13.38% for the bubble shape and PDF as reported in Fig. 5.43. The lack of parity between the two histograms is obvious although the data fit was quite good. Attempts were made to once again match the experimental PDF with the remaining 179 bubbles, which resulted in identifying the bubble shape shown in Fig. 5.44 that had a PDF histogram whose parity with the experimentally generated PDF histogram was excellent, moreover the error of the data fit in this case was only 13.38%.

Another attempt was made to establish the efficacy of the fit, by matching the PDF of the remaining 178 bubbles with the PDF of the experimental data set. This attempt also resulted in a good fit with an error of only 14.1%. The bubble PDF and shape are shown in the Fig. 5.45. In this case too there is good parity between the histograms of the experimental data and matched bubble. After due consideration the spherical cap bubble of Fig.5.44 was chosen as the representative shape for the family of bubbles in view of the greater parity between the two PDF histograms.

**Case III \(U_{e}-U_{mf}=0.16 \text{ m/s} \); considering variation in sensor location**

With an idea to obtain representative bubble shapes at higher velocities, the bed was fluidized at an excess gas velocity of 0.16 m/s under otherwise identical conditions (220 µm resin, \(t=0.01m\), \(H_s=0.29m\), sensor location = 0.21m). The maximum string size obtained in the bed, at this velocity was 97. This resulted in system \(Y_{max}=18.92\text{cm}\) using bubble rise velocity of 0.39 m/s. The longest string size measured at the sensor location was 48 and the corresponding bubble rise velocity at that location was 0.38 m/s, yielding \(Y\) of 9.12 cm. Hence, the range of the experimental chord length obtained was up to 0.5 \(Y_{max}\).

Comparing the chord length distribution PDF of the experimental data set with the PDF's generated for the 180 bubble shapes, it was found that the best fit by the least square method returned an error of 17.58% for the bubble shape and PDF histogram reported in Fig. 5.46. Since there was a lack of parity between the histograms of the experimental PDF and the best-fit bubble PDF, the matching was done once again for the 179 bubble PDF's with the PDF of the experimental data. In the second case the best fit was again obtained.
Chapter 5: Imaging Of 2-Dimensional Fluidized Beds with Optical Fiber Probes

Fig. 5.43 (E = 13.38 %)

Fig. 5.44 (E = 13.38 %)

Fig. 5.45 (E = 14.1 %)

Fig 5.43 to 5.45 Comparison of experimental and generated PDF and bubble shape
(220 μm resin, t = 0.01m, H_s = 0.29m, sensor location = 0.21m, (U_0 - U mf) = 0.112 m/s)
for a bubble shape whose PDF also fitted the experimental data with the same error of 17.58%. However, the histograms of the experimental data and the bubble shape obtained in this case have high order of parity, almost resembling each other as seen in Fig.5.47.

One more trial was done to match the experimental PDF with the remaining 178 bubbles. This attempt resulted in identifying the bubble shape shown in Fig 5.48. The errors were of the order of 18.82%. Although the parity between the histograms of the experimental PDF and the bubble PDF were not as close as that obtained in the previous case but still there was good parity in terms of the range of R and Y.

Thus unhesitatingly one can state the spherical cap bubble observed in Fig.5.47 was the representative of the family of bubbles obtained at an excess gas velocity of 0.16 m/s in a 220 μm resin bed that was sensed at 0.21 m bed height above the distributor.

The results obtained were further validated by considering the effect of sensor location. Measurements made at sensor location of 0.18 m under identical conditions had the longest string size of 49, with rise velocity of 0.38 m/s it resulted in Y of 9.3 cm. Therefore in this case too the range of experimental chord length was up to 0.5Y_max. The experimental PDF of chord length is shown in Fig. 5.49 which is very similar to that observed in Fig. 5.46.

Comparing the experimental PDF of chord length with the PDF's of bubble shapes yielded the results identical to that obtained for 0.21 m sensor location. The bubble PDF that yielded the best fit with the experimental PDF, having an error of only 17.14%, did not have parity with the experimental PDF in terms of the range of R and Y. Hence eliminating this shape the match was done once again, that yielded the results shown in Fig. 5.50. Which had not only good fit with a marginal increase in error i.e. E = 18.27% but also had very good parity in terms of range of R and Y. One more attempt was made at matching experimental and bubble PDF's that yielded the results shown in Fig. 5.51 and it is apparent that although the fit for this case was also acceptable but it was inferior to that obtained in the previous case. Hence the spherical cap shaped bubble shown in Fig.5.50 was considered as the representative of the bubble shapes at 0.18 m sensor location.

These results once again confirm the efficacy of this analysis not only for changing excess gas velocities but also over the specified range of distance travelled.
Fig. 5.46 to 5.48 Comparison of experimental and generated PDF and bubble shape
(220 μm resin, t = 0.01m, H_s = 0.29m, sensor location = 0.21m, (U_0 − U_m) = 0.16 m/s)
Fig. 5.49 to 5.51 Comparison of experimental and generated PDF and bubble shape
(220 μm resin, t = 0.01 m, Hs=0.29 m, sensor location = 0.18 m, (U₀-Umf) = 0.16 m/s)
5.5 CONCLUSIONS

A novel experimental set up was designed by sandwiching a two dimensional fluidized bed between two acrylic sheets on which at one end a laser light source and on the exactly opposite end a optical fiber probe was mounted. The laser light passed through the bed when the light was not obstructed by particles thereby sensing the presence of bubbles and voids. After data acquisition and filtering by appropriate methods, the data was analyzed to get an estimate of bubble frequency under various operating conditions. Thereby the effect of excess gas velocity, bed thickness, static bed height, height above distributor and particle size on the prospective bubble size was established.

An algorithm was developed to estimate the bubble size distribution was developed and the effect of various operational and design parameters on the bubble size distribution was established. Further a algorithm was developed to estimate the bubble shape and size that was likely to represent all the bubbles for a set of parametric conditions in the fluidized bed. This method was established to estimate the size and shape of the bubble that best represented the experimental data for 256 μm glass bead and 220 μm resin considering not only the effect of fluidization velocity but also changes in the measurement location.