‘Fluidization’ has been an important Gas-Solid contacting technique, with wide spread application for over the past nine decades. The major milestones in the commercial journey of fluidization has been Winklers coal gasification process 1922, Fluidized catalytic cracking 1942, Sohio process for acrylonitrile production 1969, Synthesis of polyolefines by Unipol process 1984. In addition to its numerous applications as a reactor, fluidized beds are also widely used for drying, granulation and coating applications. Currently, the processes developed for industrial production of carbon nano tubes use fluidized beds.

In spite of its great commercial application and the enormous amount of research put in this area, fluidization still remains more of an art. The complexity of the fluidized state defies precise analysis. Although considerable amount of information has been obtained over the years and the structure of fluidized state has been widely explored, but still a deep uncertainty persists in the level of understanding of fluidized systems. It is this uncertainty that motivates investigators in this area to develop newer tools and techniques to gather information and attempt greater understanding of the fluidized state. The motivation for this work has also been to acquire an understanding of the fluidized state by gathering information on freely bubbling Gas-Solid fluidized beds using non-intrusive as well as intrusive techniques. The Thesis is presented in seven Chapters. The first Chapter ‘Introduction’ details the motivation and scope of this work.

Chapter 2 ‘Literature Survey’ presents the key ideas of fluidization, bubble properties and their predictive correlations, measuring techniques and tools used in fluidization research. The classification of particles based on the Zenz and Othmer plot and the Geldart plot are discussed. The conceptual understanding of bubbling fluidized bed including the two-phase theory developed by Toomey and Johnstone (1952) and its numerous modifications are detailed aspects of particle dynamics and its measurement are also surveyed.
Concepts of bubble dynamics with a summary of the principle differences between the various theoretical analysis are presented. It appears that even today the Davidson and Harrison's (1963) model is perhaps the best accepted treatment for bubble dynamics and is widely used for modeling bubbling fluidized bed systems.

Accurate predictions of bubble properties is essential for successful design and scale up of fluidized bed systems. Hence, the predictive correlations for bubble diameter and bubble rise velocities are surveyed. In literature there exist numerous correlations to predict the bubble size in 2-dimensional as well as in 3-dimensional beds, the summary of these correlations with their range of parametric variations are presented. However, it was found that the efficacy of these correlations are not yet established. Same is the case with the correlations developed for bubble rise velocity which are widely used in design but their efficacy is not yet fully established. Features of bubble coalescence, bubble splitting and their effect on bubble size, bubble density and bubble rise velocity are also surveyed. Aspects of slugging in freely bubbling beds with different type of particles and the mechanism of slug formation are also discussed.

The various measuring techniques and tools developed in the last five decades and widely used to study the hydrodynamic features of Gas-Solid fluidized beds are surveyed. Broadly the measuring techniques have been classified as intrusive and non-intrusive techniques. The intrusive techniques include optical sensors, capacitance probes, inductance and impedance probes, pressure sensors etc. The features of these devices and their relative performance in determination of bubble properties have been surveyed. Non-intrusive techniques such as photographic, X-ray, v-ray technique have also been surveyed and compared. Summary of the existing techniques for measuring bubble properties have been presented in a tabular form.

Detail literature survey revealed the following:

i. The 2-D fluidized bed is the most convenient device for investigation of bubble size and behavior. Since the ambiguity of identification of the size and shape of the bubbles is considerably reduced.

ii. Digital photography of bubbling phenomena is the easiest and cheapest technique currently available to fetch information on bubbling beds.
iii. Precise determination of bubble boundaries even in 2-D beds using digital imaging techniques is still problematic.

iv. There is dearth of information and data on pattern formation in 2-D fluidized beds.

v. Non-invasive techniques for the determination of bubble size distribution have not been developed.

vi. Identification of bubble coalescence and slugging phenomenon using pressure fluctuation data has not yet been reported.

Chapter 3 ‘Materials and Methods’ describes the constructional features and detailed dimensions of each component of the experimental set-up and details the physical properties of the particles used in this study.

Four different sized rectangular beds made of 0.004 m Perspex sheets were used in this study. All the units were of 0.78 m height and a width of 0.1 m. The thicknesses of these units were different and had dimensions of 0.005 m, 0.01 m, 0.015 m and 0.03 m respectively. Woven fabric cloth was used as a gas distributor. The large porosity of the fabric lead to uniform distribution of gas throughout the cross-section of the bed, which resulted in excellent quality of fluidization.

A wide spectrum of particles belonging to Geldart group A, B and D were selected for this investigation. While resin, glass-beads and mustard could be considered as spherical particles, sand was the irregular shaped particle used. Fresh FCC catalyst was the only group A particle investigated, other particles were mostly group B and group D. Resin and glass-beads particles were available in three sizes, while sand and mustard in two different sizes. Thus ten different particles sizes were investigated.

Minimum fluidization velocity of the particles were determined experimentally and compared with the predictions from Ergun’s equation that showed close agreement.

Chapter 4 ‘Digital imaging of 2-dimensional fluidized beds’ is a videographic study of bubbling phenomena and pattern formation in 2-dimensional freely bubbling Gas-Solid
fluidized beds. A Sony make video camera equipped with Carl Zeiss Vario-Tesser lens with 25 mm diameter filter, 10 x (optical) and 120 x (digital) zoom with focal length of 46 – 480 mm for movies and 38 – 380 mm for still images having 6,90,000 effective pixels for movie was used as a tool to image the bubble and gather relevant information such as bubble size, bubble rise velocity, bubble coalescence and bubble splitting, slugging, bed density and bed expansion from them. The color images of the bubbles obtained were converted to Black and White images using the RGB color model. Threshold RGB values were optimized for each particle to determine bubble boundaries precisely and in each frame bubbles were tagged. The bubble size in terms of ‘d_x’ and ‘d_y’ were measured and corresponding volume mean surface diameter was evaluated for all the bubbles.

The influence of various design and operational parameters on bubble size were studied. It was observed that bubble sizes increase with an increase in excess gas velocity and height above the distributor. Lower static bed heights yield larger sized bubbles. Increasing thickness of beds, lead to a decline in bubble sizes. Denser particles yield smaller sized bubbles in comparison to the lighter particles having the same size and fluidized at nearly identical conditions. Smaller sized particles form larger bubbles when fluidized under identical conditions. Bubble size ranges (d_{min}-d_{max}) vary widely in thin beds with increase in excess gas velocity. The increase in ‘d_y’ is particularly prominent. As bed thickness increases the range of variation of bubble size with an increase in excess gas velocity becomes narrow.

An attempt was made to determine the geometrical features of the bubbles from its shape, its aspect ratio and perimeter for resin and sand system. The shapes of the bubbles formed with resin, as well as sand were predominantly elliptical. With increase in resin particle size there was a decline in the ellipsoidal shaped bubbles and a corresponding increase in the irregular shaped bubbles. Irregular shaped bubbles occurred more in sand system. Bubble aspect ratio increased with increase in the excess gas velocities. Wake angle variation was random with sand but orderly with resin.

The efficacy of twelve correlations for bubble size predictions were assessed by comparing their predictions with the experimentally obtained bubble sizes for all different types and size of the particles. It was observed that not a single correlation was good enough to fit the entire data.
The bubble sizes formed with lighter particles were best predicted by the Denton-II (1977)
correlation \[ d_b = \frac{8(2^{3/4} - 1)(U_o - U_{mf})}{\lambda g \left( \pi(2^{3/4} - 1) A \right)} \] over a wide particle size range. This correlation predicted data obtained for both the resin and mustard system with an absolute error of 23%.

The Park (1969) correlation \[ d_b = 33.3d_p^{1.5} \left( \frac{U_o}{U_{mf} - 1} \right)^{0.77} \] predicted the bubble diameters of 250 \( \mu \)m sand system in 0.01m thick bed with an absolute error of 29.26%, all other correlations returned far greater error values.

Werther (1978) correlation \[ d_b = 0.853 \left[ 1 + 0.272(U_o - U_{mf}) \right]^{0.3} \times \left[ 1 + 0.0684(h + h - d_{br}) \right]^{0.21} \] gave the best fit for the entire range of glass-beads in 0.015 m thick beds, with an absolute error of 38.8%. It was observed that the smaller diameters were over predicted by the correlation while the larger diameters were under predicted.

Kato and Wen (1969) correlation \[ d_b = 1.4 \rho_p d_p \left( \frac{U_o}{U_{mf}} \right) h + d_{br} \] predicted the height-bubble diameter profile closely for resin particles. The correlations by Geldart and Darton-II could also predict the trend of bubble diameter but with considerable deviation.

Bubble rise velocity \( U_{br} \) were calculated by determining the change in the bubble centroid position in consequent images. It was observed that bubble rise velocities increase with increase in excess gas velocity \( U_o - U_{mf} \). It was observed that the well established Clift (1985) correlation \[ U_{br} = 0.71(gd_p)^{1/2} \] did not fit the data well. While, the Clift, Grace and Weber (1978) correlation \[ U_{br} = 0.35(gd_p)^{1/2} \] for slugs fitted the data moderately well.

The correlation developed by Al-Zahrani and Daous (1996),

\[
U_{br} = \frac{1}{\alpha} \left[ \frac{(1-\varepsilon_s)H_s g(2-\varepsilon_{mf})}{3\varepsilon_{mf} (1-\varepsilon_{mf})} \right]^{1/2}
\]
and by Gera and Gautam (1995),

\[ U_{br} = K(ga^*)^{1/2} \]

were also used to predict the bubble rise velocities, it was found that both the above mentioned correlations closely predicted the bubble rise velocity in a bed of mustard.

Static bed height was found to have a pronounced effect on bed expansion particularly for dense large particles. Bubble densities were found to increase with an increase in excess gas velocity and decrease with an increase in static bed height. Bubble densities were found to increase during coalescence of bubbles.

Various patterns and transient structures were observed in freely bubbling Gas-Solid fluidized beds. The channeling, draining, absorbing types of bubble coalescence were observed. Different types of slugs viz. ‘round nose’ and ‘square nose’ were observed in the course of investigations. Transient structures such as cavities as well as clusters were also observed in the bed.

Chapter 5 ‘Imaging of 2-dimensional fluidized beds with optical fiber probes’ presents a unique, continuous and non-intrusive experimental technique using LASER as a light source to fetch information of bubble sizes in terms of chord lengths measured digitally at high frequency rates of 200 data/second. To achieve this, an experimental set-up was designed by sandwiching the 2-dimensional fluidized bed within two plates. The laser light source was fixed on one of the plate and at the opposite end, in the other plate, an optical fiber probe was fixed. The light emitted from the source passed through the bed and was in turn collected by the optical fiber probe when not obstructed by the particles in the bed.

A bubble when it crosses the sensing location allowed light to pass through the bed which records the presence of the bubble, but when the emulsion phase existed at the sensing location light could not pass through and the absence of bubble was recorded. From this
information bubble frequency, bubble size distribution and probable bubble shape were inferred.

Bubble frequency \( f = \frac{n}{t} \) increased with an increase in the excess gas velocity and decline in static bed heights. Bubble frequency varied randomly with particle size, it was found to be more with 350 \( \mu \)m sand in comparison with 250 \( \mu \)m sand. However, with mustard the dependency on particle size was different and it was more with 1002 \( \mu \)m mustard than 2084 \( \mu \)m mustard.

The probability distribution function (PDF) of chord lengths is given as:

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

The PDF of chord lengths was used to develop histograms of frequency vs chord length. The effect of various design and operational parameters on bubble size distribution was analyzed. It was observed that increase in excess gas velocity increases the size of the bubbles and also changes the pattern of chord length distribution. Effect of bubble coalescence and splitting were identified. The bubble size distribution narrowed down with an increase in static bed height. Further, slender beds had a wider size distribution than thick beds due to the directional bias for bubble growth in thin beds.

The probable bubble shape and size of the bubble were also identified for given conditions. To attain this objective 180 plausible bubble shapes were identified taking clue from the bubble aspect ratio variations observed in Chapter 4. Probability distribution function (PDF) of chord length distribution of these 180 bubbles was generated and compared with experimental chord length distribution PDF’s. The matching chord length distributions with minimum error were considered as the representative shape of the bubble.

Chapter 6 presents ‘Pressure fluctuation analysis of 2-dimensional fluidized beds’. In this work, absolute pressure fluctuations at different axial locations were measured using
piezo-electric pressure transducer. Approximately 9000 data points were sampled for each run. Using the pressure time series data the transition from bubbling to turbulent fluidization was identified using state-space analysis, which includes state-space properties such as Kolmogorov entropy, maximum Lyapunov exponent and Correlation dimension. These properties were plotted against different \( \left( \frac{U_o}{U_{mf}} \right) \) values for different particle systems. The change in pattern of these plots indicated a transition from bubbling to turbulent fluidization.

It was observed that the transition velocity passes through maxima as the measurement height increased. Transition velocity increased with increase in particle density as well as with an increase in particle size. Two distinct transition peaks were observed when 150 \( \mu \text{m} \) size fresh FCC catalyst was fluidized in 0.03 m thick bed. This particular case was unique in view of the fact that the ratio of bed thickness to particle diameter was 200, i.e. in the domain of 3-D fluidization.

An attempt was also made to determine the bubble size by decomposing the pressure time series into two components the incoherent component (IOP\(_{xy} \)) (consisting of local bubble passages or local fluctuations) and coherent component (COP\(_{xy} \)) (mainly due to bubble coalescence, bubble generation, bubble eruption etc). The incoherent component (IOP\(_{xy} \)) of the power spectrum was analyzed and its standard deviation \( (\sigma_{xy,i}) \) was determined. The standard deviation was related to the bubble diameter using the following equation:

\[
\frac{\sigma_{xy,i}}{(\rho_p g (1-e_{mf}))} = \frac{1}{2} d_b
\]

The bubble size for 460 \( \mu \text{m} \) glass-beads, 450 \( \mu \text{m} \) resin and 350 \( \mu \text{m} \) sand were determined by this method and it was in fair agreement with the bubble size obtained by digital video imaging technique.

Chapter 7 ‘Summary and Conclusions’ summarizes the main conclusions of the Thesis. This work has been able to provide a rationale frame work based on data of over 65000 bubbles to adjudge the most reliable correlations in existence for the prediction of bubble
size and bubble rise velocities using digital image analysis techniques. Further, using optical imaging technique not only information on bubbling rates but also the size distribution of bubbles could be assessed. Importantly the concept of ascertaining a bubble shape as the representative of a family of bubbles introduced in this work could make important contribution in the design of fluidized bed system. The establishment of close parity in the bubble sizes obtained from pressure analysis and video imaging is highly encouraging, since it provides an opportunity to get an idea of bubble sizes in actual industrial units.

This Chapter also highlights the scope and opportunities for future work on bubbling Gas-Solid fluidized beds.

**Nomenclature**

- $a^*$: Bubble size coefficient, $a^* = \left[ \frac{1}{(1-e^2)^{1/2}} \left( \frac{A_o}{\pi} \right) \right]^{1/2}$
- $A_o$: Area of orifice (m)
- $d_x$: Largest distance based on x-axis (m)
- $d_y$: Largest distance based on y-axis (m)
- $d_b$: Area equivalent bubble diameter (m)
- $d_{so}$: Initial bubble size (m); $d_{so} = \left( \frac{6G}{\pi} \right)^{0.4} \left( \frac{g}{0.2} \right)^{0.2}$
- $d_p$: Diameter of the particle (μm)
- $f$: Frequency of bubble (sec$^{-1}$)
- $g$: Gravitation constant (m/s$^2$)
- $G$: Volumetric flow rate of gas (m$^3$/s)
- $h$: Height above distributor (m)
- $H_s$: Static height of the solid material (m)
Bubble rise velocity coefficient, $K = \frac{(1-e^3)^{1/2}}{1+(1-e^3)^{1/2}} \left[ \frac{\theta_s - \sin(\theta_s) \cos(\theta_s)}{\pi} \right]^{1/4}$

n Number of bubble occurrence (-)

t Time (sec)

$T$ Bed thickness (m)

$U_{br}$ Rise velocity of a single isolated bubble (m/s)

$U_{mf}$ Minimum fluidization velocity (m/s)

$U_0$ Superficial gas velocity (m/s)

$Y_i$ Chord length (cm)

$\varepsilon_{mf}$ Minimum bed voidage (-)

$\varepsilon_s$ Bed voidage at static bed height (-)

$\lambda$ Bubble size correlation constant

$\theta_w$ Wake angle (degree)

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

$\sigma_{xy,i}$ Standard deviation of the incoherent pressure fluctuations (Pa)

References


