CHAPTER II
BACKGROUND AND LITERATURE SURVEY

2.1 Background

Gas-solid fluidization is an operation by which fine solids are transformed into a fluid-like state through contact with a gas. At low gas flow rates, the fluid merely percolates through the void space between stationary particles. As the flow of the gas increases through the bed of the particles, it eventually reaches a condition at which the particles are lifted out of permanent contact with one another, which is called incipient fluidization. Beyond this point the flow causes the bed expansion and the gas-solid characteristics exhibit as an ordinary liquid; its upper surface level is horizontal when the apparatus is tilted, and it hardly impedes the movement of objects floating on the surface. The rapid movement of particles in the bed results in an improvement of the heat transfer rate. Uniformity of temperature, rapid mass transfer and rapid mixing of solids account for the great utility of fluidized beds in process applications.

For a gas-solid fluidized bed in which the gas velocity is greater than the minimum fluidizing velocity, some parts of gas pass through the bed as bubbles that burst when they reach the top surface of the bed. From this behavior, the bed is in a state of aggregative fluidization, which usually occurs when a gas fluidizes solid particles. The bubbles agitate the bed, and its height fluctuates as the bubble break through the surface (Davidson and Harrison, 1963).

2.1.1 The Two-Phase Theory of Fluidization

A model of aggregative fluidization is set up by considering a bed as a two-phase system. The system consists of a particulate phase, in which the flow rate is at incipient fluidization, and the bubble phase, in which all fluid beyond that required for incipient fluidization passes through the bed. The theory appears to be reasonable for fluidized systems whose behavior is largely characterized by random bubbles. Thus the theory is not directly applicable to beds exhibiting extensive channeling, spouting, or pneumatic transport (Davidson and Harrison, 1963).

The gas flow pattern depends on the rise velocity of the bubble and the incipient interstitial gas velocity (minimum fluidizing velocity divided by the void fraction of the bed). For slow moving bubbles or small bubbles, the bubble rise velocity is less than the incipient interstitial air velocity. Gas enters the bottom of the bubble and leaves at the top. There is an excellent interchange of gas between the bubble and the particles. For fast moving bubble or large bubble, the bubble rise velocity is higher than the incipient interstitial gas velocity. Gas moves around and returns to the bubble. The region around the bubble penetrated by circulating gas is called the cloud. The rest of the gas in the bed does not mix with this re-circulating gas. The fluid interchange between the bubble and the particles is limited to a small zone in the vicinity of the bubble. To consider the effect of the bubbles in the fluidized bed, the characteristics of the bubbles are observed fluidization (Kunii and Levenspiel, 1977).

2.1.2 The Rise Velocity of a Single Bubble

The bubbles generated in the gas-solid fluidized bed have two characteristics; rising at a finite velocity and growing in size as they move up through the bed. In a liquid of small viscosity, inertial forces, surface tension, and viscous effects are negligible when the large bubble rises. Because the shape of the bubble is determined by the outside flow, the shape adjusts itself so that the pressure in the bubble is constant, and the density of the gas within the bubble is small. To obtain the rise velocity in the fluidized bed, the behavior of the bubble rising through an inviscid liquid is approximated when viscosity, inertial forces, and surface tension effects are unimportant and the pressure in the bubble is constant. The velocity is obtained by satisfying Bernoulli's equation near the frontal stagnation point. This procedure gives the rise velocity of the plane bubbles between infinitely wide parallel plates in an infinite liquid; the rise velocity is found to be proportional to the square root of its radius of curvature,

$$U_{b,\infty} = 0.5(ga)^{1/2} \tag{2.1}$$

where:

$U_{b,\infty}$	=	rise velocity of bubble in infinite fluid
g	=	acceleration of gravity
a	=	frontal radius of curvature of bubble

In a two-dimensional fluidized bed, the bubbles are rarely circular but they are elliptical with the major vertical axis that is twice as large as the minor horizontal axis. The wake fraction is constant in the two-dimensional fluidized bed and approaches zero. The resistance to the bubble motion is large because of wall effects, so the rise velocity in the bounded fluid is slower than one in a fluid of infinite extent. The average bubble size increases quite rapidly with the bed height as a result of coalescence. It also increases due to the overall gas expansion. Although the pressure decreases with the bed height, it is a small effect except with the very dense particles or a very low overhead pressure. The rise velocity tends to increase as the particle size decreases and associate with the wake fraction. The rise velocity reciprocally related to the drag coefficient representing the retarding force opposing the bubble motion.

2.1.3 The Volume of the Bubble Formed at an Orifice

The formation of the bubbles is one of the most characteristic phenomena of the fluidized beds. Therefore, accurate predictions of the bubble characteristics such as the size distribution and the bubble frequency depend on the initial bubble formation at the gas distributor. The characteristics of the bubbles are observed by forming a bubble at the orifice. As the bubble rises, it accelerates the surrounding liquid. Although a bubble has essentially zero density, it has an effective mass because any bubble motion also causes the surrounding liquid to move. The momentum balance for estimating the bubble volume detaching at the orifice is defined by balancing the buoyancy force against the rate of increase of effective momentum of the liquid surrounding the bubble. We assume that the gas flow rate is constant so that it is independent of the pressure in the bubble. Since the surface tension and the inertia are insignificant (Wilkes, 1999), the volume of the bubble depends only on the gas volumetric flow rate,

$$V_b = \left(\frac{16}{\pi T}\right)^{1/3} \frac{G^{4/3}}{g^{2/3}} \qquad (2.2)$$

where:

V_b = bubble volume

T = bubble thickness

G = gas flow rate

Many unique properties of fluidized beds are related to the bubble behavior. To consider no gas leakage during the bubble formation, the departure time, t_b, depends on the gas volumetric flow rate, and the frequency of the bubble formation, n_b, reciprocally relates to the departure time.

$$t_b = \left(\frac{16\,G}{\pi g^2 T}\right)^{1/3} \tag{2.3}$$

$$n_b = \frac{1}{t_b} \tag{2.4}$$

2.1.4 The Rise Velocity of a Continuous Swarm of Small Bubbles

By increasing the gas flow rate through the bed above the minimum fluidizing velocity, the bed expands when the bubbles are produced at the holes on the distributor. The phenomenon of the bed expansion occurs because the bubbles form and pass through the bed to increase the total volume of the bed. Assuming that the gas flow rate above that needed for incipient fluidization passes through the bed as bubbles, the rise velocity of continuously generated bubbles is:

$$U_c = \frac{G}{A} - U_{mf} + U_b \tag{2.5}$$

where:

U_c = rise velocity of continuously generated bubbles

A = cross-sectional area of the fluidized bed

U_{mf} = minimum fluidizing velocity

U_b = rise velocity of the single bubble in bounded fluid

The rise velocity of continuously generated bubbles is augmented by an upward flow of the gas above that needed for incipient fluidization (Harrison and Davidson, 1971). Because the bubbles occupy space in a bubbling fluid bed, the bed expansion becomes a function of both the bubble velocity and the volume of the gas entering the bed,

$$\frac{U_b}{G/A - U_{mf}} = \frac{h_0}{h - h_0} \tag{2.6}$$

where:

h = bed height

h_0 = bed height at incipient fluidization.

From Equation 2.6, the rise velocity of a single bubble or the equivalent bubble diameter is estimated by measuring *h* as a function of *G/A*. This equation is used to describe the bubble size in gas-solid systems if the bubbles are randomly generated and the interparticle forces are negligible.

2.2 Literature Survey

The available area of the liquid flow passing a plane bubble between infinite plates is unlimited, so the geometry of the infinite plate was reduced from the three-dimensional to the two-dimensional infinite case. In the two-dimensional case, Maneri and Mendelson (1968) showed that the rise velocity of bubbles in an infinite medium for deep inviscid liquids was

$$U_{b,\infty} = \left[\frac{\pi\sigma}{(2+\gamma)\rho} + \frac{g\, r_e (2+\gamma)}{\pi}\right] \tag{2.7}$$

For large bubble volume and small spacing, $\gamma = T/r_e$, $\gamma \rightarrow 0$ and the surface tension term was negligible so that Equation 2.7 became

$$U_{b,\infty} = 0.5642 (g\, D_e)^{1/2} \tag{2.8}$$

where:

D_e = equivalent diameter of the cylindrical bubble that is the same bubble volume as the irregular bubble from the experiment

r_e = equivalent radius of the cylindrical bubble that is the same bubble volume as the irregular bubble from the experiment

ρ = liquid density

σ = surface tension

The rise velocity of the plane bubbles between infinitely wide parallel plates in an infinite liquid is proportional to the square root of its radius of curvature. The rise velocity of bubble in a bounded liquid approaches one in infinite fluid, when the bed size is larger than the bubble diameter.

To consider the gas leakage during the bubble formation, Zenz (1968) assumed that there was gas leakage from the bubble and the superficial air leakage velocity at the bubble boundary equals to the superficial minimum fluidizing velocity according to the two-phase theory of fluidization. The mass and momentum balances of the gas were used to investigate the process of bubble formation. For the case of the circular bubble formation and constant fluid density, the mass balance of gas was:

$$\frac{d}{dt}(V_b) = G - U_{mf} A_b$$

or

$$\frac{d}{dt}\left(r_b^2\right) = \frac{G}{\pi T} - 2U_{mf}\, r_b \tag{2.9}$$

and the momentum balance was:

$$\frac{d}{dt}\left[V_b\left(\frac{ds}{dt}\right)\right] = V_b\, g$$

or
$$\frac{d}{dt}\left[r_b^2\left(\frac{ds}{dt}\right)\right] = r_b^2 g \tag{2.10}$$

where:

r_b = bubble radius

s = distance between the bubble and the orifice.

The bubble diameter and the detachment time were obtained by simultaneous numerical integration of Equations 2.9 and 2.10, and the condition of the bubble detachment was imposed at $s = r_b$. The bubble diameter from the calculation is lower than the bubble diameter from Equation 2.2 due to gas leakage through the bubble formation. The overall gas volumetric leakage from the bubble, Ω, was calculated from:

$$\Omega = Q t_b - V_b \tag{2.11}$$

and the percentage of air leakage was

$$\Omega = \frac{Q t_b - V_b}{Q t_b} \times 100\% \tag{2.12}$$

Nguyen and Leung (1972) considered the leakage of gas into particular phase during the process of bubble formation by injecting air through an orifice to an incipiently two-dimensional fluidized bed of alumina particles. They correlated their observed bubble volumes with inlet gas flow rate and frequency of the bubble formation, n_b, as:

$$V_b = 0.53\frac{Q_{or}}{n_b} \tag{2.13}$$

where Q_{or} was the volumetric gas flow rate through the orifice. They found that the bubble formation frequency varied with increasing Q_{or} and indicated 47% of the gas leaked during the process of the bubble formation. Yates *et al.* (1984) explained that the high flow rates of gas leakage from a bubble during its formation at an orifice led to considerable deviations from the ideal two-phase theory of fluidization.

Because some gases entering the bed do not form bubbles, gas channeling occurs and bubbles coalesce in the system. A method for considering the bubbles at the different gas flow rates was offered by Cranfield and Geldart (1974) to estimate bubbles generated in the system. They measured the volumetric bubble flow rate, Q_b, at the surface and related it empirically to the bed height, h, and the gas flow rate in excess of the minimum bubbling superficial gas velocity, $(U\text{-}U_{mb})$:

$$\frac{Q_b}{A} = 0.363\left(U - U_{mb}\right)^{1.17} h^{0.09} \quad (\pm 22\%) \tag{2.14}$$

where:

Q_b = Volumetric bubble flow rate

U_{mb} = Minimum bubbling velocity.