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AN INVESTIGATION INTO THE INFLUENCE OF SUSPENDED
GLASS PARTICLES ON BUBBLE DIAMETER, GAS HOLDUP, AND
INTERFACIAL AREA IN AN AGITATED TANK

By

PAUL M. RANDALL

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Science
in
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UNIVERSITY OF RHODE ISLAND

1985

MASTER OF SCIENCE THESIS

OF

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1985

ABSTRACT

An investigation into the influence of suspended glass particles on bubble diameter, gas holdup, and interfacial area in an agitated tank.

(May, 1985)

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Directed by: Dr. Donald J. Gray

Design of three-phase, gas-slurry, reactors is of continual interest and intrigue to the chemical engineer. The interest stems from the importance of gas-slurry reactors in the chemical, biochemical, and pharmaceutical industry. The intrigue is in the unknown (or poorly understood) relationships among key design variables that are potentially important to developing truly optimum equipment.

Developing methods for a more rational design of an agitated gas-slurry reactor requires experimentation. Without preliminary experimentation it is almost impossible to determine bubble diameter and gas holdup. Design and scaleup of gas-slurry reactors are based on mass transfer

rate models which require knowledge of the average bubble size and volume fraction occupied by the gas in the dispersion. To date, there is very little information on the effect of solids on bubble size in gas-slurry reactors.

An investigation was conducted to determine the influence of suspended glass particles on bubble diameter, gas holdup, and interfacial area. The experiments were conducted in a 45.72 cm diameter flat bottom plexiglass tank. A new measuring technique was developed to determine local gas holdup and bubble sizes using the light transmission method. Interfacial area can then be calculated by using the well known relationship $a = 6 \phi G/D_B$.

Consistently, experimental results show significant decreases in bubble diameter, gas holdup and correspondingly a decrease in interfacial area with the initial addition of 25 μ m glass particles (0.3 wt %). When more solids are added (0.6-1.2 wt %), further decreases are observed but not in the same order of magnitude decreases as the initial addition of solids. Overall, gas holdup decreased by 10-40%, mean bubble size decreased by 5-20%, and interfacial area decreased by 6-23%.

The results are interpreted in terms of more bubble coalesces taking place with particles versus no solids so that bubbles are larger, faster rising which would reduce the gas holdup. The fact that the bubbles are also smaller appears to be due to the reduction in the gas holdup since all the data can be correlated together into one equation.

Larger particles ($70\mu\text{m}$, $200\mu\text{m}$) are observed to have little effect on holdup or bubble size and tend to move more independently from the liquid.

Linear correlations of the data resulted in some dependences of the bubble diameter which agree with work of Shinnar and Calderbank in the coalescence controlled regions.

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NOMENCLATURE

a	local interfacial area per unit volume of dispersion, cm^{-1}
b	baffle size, cm
d_o	diameter of orifice, cm
D	diameter of agitator, cm
D_B	bubble diameter, cm
H_A	distance of the agitator from the bottom of the tank, cm
H_L	height of the liquid, cm
N	rotational speed of agitator, RPM
N_A	Q/ND^3 , Aeration number, dimensionless
P_o	mechanical power transmitted by the agitator in the liquid only, $\text{Ft-lb}_F/\text{sec}$
P_G	mechanical power transmitted by the agitator in an aerated medium, $\text{Ft-lb}_F/\text{sec}$
q	height of agitator blades, cm
Q	gas feed rate, Ft^3/min
r	radius of tank, cm
T	diameter of tank, cm
V_s	superficial gas velocity relative to the cross sectional area of the tank, cm/sec
V_t	velocity of ascent of a gas bubble, cm/sec
V	liquid volume, cm^3
k_L	liquid side mass transfer coefficient, cm/sec

GREEK LETTERS

μ_G

dynamic viscosity of the gas, cp

μ_L

dynamic viscosity of the liquid, cp

ρ_G

mass density of the gas, gm/cc

ρ_L

mass density of the liquid, gm/cc

σ_L

liquid surface tension, dynes/cm

ϕ_G

overall gas holdup, volume fraction of gas

ϕ

local gas holdup, point volume fraction of gas

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CHAPTER I

INTRODUCTION

Many chemical processes involve the dispersion of a gas in a liquid in which a solid phase is maintained in suspension. An easy way to achieve such a dispersion is to bubble the gas into the liquid slurry through one or several orifices placed under a mechanical agitator. Mechanical agitation disperses the gas phase, increases the contact time of the bubble with the liquid slurry, can increase the heat transfer with the wall or coil, and can maintain the solid phase completely suspended.

In many applications the solids are finely divided and generally fall into one of the following five categories: (1) Gas absorption into slurries, usually with some kind of chemical reaction; (2) precipitation of a solid resulting from absorption of a gas into a liquid; (3) slurry absorption of gases; (4) slurry adsorption of gases; and (5) slurry sorption of gases. A brief description of these processes and the influence that solids has on the physical characteristics are described below to demonstrate the diverse nature of slurry reactions.

1. Gas Absorption into Slurries, with Chemical Reaction

The chemical, biochemical and pharmaceutical industries often encounter this type of slurry reactor. The

solid in suspension can behave as a reactant, a catalyst or a catalyst carrier.

When the solid behaves as a reactant, absorption of a solute gas followed by a chemical reaction with the suspended solid is quite common. Some examples of the solid behaving as a reactant are the carbination of lime slurries (Shreve, 1956); absorption of sulfur dioxide into milk or lime as in the paper industry or water slurries of lime or limestone to remove SO_2 from furnace gases (Mallette, 1955); chlorination of paper pulp (Shreve, 1956); aerobic fermentation (Blakeborough, 1967, Peppler, 1967); aeration of activated sludge in sewage treatment (Eckenfelder, 1963); and absorption of CO_2 in thermal coal solvation with associated products and byproducts. Ramachandran and Sharma (1969), Uchida et al (1975), Uchida and Wen (1977), Sada et al (1977a, 1977b, 1977c), Tsao and Kempe (1960), Bennette and Kempe (1964) and Tsao et al (1972) all have looked at this type of system.

For the reactant solid, it has been found that the rate of absorption is considerably higher for small particles, that is smaller than the gas-liquid diffusional film thickness (Uchida et al, 1975). For large particles (diameter greater than the liquid film thickness) Sherwood and Farkas (1966), Satterfield (1970), and Zaidi et al (1979) indicates that the resistance in series concept works well for the system. For example,

Sherwood and Farkas analyzed the hydrogenation of methyl styrene and cyclohexane using 55mm and 30mm size palladium black as a catalyst respectively. For the hydrogenation processes, the gas dissolution, diffusion, reaction in series model would apply.

Solids can also behave as catalyst. The addition of activated carbon to a gas-liquid system showed increases in k_L (Alper et al 1980, Wichtendahl (1978) and Kars et al (1979) therefore indicating that solids can act as a transporting mechanism thereby enhancing the mass transfer rate.

Solids behaving as catalysts carriers are necessary especially in the fermentation industry. Enzyme immobilization by absorption onto solid particles allow recovery and reuse of the enzymes which is less expensive than generating new enzymes. The influence that these solids have on the transfer and reaction steps would be similar to when solids act as catalysts directly.

2. Precipitation of Solids Resulting from Absorption of a Gas

Several of the processes for absorbing SO_2 or HS are of this type. Examples are the Townsend process where HS is absorbed into a solution of SO_2 in Diethylene glycol resulting in precipitated sulfur (Kohl and Riesenfeld, 1974) or in the Citrex process where SO_2 is absorbed in a buffered citrate process and then

countercurrently contacted with HS to precipitate sulfur (Vassan, 1975).

In the above mentioned processes, the precipitated sulfur is of micron size. It is suggested that the solids coat the gas bubbles and act as a barrier to mass transfer of the gas phase. Also the particle barrier may reduce k_L considerably.

3. Slurry Absorption of Gases

This type of operation is commonly found in the air pollution control industry in which a solute gas is removed from a gas mixture by absorption into a slurry. The controlling step is the rate of absorption of the gas into the liquid phase. The solids are usually inert. An investigation by Lee et al (1982) indicated that the rate of absorption of CO_2 into a carbonate-bicarbonate solution dropped 20-30% of the rate without solid particles. The solid particles were inert glass beads of sizes 41-109 μm . The results were explained in terms of particles blocking the diffusive mass transfer and damping the turbulence in the system causing increases in bubble size and decreases in gas holdup.

Other studies of this type of operation are by Joosten et al (1977) and Schmitz et al (1982) who indicated little influence on gas-liquid interfacial area with moderate solids concentration.

4. Slurry Adsorption of Gases

This operation is commonly used in purifying

gaseous streams. Resistance to mass transport through the liquid phase near the gas bubble to near the particle is negligible for agitated slurries. This was confirmed by experimental studies (Kolbel and Siemes (1957); Siemes and Weiss (1959)). So the predominate mass transfer mechanism is the adsorption of the gas by the solids. Mehta and Calvert (1967) found that the adsorption capacity could be as high as that for the dry particles.

In this case, it is better to adsorb the gas into slurries because it is easier to handle for continuous operation and regenerating adsorbing sites. Misic and Smith (1971) studied a similar type of system where adsorption capacities of aqueous slurries of carbon particles were established for benzene.

5. Slurry Sorption of Gases

The combined process of absorption and adsorption is called "sorption". Slurry sorption studies has been reported since 1951 (Munemori, 1951; Nagy and Dezso, 1959, Nagy and Schay, 1958; Pozin et al, 1957; Tibor et al 1956).

The investigation of gas-liquid-solid agitated systems is complicated by the lack of understanding of gas-liquid agitated systems. Although there has been an effort to unify the results for both gas-liquid and gas-liquid-solid contactors, great confusion remains. To date, little is available in the literature as to the influence particle

properties have in relation to gas holdup, bubble diameter or gas-liquid mass transfer rates.

There have been some investigations (Lee et al (1982), Kohl et al (1974), Vassan (1975), Ching (1983) of the effect of suspended solids on the mass transfer rates in slurry reactors. However, no models have been developed to systematically predict the bubble size distribution. Mass transfer data requires some knowledge of the bubble surface areas in terms of the distribution within the reactor.

In the present investigation, we simultaneously measure the volumetric fraction occupied by the gas in dispersion (gas holdup) and the average diameter of the bubbles. From this information, interfacial area is calculated from the relationship $a = 6 \phi_G / D_B$. It is important to better understand this physical entity which appears in generally all mass transfer models. In the literature, interfacial area information is limited because it is difficult to measure.

It is our objective to study the effect of solids on the bubble sizes and gas holdup in gas-slurry systems by comparing functionalities in air-water and air-water-solid systems. The variation with solid concentration and particle size will also be investigated. Furthermore, the results can be averaged over the entire upper region of the vessel which has given overall gas holdup and overall interfacial area. Models will also be proposed to predict D_B as a function of gas holdup and gassed power input.

CHAPTER II

LITERATURE SURVEY

A survey of the technical literature shows extensive studies related to two phase (gas-liquid), semibatch (gas flow rate continuous) systems have been carried out and this would indicate that the subject is well explored. Although there have been a substantial number of studies of $K_L a$ (Yoshida and Miura 1963, Robinson and Wilke 1974), interfacial area (Calderbank 1958, Sridhar and Potter 1980, Westerpterp et al 1963, Hughmark 1980, Hassan and Robinson 1980), gas holdup (Bimbinet 1959, Calderbank 1958, Hassan and Robinson 1977, Sridhar and Potter 1980) and power consumption of impellers (Calderbank 1958, Clark and Vermeulen 1963, Hasson and Robinson 1977, Michel and Miller 1962, Van't Riet et al 1976) in two phase systems, such information as to local gas holdup and bubble sizes in the gas phase are limited.

In order to compare functionalities of two phase with three phase systems, a fundamental understanding of the past research and methodology performed is essential. So the following will discuss some of the theory and work which has been done in the area.

Bubble Diameter in Dispersions

There are various methods for measuring the bubble sizes. Calderbank (1958) and Lee and Meyrick (1970) used

optical methods making use of the reflection or diffraction of light.

Other ways are to simultaneously measure interfacial area and holdup by chemical means to calculate the average diameter or the surface mean diameter of the dispersion. Holdup, bubble diameter and interfacial area are related by:

$$D_B = \frac{6\phi G}{a}$$

If the bubble diameter is directly tied to the holdup, the principle results can be reported without much commentary.

Calderbank (1958) proposed an explicit relationship concerning bubble diameter for pure liquids or aqueous solutions of aliphatic alcohols. He proposed:

$$D_B = 1.90 \left(\frac{\sigma_L^{0.6}}{\left(\frac{P_G}{V}\right)^{0.4} \rho_L^{0.2}} \right) \phi_G^{0.65} \left(\frac{\mu_G}{\mu_L} \right)^{0.25}$$

Calderbank also modified results by Vermeulen et al (1955). Vermeulen's measurements, which were made close to the tip of the impeller, were not representative of average values for the whole tank and so he proposed the following equation:

$$D_B = 4.15 \left(\frac{\sigma_L^{0.6}}{\left(\frac{P_G}{V}\right)^{0.4} \rho_L^{0.2}} \right) \phi_G^{0.5} + 0.09 \text{ cm}$$

Here bubble size depends on a balance of forces due to surface tension and to turbulence.

Yoshida and Miura (1963) measured interfacial area by a chemical method and then calculated D_B from $\emptyset$. They presented their results in the form:

$$D_B \sim N^{-Y_1} D^{-Y_2}$$

with $Vs < .76 \text{ cm. s}^{-1}$

for turbines: $y_1 = 0.3$ $y_2 = 0.1$

They found only a weak influence of impeller speed on D_B .

Generally, products which alter the properties of the gas-liquid interface tend to reduce the bubble diameters. This is found to be true for soluble products in solutions with relatively weak viscosities ($\mu_L < 0.1 \text{ Pa.s}$). For large viscosities, the viscous forces dominate over the surface forces. Ganguli (1975) observed this for insoluble surfactants in liquids. Levich (1962) also predicts this type of behavior in his theoretical work.

Gas Holdup in Dispersions

The functional gas holdup in a gas-liquid system is defined as the volume of gas divided by the total of gas volume and liquid volume. Normally, gas holdup is measured by observing the change in height above the tank bottom between the gas-liquid dispersion and the ungassed liquid. However, the level can fluctuate so large variations in the

holdup can result.

Nienow et al (1977) have successfully used a small suction probe to measure point holdup values in an agitated gas-liquid system. Samples were withdrawn through a 0.33 mm diameter by 3 mm long capillary where then the gas and liquid was separated. Local holdup values were observed to change with increasing impeller speed.

In our literature survey of gas holdup, there were few correlations on the subject. The dependence of gas holdup on the operating parameters (i.e. impeller speed and also solids concentration) is rather complex and difficult to measure accurately. Van Dierendonck et al (1960) attempted to represent ϕ as a function of N . Other authors have used dimensional analysis groups and notably the Weber number to determine the influence of surface tension on the bubble diameter and therefore on ϕ .

Finally, other studies of holdup have used the mechanical energy dissipation into a fluid to correlate these parameters. The best known correlation using PG/V is certainly that of Calderbank (1958), which proposed for a standard geometry:

$$\phi_G = \left(\frac{V_s \phi_G}{V_t} \right) + 0.0216 \left[\frac{\left(\frac{P_G}{V} \right)^{0.4} \rho_L^{0.2}}{\sigma_L^{0.6}} \right] \left(\frac{V_s}{V_t} \right)^{0.5}$$

Here V_t is the terminal velocity for a bubble in the systems studied. Calderbank observed a unique value of V_t

equal to:

$$26.5 \text{ cm. s}^{-1}$$

In general, gas holdup is very sensitive to all additives in the liquid phase capable of modifying the size of bubbles or influencing their movements relative to the liquid. Lee et al (1982) studied absorption of CO_2 into a carbonate-bicarbonate solution containing suspended particles. Hold-up decreased significantly with increasing solids concentration. The results are explained in terms of the particles damping turbulence and increasing the mean bubble sizes.

Ranede and Ulbrecht (1978) studied the behavior of gas dispersions in solutions of carboxy methyl cellulose and polyacrylamide. The gas holdup decreased as the polyacrylamide concentration increased. This is explained by a growth in the elasticity of the interface thus inhibiting the division of the bubbles.

Kato et al (1973) investigated gas holdup in bubble columns with glass particles of different sizes and different concentrations and reports that gas holdup decreases with increases in particle size and concentration of glass particles.

In addition, (Ganguli (1975, 1978, 1980) examined the influence in the concentration of finely dispersed Kieselguhr on holdup. In this case, the holdup increased with concentration. Of course, the mechanism of suspended Kieselguhr is complex. This Kieselguhr contains 55% fines

($d_p < .42 \mu\text{m}$) and 45% particles of slightly larger size ($d_p = 0.42 - 3.0 \mu\text{m}$). The smaller fines can be adsorbed at the gas-liquid interface and thus strengthen these by playing a role analogous to soluble surfactants. This phenomenon is strong for low solid concentrations.

Interfacial Area in Dispersions

Interfacial area is an important mathematical parameter which appears in most mass transfer models. Studies in the past to determine this parameter have been generally applied to gas-liquid dispersions using one of these methods: (1) chemical measurement of surface area, (2) light transmission, or (3) photography. Each of these methods can give good results in gas-liquid dispersions but appear somewhat impractical in a gas-slurry reactor.

The chemical technique involves absorption followed by a fast chemical reaction. This technique has been widely used (Danckwerts (1970), Sharma et al (1970), Ganguli et al (1978, 1980), Robinson et al (1970, 1974), Mehta et al (1971), Westerterp et al (1963), Yoshida et al (1960)). The use of the chemical technique would be difficult to apply in gas-liquid-solid systems since the rate of absorption is not really known and other mechanisms are occurring besides molecular diffusion.

The photographic technique is well known. The count of bubbles taken from a photograph determines the distribution

of bubble diameters and the sauter mean surface area. This leads to an average interfacial area.

When measuring bubbles from a photograph, personal judgement is necessary in order to determine which ones should be included in the desired region of study. Furthermore, a two dimensional view is not adequate to determine sizes of bubbles which may overlap. When adding solids, the photographic technique is impractical. Solids tend to scatter the light to such a degree that a clear picture becomes difficult.

In view of the above problems, a technique which does have promise is the light transmission method. The light transmission method uses a parallel beam of light which passes through a dispersion scattering it by diffraction, refraction, and reflection. Some investigators have used this for gas-liquid systems (Calderbank (1958), Vermuelen et al (1955), Lee and Meyrick (1970)). When adding solids, this method is difficult when measuring interfacial area in the tank. However, if the bubbles can be removed from the vessel through a glass capillary and analyzed by a light transmission source like a laser, it may be a practical means of studying local distribution of interfacial area. Indeed, this method was investigated further.

Kawecki et al (1967) and Reith and Beek (1970) have had success in removing bubbles in an air-water system. The method appears to be quite practical for removing bubbles in gas-liquid systems and also gas-liquid-solid. Also, it

allows local measurements in reactors of any size and the evaluation of the overall interfacial area coming from a spatial integration of the experimentally determined local information of holdup and bubble diameter. Incorporating the method by Kawecki and Reith and Beek with a He-Ne laser was then used successfully to determine this local information.

The Power of Agitation in Dispersions

With aeration, the power of agitation drops off due to the presence of the gas cavities which form behind the agitator blades. There are relationships correlating this reduction in power phenomena and the aeration number, N_A .

Calderbank (1958) proposed for two standard configurations of 5ℓ and 100ℓ, two correlations of the gassed power to ungassed power ratio (P_G/P_0) and the dimensionless aeration number, NA in a dispersion of air in water, ethanol or glycol (see Figure 1).

$$P_G/P_0 = 1-12.6 NA \quad NA < 0.03$$

$$P_G/P_0 = 0.62-1.85 NA \quad NA > 0.035$$

Warmoeskerken et al (1982) measured for different impeller speeds the power ratio P_G/P_0 versus the aeration number for turbine agitated vessels as the flooding point is approached. The phenomena referred to as flooding is when

Figure 1- Power of Agitation. From Calderbank(1958).

the radial distribution of the bubble disappear and the gas rises directly through the impeller to the liquid surface. In practice for large units, normally the agitated vessels are operated near the flooding region. In our research, studies were carried out near the flooding region and the power of agitation in the aerated medium was calculated based on this work by Warmoeskerken (see Figure 2,3).

This summary has presented essential information from the literature to understand the behavior of gas-liquid agitated reactors. This information includes bubble diameter, gas holdup, interfacial area, and the gassed power. To extend this knowledge to a gas-liquid-solid system is difficult and complex. Without preliminary experimentation, it is almost impossible to determine the interfacial area accurately and centers on one of the main objectives of our study.

Figure 2 - The Relation Between the Observed Two Phase Flow and the Power Consumption.

Figure 3 - The Gassed Power Curves for Different Impeller Speeds. From Warmoeskerken (1982).

CHAPTER III

EXPERIMENTAL APPARATUS AND PROCEDURESExperimental Apparatus

A schematic diagram of the experimental apparatus is shown in Figure 4. The major piece of equipment utilized in this research is a fully baffled 75ℓ flat bottom plexiglass tank. Other required apparatus is the following: (1) a He-Ne laser, (2) neutral density filters, (3) a light sensitive photodiode, (4) a storage oscilloscope, (5) electrical power supply and associated circuitry, (6) an air rotameter with air filter and pressure gauge, (7) a glass sample probe to traverse the tank, (8) separator and collector, (9) a vacuum pump, and associated manual control valves, block valves, supports, filters and plastic tubing.

Figure 5 shows the diagram of the tank. The tank had an outside diameter (T) of 45.72 cm (44.45 cm inside diameter) and a height of 60.96 cm. The liquid height (HL) was equivalent to the tank diameter. Contained in the tank is the agitator shaft, a six (6) blade Rushton turbine impeller, two gas spargers and the sample probe. Fully baffled conditions are provided by four plexiglass baffles (4.572 cm wide and 60.96 cm long) equally spaced around the circumference of the tank. Total coverage of the tank height is provided.

The concentrically positioned shaft is fitted with a

FIGURE 4 - FLOW DIAGRAM OF EXPERIMENTAL APPARATUS

LEGEND FOR FIGURE

A	Filter
B	Pressure gauge
C	Rotameter
D	Agitator drive motor
E	Agitator motor control
F	Agitator shaft
G	Coupling
H	6 blade Rushton impeller
I	Tank
J	Baffles
K	Sample probe
L	Spargers
M	Phase separator
N	Phase collectors
O	Vacuum pump
P	Power supply & assorted circuitry
Q	Storage Oscilloscope
S	Laser
T	Photodiode
U	Neutral density filters
V	Valves

For $25\mu\text{m}$ GLASS PARTICLES, $H_A = T/2$

For $70\mu\text{m}$, $200\mu\text{m}$ GLASS PARTICLES, $H_A = T/4$

FIGURE 5: TANK SCHEMATIC

flat-blade disc turbine impeller which has 6 blades (each blade is 3 cm by 3.75 cm) and an impeller diameter of 15.24 cm. A lightnin variable speed mixer (1/4 hp, 60 Hz, 1 pH) supplied the power to rotate the impeller at the desired speeds. A stroboscope was used to adjust the impeller speed to the desired values during operation. In the research, the impeller speeds chosen are 150 RPM, 200 RPM, and 250 RPM (air is sparged under flooding conditions). Two stainless steel gas spargers ($d_o = 4.29$ mm) are located 10 cm below the midplane of the impeller at all times.

The liquid used in the experiments was tap water and the gas was air. Glass beads of average sizes $25\mu\text{m}$, $70\mu\text{m}$, and $200\mu\text{m}$ are used in varying concentrations. The compressed air was filtered prior to entering the tank. The pressure and flow rates were monitored by a pressure gauge and the air rotameter. In general, all experiments are run at $1.7\text{ FT}^3/\text{MIN}$ except for one gas-liquid study which is performed at $3.0\text{ FT}^3/\text{MIN}$. (See Appendix.)

The Spectra Physics model 155 Helium-Neon laser (see Figure 6) is set outside the tank. The laser produces 0.5 mW of radiant power over an area of about 2 square millimeters ($\sim$ intensity of $.025\text{ watts/cm}^2$). The light from the laser is bright red with a wave length of 632.8 nanometers. The laser beam (beam diameter $\sim .9$ mm) is focused on the light sensing photodiode surface. The photocell is a Hamamatsu S780 type with a photosensitive surface area of 7.3 mm^2 (2.7×2.7 mm). The photodiode is

MODEL 155 FINAL ASSEMBLY

Unless otherwise noted all resistance values are Ω (ohms).

Unless otherwise noted all capacitance values are μF (microfarad).

Unless otherwise noted all inductance values are H (Henry).

Item #	Sch Ref #	Part #	Description
1		408-528	Plasma Tube-Power Supply Assembly
2		420-581-1	Rear Panel Assembly 115 V
3		420-588	Notched Housing
4		420-549	Shutter Assembly
6		1406-0410	Rubber Stick-on Bumper
7		7411-0406	Self Tapping Screw 4-40x3/8
8		420-581-2	Rear Panel Assembly 220 V
9		4706-0500	Resistor 33k 1/2W 10%
11		6011-0670	Tyrap
15		408-757	Optical Mount
18		420-581-3	Rear Panel Assembly 100V

Figure 6- Spectra Physics Model 155 He-Ne Laser

on a vertical probe surrounded with a glass sleeve to keep out moisture. The probe is clamped tightly behind the 6 mm inside diameter (8 mm O.D.) glass capillary tube. When a gas bubble passes in front of the photodiode through the glass tube, a signal from the photocell is amplified and sent through the associated circuitry (see Figure 7) to a storage oscilloscope. A combination of neutral density filters (Oriel Corp. model # 5082, normal density = 0.6 and # 5083 normal density = 1.0) is used in front of the beam to attenuate the incident light striking the photodiode surface thus improving the methods' detection of gas bubbles. Trial runs were performed to determine the proper combination of neutral density filters.

The Tektronix type 564B storage oscilloscope was necessary to count the number of gas bubbles collected in the experiments. Time-base operation was used. By use of this arrangement the number of bubbles passing across the beam could be observed for known amounts of time. The time interval itself had to be varied so that the bubble frequencies could be countable.

Experimental Procedures

A new measuring technique was developed using the He-Ne laser to gather experimental data on local gas holdup and bubble sizes. From this, interfacial area can be calculated by using the well known relationship $a = 60G/DB$.

A series of experiments were performed to test the

$$V_o = (-R_2/R_1) \cdot V_1$$

FIG. 7 : Photocell biasing and operational amplifier circuitry.

method. A single gas sparger and a bell shaped glass thistle tube was used to collect a known volume of gas whereby it was pulled by a vacuum into the dispersed phase separator and collectors. By the suction method, the gas-liquid sample was pulled into the columns and the displacement measured. The method was repeated many times with excellent results.

Next the laser/photodiode and other equipment was tested. A particular bubble rise frequency was set at the outlet of the gas sparger. When a bubble was pulled through the glass sample probe in front of the photodiode a signal was transmitted onto the oscilloscope screen and the frequency determined. The visual bubble count coincided with the count on the screen of the oscilloscope.

After these tests, gas holdup data was collected under mechanical agitation conditions in a gas-liquid environment. The figures were compared to correlations determined by Calderbanks. The overall holdup values were very close to the ones predicted by Calderbank for an air-water system.

Common flow patterns exist with increasing impeller speed (see Figure 8). It is generally accepted to feed the gas beneath the impeller because it encourages the gas to pass outwards through the high shear region, thereby improving the change of gas dispersion.

In (a) we have little or no gas dispersion at low impeller speeds. In (b) we have sufficient dispersion in the upperpart of the vessel to act like a bubble column.

Figure 8 - Flow Patterns in a Mixing Tank.

And with further increase, (c), we have circulation in the upper part with some movement to the lower part. And in (d), circulation occurs both in the top and lower regions of the vessel. The experiments were conducted between (b) and (c).

Experiments using the new method began by sparging the vessel at a constant volumetric gas rate and increasing the impeller speed to attain an effective dispersion. The bubbles at this point will be dispersed throughout the upper impeller region with only few bubbles recirculated to the lower impeller regions. In doing so, our experimental method can be limited to only above the mid plane of the impeller.

Samples of a gas-liquid or a gas-slurry system are taken using the combination suction method/laser technique. Figure 9 gives a top and side view of the sampling locations in this study. A total of eighteen (18) locations within one upper quadrant were sampled. The volume surrounding the sampling locations are viewed as individual cells into which bubbles enter, possibly undergo coalescence and leave these cells on a steady state basis. These sample locations were used for all gas-liquid runs and all $25\mu\text{m}$ glass bead runs.

For the heavier, denser solids ($70\mu\text{m}$, $200\mu\text{m}$) the impeller height was lowered to fully suspend the solids. Thus the sampling locations then increase from eighteen to twenty-four individual cells. Samples were collected but not all of them due to time and unavailability of a sample probe to reach the lower levels. This may be a subject for

further research.

LOC 7

13

X-4

LOC 8

9

$\pi/2$

CELL

1

COUPLING LOCATIONS

13

COUPLING LOCATIONS

SIDE VIEW

TOP VIEW

FIGURE 9 : SAMPLING LOCATIONS

CHAPTER IV

EXPERIMENTAL RESULTS

Very little is known of the particle effects on the gas liquid interface. An attempt was made to examine some of the major parameters which effect bubble size distribution and to correlate the functionalities. Two systems were chosen: air-water and air-water-solid. Experiments were carried out to collect data on local gas holdup (volume fraction of gas in a local area) and bubble diameter simultaneously. A literature survey indicates the laser has not been used for this purpose before. Tests have provided good results with correlations which are in agreement with some of the literature.

Effect of Solids Concentration - 25 μ m Glass Particles

The effect of increasing solid concentration of 25 μ m glass particles on local gas holdup and bubble diameter is shown in Tables 1-6.

In Table 1 and 2 at a constant impeller speed and gas rate, the concentration is varied. Experiments are carried out for the gas-liquid system (0%) and then solids are added to adjust the wt % concentration (.3, .6, 1.2 wt %). At an impeller speed of 150 RPM, the impeller does not disperse the gas and therefore has little gas detected outside the

TABLE 1 Effect of 25 μ m glass particles on local gas holdup with increasing solids concentration (wt percent).

HA = 1/2
N = 150 RPM

HL = 45.72 CM
PG = 2.71 PT-LBF/SEC

C = 1.7 CFM

ROW	LOC	ϕ			
		0.0	0.3	0.6	1.2
1	1	0.152	0.071	0.232	0.215
2	2	0.014	0.002	0.003	*
3	3	0.000	0.026	0.006	*
4	4	0.001	0.019	0.025	*
5	5	0.000	0.000	0.000	*
6	6	0.000	0.001	0.001	*
7	7	0.108	0.076	0.032	0.081
8	8	0.038	0.021	0.007	0.003
9	9	0.000	0.002	0.000	0.002
10	10	0.047	0.018	0.006	0.006
11	11	0.002	0.004	0.011	0.003
12	12	0.008	0.011	0.004	0.002
13	13	0.131	0.100	0.061	0.077
14	14	0.045	0.035	0.017	0.020
15	15	0.038	0.004	0.002	*
16	16	0.067	0.021	0.031	0.040
17	17	0.008	0.010	0.005	*
18	18	0.031	0.010	0.007	0.003
$\phi =$		0.033	0.020	0.020	0.023
$\phi G = \phi / 2 =$		0.016	0.010	0.010	0.012

TABLE 2 Effect of 25 μ m glass particles on bubble diameter with increasing solids concentration (wt percent).

HA= T/2
N= 150 RPM

HL= 45.72 CM
PG= 2.71 FT-LEF/SEC

Q=1.7 CFM

RCW	LOC	DB			
		0.0	0.3	0.6	1.2
1	1	0.71	0.51	0.710	0.654
2	2	0.41	0.20	0.380	*
3	3	*	0.40	0.330	*
4	4	0.36	0.40	0.540	*
5	5	*	*	0.260	*
6	6	*	*	*	*
7	7	0.57	0.47	0.470	0.554
8	8	0.47	0.38	0.410	0.240
9	9	0.30	0.44	*	0.315
10	10	0.47	0.43	0.390	0.330
11	11	0.38	0.33	0.500	0.370
12	12	0.44	0.41	0.450	0.310
13	13	0.58	0.50	0.545	0.590
14	14	0.49	0.43	0.380	0.430
15	15	0.47	0.28	0.270	*
16	16	0.64	0.56	0.710	0.690
17	17	0.38	0.51	0.360	*
18	18	0.74	0.40	0.320	0.370

DB= 0.530 0.430 0.491 0.522

a=6 ϕ G/DB= 0.187 0.144 0.125 0.138

NOTE: CALDERBANK PREDICTS

ϕ G= 0.025

DB= 0.846 CM

a= 0.174 CM⁻¹

impeller shaft region (loc 2-6, 8-12, 14-18). For example, at location 1, $\theta = .152$ for 0% then decreases with the initial addition of solids ($\theta = .0711$ @ 0.3 wt %). Locations 2-6 has so little gas fractions collected that no trend is possible except to say that the impeller is flooded. Then at locations 7, 13, the decrease in local gas holdup is more evident with solid addition.

Table 3, 4 introduces θ and D_B at impeller speeds of 200 RPM. There is improved gas dispersion which results in higher gas fractions in the outer cell locations. Due to the higher impeller speed, little gas is in location 1. Other locations show a definite decrease in local gas holdup and bubble diameter with increasing concentration. The interfacial area, a , also decreases (see Appendix for further information). The first addition of solids (.3 wt %), the overall interfacial area decreases by 10%. The overall holdup decreases by ~13%. The mean bubble diameter decreases by ~5%. With further addition of solids (.6, 1.2 wt%), the overall holdup decreases by ~17%, the bubble diameter by ~10%, and the overall interfacial area by 6-10%.

Table 5-6 also summarizes the results of experiments to examine the effect of 25 μ m glass particles on local gas holdup and bubble diameter with increasing solids concentration, but a yet higher impeller speed of 250 RPM. Gas dispersion extends from the impeller blades to the vessel walls but with very little recirculation below the impeller. Once again the data strongly suggests that the presence of

TABLE 3 Effect of 25 μ m glass particles on local gas holdup with increasing solids concentration (wt percent).

HA= T/2
N= 200 RPM

HL= 45.72 CM
PG= 5.72 FT-LEF/SEC

Q= 1.7 CFM

RCM	LOC	ϕ			
		0.0	0.3	0.6	1.2
1	1	0.007	*	0.000	0.003
2	2	0.099	0.075	0.062	0.083
3	3	0.029	0.064	0.027	0.042
4	4	0.070	0.064	0.113	0.079
5	5	0.033	0.038	0.042	0.042
6	6	0.047	0.060	0.059	0.040
7	7	0.064	0.036	0.074	0.036
8	8	0.085	0.052	0.072	0.031
9	9	0.063	0.069	0.058	0.056
10	10	0.111	0.081	0.083	0.117
11	11	0.061	0.059	0.069	0.066
12	12	0.081	0.074	0.061	0.067
13	13	0.068	0.065	0.068	0.069
14	14	0.085	0.058	0.048	0.042
15	15	0.074	0.039	0.033	0.015
16	16	0.078	0.072	0.077	0.107
17	17	0.073	0.061	0.051	0.051
18	18	0.059	0.069	0.054	0.067
$\phi =$		0.067	0.059	0.059	0.058
$\phi_G = \phi / 2 =$		0.033	0.0295	0.0295	0.0290

TABLE 4 Effect of 25 μ m glass particles on bubble diameter with increasing solids concentration (wt percent).

HA= T/2
N= 200 RPM

HL= 45.72 CM
PG= 5.72 FT-LBF/SEC

Q= 1.7 CFM

ROW	LOC	DB			
		0.0	0.3	0.6	1.2
1	1	0.74	*	*	0.510
2	2	0.64	0.45	0.520	0.450
3	3	0.48	0.48	0.435	0.420
4	4	0.51	0.58	0.660	0.500
5	5	0.47	0.64	0.395	0.425
6	6	0.48	0.59	0.530	0.422
7	7	0.53	0.46	0.510	0.415
8	8	0.49	0.46	0.515	0.520
9	9	0.47	0.46	0.420	0.450
10	10	0.55	0.56	0.490	0.570
11	11	0.44	0.46	0.640	0.540
12	12	0.56	0.48	0.500	0.490
13	13	0.44	0.47	0.490	0.480
14	14	0.56	0.45	0.435	0.410
15	15	0.51	0.40	0.390	0.350
16	16	0.60	0.59	0.485	0.930
17	17	0.58	0.54	0.410	0.490
18	18	0.56	0.51	0.420	0.480

DB= 0.514 0.487 0.472 0.470

a=6 ϕ G/DB= 0.391 0.363 0.375 0.370

NOTE: CALDERBANK PREDICTS

ϕ G= 0.027

DB= 0.632 CM

a= 0.255 CM-1

TABLE 5 Effect of 25 μ m glass particles on local gas holdup with increasing solids concentration (wt percent).

HA= T/2
N= 250 RPM

HL= 45.72 CM
PG= 10.26 FT-LBF/SEC

Q= 1.7 CFM

RCW	LOC	ϕ			
		0.0	0.3	0.6	1.2
1	1	0.007	0.000	0.006	0.012
2	2	0.055	0.077	0.061	0.066
3	3	0.066	0.070	0.065	0.062
4	4	0.075	0.035	0.054	0.070
5	5	0.048	0.040	0.054	0.052
6	6	0.059	0.062	0.062	0.048
7	7	0.055	0.055	0.055	0.052
8	8	0.057	0.057	0.059	0.051
9	9	0.094	0.072	0.098	0.082
10	10	0.064	0.059	0.072	0.084
11	11	0.059	0.060	0.062	0.073
12	12	0.083	0.060	0.077	0.082
13	13	0.080	0.074	0.054	0.075
14	14	0.075	0.064	0.059	0.057
15	15	0.107	0.047	0.036	0.032
16	16	0.081	0.082	0.077	0.077
17	17	0.089	0.068	0.070	0.046
18	18	0.086	0.070	0.065	0.066

$\phi =$ 0.070 0.059 0.062 0.061

$\phi_G = \phi/2 =$ 0.035 0.0295 0.031 0.0305

TABLE 6 Effect of 25 μ m glass particles on bubble diameter with increasing solids concentration (wt percent).

HA= T/2 HL= 45.72 CM Q= 1.7 CFM
N= 250 RPM PG= 10.26 FT-LEF/SEC

ROW	LOC	DB			
		0.0	0.3	0.6	1.2
1	1	0.78	0.30	0.622	0.36
2	2	0.56	0.48	0.580	0.47
3	3	0.50	0.46	0.550	0.41
4	4	0.54	0.40	0.590	0.51
5	5	0.46	0.51	0.400	0.44
6	6	0.47	0.54	0.435	0.45
7	7	0.48	0.46	0.405	0.36
8	8	0.44	0.46	0.440	0.47
9	9	0.52	0.46	0.470	0.50
10	10	0.43	0.42	0.460	0.49
11	11	0.43	0.42	0.590	0.46
12	12	0.46	0.44	0.430	0.51
13	13	0.49	0.46	0.455	0.42
14	14	0.48	0.57	0.460	0.40
15	15	0.50	0.40	0.415	0.35
16	16	0.51	0.47	0.395	0.64
17	17	0.49	0.49	0.390	0.49
18	18	0.55	0.47	0.410	0.44

DB= 0.484 0.457 0.441 0.442

a=6 ϕ /DB= 0.434 0.382 0.422 0.414

NOTE: CALDERBANK PREDICTS

ϕ G= 0.029

DB= 0.512 CM

a= 0.339 CM-1

solids at low concentration greatly effects the overall gas holdup, bubble diameter and thus the interfacial area. Quantitatively speaking, with the initial addition of solids, the overall gas holdup decreases by ~18%, the bubble diameter also decreases by ~6% and the overall interfacial area decreases by more than 20%.

The data summarized in Tables 1-6 are averaged local gas holdup and bubble diameter for locations 1-18. For further information see Raw Data in Appendix.

70 μ m Glass Particles

Table 7 summarizes experimental data points for the effect of 70 μ m glass particles on local gas holdup and bubble diameter with increasing solids concentrations. Only solids concentration of .3 wt% and 1.2 wt % was examined due to the tedious nature of the experimental method. The impeller height off the bottom is 4.5" ($H_A = T/4$) In examining the data, there appears to be very little change of local gas holdup or bubble diameter. Whatever locations increase with solids there is also an equal number that decrease so possibly for the larger particles (70 μ m), there is essentially no change in local gas holdup or bubble diameter. To evaluate the overall changes in holdup and bubble diameter, more data is required at the lower levels.

Table 8 summarizes the results at impeller speeds of 250 RPM. Again, the data suggests little change of local

TABLE 7 Effect of 70 μ m glass particles on local gas holdup and bubble diameter with increasing concentration. (wt percent).

HA= T/4 HL= 45.72 CM Q= 1.7 CFM
N= 200 RPM PG= 5.72 FT-LBF/SEC

ROW	LOC	ϕ			DB		
		0.0	0.3	1.2	0.0	0.3	1.2
7	7	0.090	0.072	0.092	0.55	0.58	0.60
8	8	0.059	0.058	0.075	0.54	0.50	0.56
9	9	0.034	0.030	0.037	0.42	0.39	0.43
10	10	0.042	0.053	0.060	0.46	0.49	0.47
11	11	0.027	0.030	0.027	0.36	0.46	0.37
12	12	0.036	0.039	0.045	0.42	0.40	0.44
13	13	0.067	0.060	0.073	0.49	0.50	0.65
14	14	0.031	0.034	0.037	0.42	0.45	0.50
15	15	0.012	0.008	0.021	0.39	0.33	0.42
16	16	0.026	0.045	0.045	0.38	0.42	0.46
17	17	0.012	0.012	0.017	0.42	0.39	0.42
18	18	0.026	0.040	0.025	0.39	0.41	0.39

TABLE 8 Effect of 70 μ m glass particles on local gas holdup and bubble diameter with increasing concentration. (wt percent).

HA= T/4 HL= 45.72 CM Q= 1.7 CPM
N= 250 RPM PG= 10.26 FT-LBF/SEC

ROW	LOC	θ			DB		
		0.0	0.3	1.2	0.0	0.3	1.2
7	7	0.075	0.067	0.071	0.51	0.63	0.54
8	8	0.069	0.054	0.074	0.52	0.50	0.56
9	9	0.043	0.031	0.054	0.49	0.34	0.41
10	10	0.076	0.075	0.083	0.47	0.56	0.52
11	11	0.041	0.050	0.050	0.39	0.52	0.38
12	12	0.075	0.068	0.076	0.40	0.40	0.42
13	13	0.063	0.060	0.074	0.50	0.45	0.57
14	14	0.035	0.042	0.049	0.42	0.40	0.52
15	15	0.011	0.012	0.029	0.36	0.35	0.44
16	16	0.046	0.060	0.065	0.45	0.42	0.48
17	17	0.023	0.032	0.029	0.40	0.43	0.42
18	18	0.060	0.072	0.062	0.40	0.39	0.45

gas holdup or bubble diameter with increasing solids concentration. It may be speculative to say at this point possibly the large particles such as $70\mu\text{m}$ size occupy the space in the liquid phase more easily than they do in the liquid film surrounding the gas bubbles. Therefore, there is little particle interaction with the gas bubbles and relatively no change in local gas holdup or bubble size.

$200\mu\text{m}$ Glass Particle

Table 9 summarizes experimental results of adding $200\mu\text{m}$ glass particles at 250 RPM. Data was collected from locations 7-24 for 0.3 wt % and 1.2 wt % solids. Even though the information is somewhat incomplete, if we take a weighted average of only loc 7-18, some interesting results occur. Averaging loc 7-18, for 0.0%, $\theta = 5.1\%$, @ 0.3% $\theta = 5.4\%$, and 1.2%, $\theta = 1.3\%$. It seems that if this trend continues that we would speculate that the overall holdup will increase somewhat. This may be due to bubble breakage by solids.

Experimental Correlations

Combining local gas holdup measurements and actual bubble sizes for gas-liquid and gas-liquid-solid (only $25\mu\text{m}$ and $70\mu\text{m}$ glass particles) with the gassed power number, some intriguing correlations were developed which were very

TABLE 9 Effect of 200 μ m glass particles on local gas holdup and bubble diameter with increasing solids concentration (wt percent).

HA= T/4 HL= 45.72 CM Q= 1.7 CFM
N= 250 RPM PG= 10.26 FT-LBF/SEC

ROW	LOC	ϕ			DB		
		0.0	0.3	1.2	0.0	0.3	1.2
7	7	0.075	0.0783	0.0920	0.51	0.51	0.52
8	8	0.069	0.0671	0.0646	0.52	0.50	0.49
9	9	0.043	0.0471	0.0615	0.49	0.50	0.48
10	10	0.076	0.0750	0.0794	0.47	0.49	0.54
11	11	0.041	0.0361	0.0568	0.39	0.58	0.60
12	12	0.075	0.0744	0.0662	0.40	0.44	0.41
13	13	0.063	0.0600	0.0933	0.50	0.46	0.59
14	14	0.035	0.0360	0.0599	0.42	0.42	0.53
15	15	0.011	0.0110	0.0296	0.36	0.37	0.44
16	16	0.046	0.0724	0.0739	0.45	0.49	0.44
17	17	0.023	0.0204	0.0289	0.40	0.40	0.45
18	18	0.060	0.0680	0.0535	0.40	0.43	0.44
19	19	*	0.0841	0.0899	*	0.51	0.48
20	20	*	0.0467	0.0554	*	0.43	0.44
21	21	*	0.0259	0.0249	*	0.38	0.40
22	22	*	0.0679	0.0442	*	0.45	0.48
23	23	*	0.0260	0.0241	*	0.42	0.39
24	24	*	0.0508	0.0398	*	0.45	0.40

similar to previously published work by Calderbank (1958). The gas bubble diameter was satisfactorily correlated to the functionalities of local gas holdup and gassed power input and is shown below:

$$D_B = 2.7 \emptyset^{.468} P_G^{-.212}$$

The form of this relation includes local gas holdup values which are only greater than .04. Values of holdup were chosen in this range because the corresponding bubble diameters were more consistent with position and representative of a large sample of the gas-liquid or gas-liquid-solid dispersion.

In addition, as you may see, only agitator speeds of 200 and 250 RPM were chosen due to once again a poor representation of the dispersion at the locations for the lower impeller speed of 150 RPM.

The absolute error of the actual bubble diameter versus the predicted bubble diameter is ~9.3%.

Further correlation of the experimental data by a linear regression will show improved functionalities of $\emptyset$ and P_G . The improved coefficients were due to only including data taken on locations 7-18 which will be the coalescing region. Shinnar (1961) has done studies in mixing vessels showing two processes which occurs simultaneously, breakage and coalescencing. The impeller region is subject to high shear stress near the agitator blades

thus bubble diameter is controlled by breakage. Away from the impeller region, the bubble diameter is controlled by coalescing. We decided to correlate in the coalescing controlled region and the results were:

$$D_B = 3.11 \emptyset^{.479} P_G^{-.274}$$

Again, only local gas holdup values greater than .04 were used and only values in locations 7-18. The absolute % deviation was lower at 9.16 %.

Next, the exponent on local gas holdup was forced to 0.5 since we suspect that the system is a coalescing controlled region. The correlation is:

$$D_B = 3.41 \emptyset^{0.5} P_G^{-.29}$$

The gassed power exponent was -.29 versus the exponent of -.4 by Calderbank. The absolute % deviation was 9.4%.

CHAPTER V

DISCUSSION OF RESULTS

The behavior of gas-slurry dispersions in mixing vessels is of special interest to chemical engineers especially since it is a common operation in the chemical industry. Obviously, there are numerous variables and even more combinations of variables which may be relevant to understanding of these systems. However, the scope of our research is centered upon bubble sizes and local distribution, gas holdup, and interfacial area and the influence of suspended glass particles on these functionalities. The following discussion will interpret the results and should provide a better understanding of particle-bubble interactions.

If gas is dispersed as bubbles in a suspension of glass particles rather than a pure liquid such as water, it is interesting to consider how the particles may interact with the bubbles especially in regard to bubble sizes, bubble interfacial area, and gas holdup.

The results of our research indicate that small suspended glass particles (25 μ m range) caused significant decreases in bubble size, gas holdup, and correspondingly a decrease in the interfacial area. Interfacial area is shown to decrease in the 7-23% range. The bubble diameters decreased by 5-20%. The gas holdup decreased by 10-40%.

In general, additions to the liquid phase can change the size of bubbles and influence their mobility through the liquid phase. Possibly, suspended solids absorbed at the gas-liquid bubble interface can create a blocking effect to further interactions between particles and bubbles. A case study by Rande and Ulbrecht (1978) found that the gas holdup decreased as the polyacrylamide concentration increased possibly because of a growth of elasticity of the gas-liquid bubble interface and therefore inhibited further divisions of the bubbles. For this to be true, no further coalescence between bubbles will occur and you would expect that the data would need to be correlated in two groups (one with solids and one without solids). However, results by Nagaraj (1984) and this author indicate that the presence of solids leads to more coalescence and can be correlated as one group. This will be discussed later.

Results similar to those found here for the influence of suspended solids were reported by other investigators such as Lee et al (1982), Ching (1983), and Kato et al (1973).

In the investigation by Lee et al (1982), glass particles of sizes 41-109 μm and wetted 7 μm polyacrylonitrile particles at volume fractions 0-0.5 were evaluated for its effect on gas-liquid mass transfer. In one series of experiments using 56 μm glass ballotini, holdup decreased by more than 10% with increasing solids content. Furthermore, Lee studied Orlon particles (7 μm range) and results showed

substantial decreases in gas holdup and interfacial area ($>12\% \emptyset$, $>50\% a$). the results are interpreted in terms of the particles obstructing the diffusion path and damping the turbulence.

Ching (1983) investigated the influence of suspended solids on oxygen transfer rates and mechanisms in the fermentation of glucose. The presence of suspended solids ($0.5 \mu m$ alumina particles) adsorbed onto the bubbles decreasing the interfacial area. Possibly, the development of internal circulation inside the bubble is hindered as a result and thus becomes a rigid sphere. These effects decreased mass transfer. Furthermore, the study exhibited dramatic decreases of kla for initial additions of solids reaching a minimum and then gradually increasing with increasing solids concentration until it reaches a value of kla as if there were no solids present.

Mehta and Sharma (1971) investigated the absorption of CO_2 in aqueous sodium carbonate-bicarbonate solutions with $CaCO_3$ as the inert solids in an agitated vessel. Initially, no change was observed with adding 1.5% solids, but as the concentration increased Kla decreased until it reached a minimum at 5% solids. Thereafter further addition of solids increased Kla similar to findings of Ching. Authors explained that the increase and then decrease in Kla in the presence of varying concentrations was due to a decrease in interfacial mobility producing a decrease in Kla and also due to the decrease in bubble size increasing the inter-

facial area. However, they were vague as to why a decrease and then increase in interfacial area.

In a stirred tank at a specific turbulent intensity, bubble breakup and coalescence are in equilibrium with one another and will usually determine the mean bubble size. Furthermore, when solids are present, the turbulent intensity in the system is affected, and hence the size and behavior of the gas bubbles. Nagaraj (1984) shows that the presence of suspended glass particles actually dampens the high level of turbulent intensity to a certain extent and leads to more coalescence between bubbles. Our results tend to agree. There apparently is an increase in the number of coalesces occurring.

Nagaraj mentioned that coalescence may occur in one of the following ways:

- (1) causing rupture of the gas-liquid film
- (2) solids adhering to the gas-liquid bubble interface may cause adhesive forces between bubbles (similar to van der Waal forces).
- (3) According to Kirkpatrick and Lockett (1974), the bubbles will not coalesce if the approach velocity is greater than a certain critical velocity. Solids may (a) increase this critical velocity (most probable) or (b) decrease bubble approach velocity by increasing the drag.

In correlating the results, we have treated the three phase system as a two phase system and performed a linear

regression. Our results indicated the following:

$$D_B \propto P_G^{0.5} N^{-0.29}$$

This empirical result was in good agreement with already well known correlations by Shinnar (1961) and Calderbank (1958).

According to Shinnar, if a dispersion remains in a quasi-stationary flow field for a sufficient duration, a dynamical equilibrium between coalescence and breakup is established. In the breakup region, the maximum diameter is estimated to be a function of the agitator speed:

$$d \propto N^{-6/5}$$

Shinnar mentioned that it is the belief that only a small number of collisions result in immediate coalescence. This is because a thin film of liquid trapped between two colliding bubbles can act as a cushion and cause them to bounce off one another. If this film thins sufficiently enough, then they may coalesce. This may be true if the bubbles are allowed to reach an equilibrium size as in Kirkpatrick and Lockett's work in which bubbles are large enough to deform.

It is the belief of this author and others that show the majority of the collisions end up in coalescence. Howarth's (1964) results show that almost every collision

resulted in coalescence. Nagaraj says that better than 50% of the collisions coalesce if the approach velocity is less than the critical velocity.

Shinnar predicted the coalescence of droplets. He found that the forces of adhesion and those of inertia are different functions of droplet diameter. Hence, for very small droplets, the turbulent energy input in the impeller region may be insufficient to overcome the adhesion energy however and thus results in coalescence.

The energy of adhesion, E_a , and the energy required to separate two droplets of unit diameter and separated by a minimum distance, h_0 , is related by

$$E_a = A(h_0)d$$

The inertial forces of two droplets relative to each other are proportional to $\rho u^2(d)d^3$. This must be larger than the energy of adhesion in order for coalescence not to occur.

The drop diameter for which separation is possible is given implicitly by

$$\frac{\rho u^2(d) d^2}{A(h_0)} = \text{constant}$$

In locally isotropic flow, $u^2(d) = C(\epsilon d)^{2/3}$ thus combining those two equations

$$\frac{C_1 \rho \epsilon^{2/3} d^{8/3}}{A(h_0)} = \text{constant}$$

Therefore, in a stirred tank

$$\frac{C_1 \rho K^{2/3} N^2 D^{4/3} d^{8/3}}{A(h_0)} = \text{constant}$$

Both $A(h_0)$ and h_0 are constant and independent of droplet diameter, d ,

Therefore, coalescence as predicted by Shinnar can be shown as

$$d \propto N^{-3/4}$$

Our results, as reflected in the exponent, do agree with this result.

It is well known that the average energy dissipation rate in agitated vessels is a function of $N(\frac{PG}{V} \propto N^3, N \propto \frac{PG}{V}^{-.33})$. From this fact, the bubble diameters can be interpreted in terms of either agitator speed or energy dissipation rate.

$$\text{Breakage region: } D_B \propto N^{-6/5} \text{ or } D_B \propto \left(\frac{PG}{V}\right)^{-.40}$$

$$\text{Coalescence region: } D_B \propto N^{-3/4} \text{ or } D_B \propto \left(\frac{PG}{V}\right)^{-.25}$$

As discussed before, we suspect that our system behaves similar to a coalescing one and our results point this out. Near the impeller region (break up dominates) gas

bubbles will be subjected to a region of high shear and will result in breakup. Correlating of our results in this region proved unsatisfactorily. Okamoto et al (1981) investigated the energy dissipation rate distribution at various locations within the mixing vessel. They reported an energy dissipate rate at a 40-fold variation in value from its maximum (near the impeller) to its minimum (upper regions of the circulation region). This fact further concludes that when correlating results within a mixing vessel, the results should be interpreted in terms of a two region model, breakup and coalescence.

Coalescence appears to be the dominate mechanism in our experimental results. When $25\mu\text{m}$ glass particles are added to the system, Nagaraj showed that the interfacial area within the impeller stream was markedly reduced. This indicates that more bubble coalescence was taking place with particles added versus no solids. The bubbles issuing from the impeller therefore are larger, faster rising bubbles which would reduce the holdup.

He also showed that some coalescence does take place within the impeller discharge stream. The coalescence efficiency is dependent upon the size of the bubble and the fluctuating velocity of the energy dissipation eddies. Generally speaking, the larger the bubble and the greater the velocity of approach of the bubbles, the greater the probability of coalescence. For a given bubble size, however, there is a maximum velocity of approach for which

bubbles will deform to such an extent that the bubbles will bounce off of each other rather than coalesce.

The role of the solids appears to be to prevent this rebounding effect. If the solid sizes are within the size range of the energy dissipation eddies, these solids tend to get caught up in the wake of the moving bubbles. When the bubbles attempt to rebound from a collision, these particles resist this rebounding effect (inertia of the bubbles attempt to reverse direction) and promote coalescence.

Larger particles ($70\mu\text{m}$, $200\mu\text{m}$) tend to move more independently from the fluid and bubble wake flow patterns and appear to play little to no role in the coalescence process.

As we move away from the impeller region, the energy dissipation eddies are larger with a slower velocity. This allows the bubbles to approach each other at a velocity at which the bubbles do not deform to the extent which prevents coalescence. The fluid between these bubbles is now allowed to drain from between the bubbles and coalescence is more probable. There still remains, however, a given bubble size for which coalescence is highly improbable and the bubbles are now in a region in which the bubble sizes are controlled totally by the coalescence process. This is reflected in the exponent $PG^{-.29}(N^{-.87})$ also $PG^{-.21}$ for all data, etc. in our equation as outlined by Shinnar for drop coalescence.

The fact that the bubbles are smaller in the coalescence region when solids are added appears to be due

to the reduction in the gas holdup since all of the data (solids and no solids) can be correlated together in one equation. The exponent $\phi^{.5}$ is consistent with the findings of Calderbank for air-water systems. It is highly probable that since the bubbles are continuously moving into regions of lower turbulent intensity as they rise up away from the impeller that the approach velocity (eddy velocities) of coalescing bubbles never exceed the critical velocity for the existing bubble sizes and therefore the solids essentially play no role in the coalescence process. The bubble sizes therefore can be correlated as one group and the results are similar to the findings of Calderbank and Shinnar for a coalescence dominated regime.

One other interesting result of correlating the data is that the numerical value of the coefficient on gas holdup is in good agreement with the value predicted by Calderbank. His work included measurements of gas bubbles for dispersions of air in water containing various solids. For the average diameter of a bubble, the most explicit relationship is by Calderbank and represents the functionality as follows:

$$D_B \propto \phi^{.5} P_G^{-.4} \quad \text{Calderbank}$$

$$D_B \propto \phi^{.5} P_G^{-.29} \quad \text{Randall}$$

A comparison of this relationship to our results re-

flect a difference in the gassed power exponent, $PG^{-.4}$. We suspect that one may expect an exponent between $-.25$ and $-.4$ for the overall bubble size.

For a summary of the literature comparisons, see Table 10.

Table 10 - Literature Comparisons

<u>System</u>		<u>Exponent</u>		<u>References</u>
<u>Liquid</u>	<u>Gas</u>	<u>ϕG</u>	<u>PG</u>	
Water, EtOH, Glycerol, Alcohols	Air	0.5	-0.4	Calderbank (1958)
Electrolytes	Air	0.4	-0.4	Calderbank
Water	Air		-0.25	Figueirido & Calderbank (1978)
Water, Glass beads	Air	0.468	-0.212	Randall ¹ (1985)
		0.479	-0.274	Randall ²
		0.5	-0.290	Randall ³

Notes: 1 Locations 1-18 Absolute error= 9.3%

2 Locations 7-18 Absolute error= 9.2%

3 Force fit of ϕG exponent= 0.5 Absolute error = 9.4%

CHAPTER VI

SUMMARY AND CONCLUSIONS

The main objectives of this research is to experimentally determine the effects of various concentrations and sizes of suspended glass particles on bubble diameter, gas holdup, and interfacial area. An experimental method extracted local samples of air-water or air-water-solid with the assist of a He-Ne laser and light sensitive photodiode and measured the local distribution of these functionalities. A comparison of the functionalities in air-water and air-water-solid systems yielded the effect of various concentrations and sizes. The results are averaged over the entire upper region of the vessel to give an average bubble diameter, overall gas holdup, and overall interfacial area.

The following conclusions may be drawn from the experimental results reported here:

1. For the different concentrations of $25\mu\text{m}$ glass particles (0 to 1.2 wt %), the presence of the finely divided suspended solids decreases the local values of bubble diameter, gas holdup, and interfacial area. These results may be interpreted as an increase in the number of bubble coalescences with faster larger bubbles thus reducing the holdup.
2. Larger particles have very little affect on the local values of bubble diameter, gas holdup or interfacial

area. Possibly this is because the large particles tend to move more independently from the fluid or bubble wake nor do the particles adsorb onto the gas-liquid interface and therefore appear not to be playing any role in coalescence.

3. All of the data can be correlated together into one equation with the exponent on the gas holdup consistent with the findings of Calderbank for air-water systems ($\theta_G^{.5}$). The mechanical gassed power exponent is lower than the one for Calderbank (-0.4 vs. -0.29) but we suspect an exponent of -0.25 and -0.4 for correlating overall bubble size versus gassed power.

APPENDIX I

ERROR ANALYSIS

As a result of a linear regression, a prediction of the bubble diameter as a function of local gas holdup and mechanical energy dissipation was determined. Generally speaking, the observed values will vary from the predicted value and are shown in the Figures A1-A4.

Figures A1 and Figure A2 show actual values of bubble diameter as they deviate from the predicted straight line correlation. The correlation is:

$$D_B = 2.7 \phi^{.468} P_G^{-.212}$$

The observed values were measured at locations 1-18 at $N = 200$ and $N = 250$ RPM.

Figures A3 and Figure A4 show the same with the observed values measured at locations 7-18 at $N = 200$ and $N = 250$ RPM. The predicted values are determined by this correlation.

$$D_B = 3.11 \phi^{.479} P_G^{-.274}$$

The absolute errors were measured for each point by:

$$\% \text{ Absolute Error} = \left| \frac{\text{Predicted} - \text{Actual}}{\text{Actual}} \right| \times 100$$

The values reported in the text are averaged absolute errors

for the mixing vessel.

Figure A1 - Bubble Diameter vs. Local Gas Holdup
at $N = 200$ rpm, $T = 20^\circ\text{C}$, $\mu = 0.01$ Pa·s, $\rho = 1000$ kg/m³.

Figure A2 - Bubble Diameter versus Local Gas Holdup at
 $N = 250$, $\phi > .04$, Locations 1-18.

Figure A3 - Bubble Diameter versus Local Gas Holdup at
 $N = 200$ RPM. $\phi > .04$, Upper Impeller Regions,
 Locations 7-18.

Figure A4 - Bubble Diameter versus Local Gas Holdup at
 $N = 250$ RPM, $\phi > .04$ Upper Impeller Regions,
 Locations, 7-18.

APPENDIX IIDERIVATIONSInterfacial Area

The derivation for the interfacial area equation,
is as follows:

Generally speaking

$$a = \text{Surface area per unit vol.} = \frac{A}{V}$$

And since gas holdup, ϕ_G , is defined as the volume of
gas in dispersion divided by the total volume, or

$$\phi_G = \frac{V_G}{V}$$

so

$$V = \frac{V_G}{\phi_G}$$

then

$$a = \frac{\pi D_B^2}{V_G / \phi_G}$$

The volume of a bubble sphere is:

$$V_G = \pi D_B^3 / 6$$

therefore

$$a = \frac{6 \phi_G}{D_B}$$

Mean Bubble Diameter

$$\bar{D}_B = \frac{\sum n D_B^3}{\sum n D_B^2} = \frac{\sum n D_B}{\sum n}$$

$$\text{where } \sum n D_B = \left(\frac{\phi V}{\frac{\pi D_B^3}{6}} \right) D_B + \dots = \frac{6 \phi V}{\pi D_B^2} + \dots$$

$$\text{and } \sum n = \frac{6 \phi V}{\pi D_B^3}$$

$$\text{therefore } \bar{D}_B = \frac{\phi / D_B^2 + \dots}{\phi / D_B^3 + \dots}$$

Gas Holdup

Local gas holdup measurements were calculated based on this equation.

$$\phi = \frac{V_G}{V_G + V_L}$$

The average of these local gas holdup values were calculated based on knowing the volumes of all 18 cells.

Locs # 1, 7, 13	=	347 cc each
2, 8, 14	=	522 cc each
3, 9, 15	=	522 cc each
4, 10, 16	=	522 cc each
5, 11, 17	=	522 cc each
6, 12, 18	=	522 cc each

The volume fraction is estimated and an average obtained.

The overall gas holdup for the entire mixing vessel is obtained by halving this value.

ONE - 1/2 CALCULATED DATA

APPENDIX III

RAW AND CALCULATED DATA

Time	Temp	Pressure	Flow	Calc. Flow	Calc. Temp	Calc. Pressure
1	25.0	1.0	0.137	0.137	25.0	1.0
2	25.0	1.0	0.168	0.168	25.0	1.0
3	25.0	1.0	0.215	0.215	25.0	1.0
4	25.0	1.0	0.264	0.264	25.0	1.0
5	25.0	1.0	0.306	0.306	25.0	1.0
6	25.0	1.0	0.367	0.367	25.0	1.0
7	25.0	1.0	0.415	0.415	25.0	1.0
8	25.0	1.0	0.475	0.475	25.0	1.0
9	25.0	1.0	0.562	0.562	25.0	1.0
10	25.0	1.0	0.689	0.689	25.0	1.0
11	25.0	1.0	0.815	0.815	25.0	1.0
12	25.0	1.0	1.000	1.000	25.0	1.0
13	25.0	1.0	1.100	1.100	25.0	1.0
14	25.0	1.0	1.200	1.200	25.0	1.0
15	25.0	1.0	1.300	1.300	25.0	1.0
16	25.0	1.0	1.400	1.400	25.0	1.0
17	25.0	1.0	1.500	1.500	25.0	1.0
18	25.0	1.0	1.600	1.600	25.0	1.0
19	25.0	1.0	1.700	1.700	25.0	1.0
20	25.0	1.0	1.800	1.800	25.0	1.0
21	25.0	1.0	1.900	1.900	25.0	1.0
22	25.0	1.0	2.000	2.000	25.0	1.0
23	25.0	1.0	2.100	2.100	25.0	1.0
24	25.0	1.0	2.200	2.200	25.0	1.0
25	25.0	1.0	2.300	2.300	25.0	1.0
26	25.0	1.0	2.400	2.400	25.0	1.0
27	25.0	1.0	2.500	2.500	25.0	1.0
28	25.0	1.0	2.600	2.600	25.0	1.0
29	25.0	1.0	2.700	2.700	25.0	1.0
30	25.0	1.0	2.800	2.800	25.0	1.0
31	25.0	1.0	2.900	2.900	25.0	1.0
32	25.0	1.0	3.000	3.000	25.0	1.0
33	25.0	1.0	3.100	3.100	25.0	1.0
34	25.0	1.0	3.200	3.200	25.0	1.0
35	25.0	1.0	3.300	3.300	25.0	1.0
36	25.0	1.0	3.400	3.400	25.0	1.0
37	25.0	1.0	3.500	3.500	25.0	1.0
38	25.0	1.0	3.600	3.600	25.0	1.0
39	25.0	1.0	3.700	3.700	25.0	1.0
40	25.0	1.0	3.800	3.800	25.0	1.0
41	25.0	1.0	3.900	3.900	25.0	1.0
42	25.0	1.0	4.000	4.000	25.0	1.0
43	25.0	1.0	4.100	4.100	25.0	1.0
44	25.0	1.0	4.200	4.200	25.0	1.0
45	25.0	1.0	4.300	4.300	25.0	1.0
46	25.0	1.0	4.400	4.400	25.0	1.0
47	25.0	1.0	4.500	4.500	25.0	1.0
48	25.0	1.0	4.600	4.600	25.0	1.0
49	25.0	1.0	4.700	4.700	25.0	1.0
50	25.0	1.0	4.800	4.800	25.0	1.0
51	25.0	1.0	4.900	4.900	25.0	1.0
52	25.0	1.0	5.000	5.000	25.0	1.0
53	25.0	1.0	5.100	5.100	25.0	1.0
54	25.0	1.0	5.200	5.200	25.0	1.0
55	25.0	1.0	5.300	5.300	25.0	1.0
56	25.0	1.0	5.400	5.400	25.0	1.0
57	25.0	1.0	5.500	5.500	25.0	1.0
58	25.0	1.0	5.600	5.600	25.0	1.0
59	25.0	1.0	5.700	5.700	25.0	1.0
60	25.0	1.0	5.800	5.800	25.0	1.0
61	25.0	1.0	5.900	5.900	25.0	1.0
62	25.0	1.0	6.000	6.000	25.0	1.0
63	25.0	1.0	6.100	6.100	25.0	1.0
64	25.0	1.0	6.200	6.200	25.0	1.0
65	25.0	1.0	6.300	6.300	25.0	1.0
66	25.0	1.0	6.400	6.400	25.0	1.0
67	25.0	1.0	6.500	6.500	25.0	1.0
68	25.0	1.0	6.600	6.600	25.0	1.0
69	25.0	1.0	6.700	6.700	25.0	1.0
70	25.0	1.0	6.800	6.800	25.0	1.0
71	25.0	1.0	6.900	6.900	25.0	1.0
72	25.0	1.0	7.000	7.000	25.0	1.0
73	25.0	1.0	7.100	7.100	25.0	1.0
74	25.0	1.0	7.200	7.200	25.0	1.0
75	25.0	1.0	7.300	7.300	25.0	1.0
76	25.0	1.0	7.400	7.400	25.0	1.0
77	25.0	1.0	7.500	7.500	25.0	1.0
78	25.0	1.0	7.600	7.600	25.0	1.0
79	25.0	1.0	7.700	7.700	25.0	1.0
80	25.0	1.0	7.800	7.800	25.0	1.0
81	25.0	1.0	7.900	7.900	25.0	1.0
82	25.0	1.0	8.000	8.000	25.0	1.0
83	25.0	1.0	8.100	8.100	25.0	1.0
84	25.0	1.0	8.200	8.200	25.0	1.0
85	25.0	1.0	8.300	8.300	25.0	1.0
86	25.0	1.0	8.400	8.400	25.0	1.0
87	25.0	1.0	8.500	8.500	25.0	1.0
88	25.0	1.0	8.600	8.600	25.0	1.0
89	25.0	1.0	8.700	8.700	25.0	1.0
90	25.0	1.0	8.800	8.800	25.0	1.0
91	25.0	1.0	8.900	8.900	25.0	1.0
92	25.0	1.0	9.000	9.000	25.0	1.0
93	25.0	1.0	9.100	9.100	25.0	1.0
94	25.0	1.0	9.200	9.200	25.0	1.0
95	25.0	1.0	9.300	9.300	25.0	1.0
96	25.0	1.0	9.400	9.400	25.0	1.0
97	25.0	1.0	9.500	9.500	25.0	1.0
98	25.0	1.0	9.600	9.600	25.0	1.0
99	25.0	1.0	9.700	9.700	25.0	1.0
100	25.0	1.0	9.800	9.800	25.0	1.0
101	25.0	1.0	9.900	9.900	25.0	1.0
102	25.0	1.0	10.000	10.000	25.0	1.0

TABLE A1

SYSTEM: AIR-WATER

ROW	LOC	N (RPM)	Q (CFM)	ϕ	DB (CM)	a (CM-1)
1	1	150	1.7	0.137	0.764	1.076
2	1	150	1.7	0.166	0.664	1.506
3	1	200	1.7	0.011	0.800	0.083
4	1	200	1.7	0.004	0.670	0.038
5	1	250	1.7	0.006	0.651	0.062
6	1	250	1.7	0.007	0.912	0.047
7	2	150	1.7	0.014	0.415	0.208
8	2	150	1.7	0.015	0.412	0.219
9	2	200	1.7	0.090	0.582	0.934
10	2	200	1.7	0.107	0.689	0.938
11	2	250	1.7	0.053	0.515	0.618
12	2	250	1.7	0.057	0.601	0.573
13	3	150	1.7	0.000	0.000	*
14	3	150	1.7	0.000	0.000	*
15	3	200	1.7	0.030	0.531	0.345
16	3	200	1.7	0.026	0.425	0.377
17	3	250	1.7	0.067	0.495	0.817
18	3	250	1.7	0.065	0.494	0.794
19	4	150	1.7	0.002	0.371	0.034
20	4	150	1.7	0.001	0.347	0.022
21	4	200	1.7	0.070	0.507	0.835
22	4	200	1.7	0.069	0.506	0.820
23	4	250	1.7	0.074	0.534	0.841
24	4	250	1.7	0.047	0.545	0.520
25	5	150	1.7	0.000	0.000	*
26	5	150	1.7	0.000	0.000	*
27	5	200	1.7	0.034	0.447	0.463
28	5	200	1.7	0.030	0.478	0.387
29	5	250	1.7	0.048	0.459	0.628
30	5	250	1.7	0.047	0.457	0.616
31	6	150	1.7	0.000	0.000	*
32	6	150	1.7	0.000	0.000	*
33	6	150	1.7	0.000	0.000	*
34	6	150	1.7	0.000	0.000	*
35	6	200	1.7	0.047	0.485	0.588
36	6	200	1.7	0.045	0.480	0.572
37	6	250	1.7	0.061	0.480	0.769
38	6	250	1.7	0.055	0.449	0.743

(Table A1 Continued)

39	7	150	1.7	0.108	0.571	1.138
40	7	150	1.7	0.108	0.561	1.154
41	7	200	1.7	0.053	0.527	0.610
42	7	200	1.7	0.074	0.531	0.838
43	7	250	1.7	0.055	0.475	0.699
44	7	250	1.7	0.053	0.469	0.689
45	8	150	1.7	0.040	0.494	0.497
46	8	150	1.7	0.034	0.450	0.465
47	8	200	1.7	0.084	0.488	1.039
48	8	200	1.7	*	*	*
49	8	250	1.7	0.054	0.458	0.708
50	8	250	1.7	0.059	0.422	0.839
51	9	150	1.7	0.000	0.267	0.009
52	9	150	1.7	0.001	0.336	0.022
53	9	200	1.7	0.066	0.448	0.883
54	9	200	1.7	0.060	0.478	0.759
55	9	250	1.7	0.114	0.549	1.250
56	9	250	1.7	0.073	0.476	0.928
57	10	150	1.7	0.034	0.435	0.479
58	10	150	1.7	0.059	0.493	0.727
59	10	200	1.7	0.083	0.498	1.004
60	10	200	1.7	0.138	0.596	1.396
61	10	250	1.7	0.062	0.443	0.841
62	10	250	1.7	0.066	0.429	0.929
63	11	150	1.7	0.000	0.000	*
64	11	150	1.7	0.005	0.450	0.067
65	11	150	1.7	0.002	0.316	0.040
66	11	200	1.7	0.062	0.462	0.816
67	11	200	1.7	0.059	0.418	0.849
68	11	250	1.7	0.057	0.434	0.788
69	11	250	1.7	0.060	0.429	0.847
70	12	150	1.7	0.007	0.396	0.111
71	12	150	1.7	0.008	0.491	0.103
72	12	200	1.7	0.085	0.549	0.937
73	12	200	1.7	0.075	0.557	0.817
74	12	250	1.7	0.080	0.460	1.050
75	12	250	1.7	0.085	0.464	1.102
76	13	150	1.7	0.128	0.559	1.375
77	13	150	1.7	0.134	0.603	1.337
78	13	200	1.7	0.064	0.431	0.891
79	13	200	1.7	0.071	0.452	0.942
80	13	250	1.7	0.079	0.466	1.019
81	13	250	1.7	0.080	0.503	0.960
82	14	150	1.7	0.055	0.523	0.633
83	14	150	1.7	0.034	0.452	0.457
84	14	200	1.7	0.075	0.546	0.826

85	14	200	1.7	0.093	0.568	0.992
86	14	250	1.7	0.071	0.461	0.927
87	14	250	1.7	0.079	0.498	0.950
88	15	150	1.7	0.034	0.469	0.445
89	15	150	1.7	0.041	0.469	0.533
90	15	200	1.7	0.075	0.509	0.890
91	15	200	1.7	0.072	0.512	0.843
92	15	250	1.7	0.105	0.491	1.283
93	15	250	1.7	0.108	0.507	1.282
94	16	150	1.7	0.052	0.631	0.494
95	16	150	1.7	0.081	0.651	0.750
96	16	200	1.7	0.067	0.586	0.685
97	16	200	1.7	0.088	0.603	0.878
98	16	250	1.7	0.079	0.516	0.926
99	16	250	1.7	0.082	0.506	0.982
100	17	150	1.7	0.006	0.363	0.109
101	17	150	1.7	0.009	0.397	0.137
102	17	200	1.7	0.055	0.569	0.581
103	17	200	1.7	0.091	0.590	0.931
104	17	250	1.7	0.078	0.458	1.020
105	17	250	1.7	0.099	0.520	1.141
106	18	150	1.7	0.030	0.745	0.243
107	18	150	1.7	0.032	0.741	0.261
108	18	200	1.7	0.057	0.563	0.609
109	18	200	1.7	0.061	0.559	0.660
110	18	250	1.7	0.084	0.565	0.891
111	18	250	1.7	0.087	0.521	1.006

TABLE A2

SYSTEM: AIR-WATER-SOLID
 SOLID TYPE: 25 μ M GLASS PARTICLES
 CONCENTRATION: 0.3 WT PERCENT

ROW	LOC	N(RPM)	Q(CFM)	DB(CM)	θ	a(CM-1)
1	1	150	1.7	0.512	0.079	0.932
2	1	150	1.7	0.452	0.070	0.931
3	1	150	1.7	0.562	0.063	0.675
4	1	200	1.7	*	*	*
5	1	200	1.7	*	*	*
6	1	200	1.7	*	*	*
7	1	250	1.7	*	*	*
8	1	250	1.7	*	*	*
9	2	150	1.7	0.157	0.002	0.104
10	2	150	1.7	0.161	0.001	0.060
11	2	150	1.7	0.269	0.002	0.057
12	2	200	1.7	0.465	0.078	1.013
13	2	200	1.7	0.431	0.071	0.989
14	2	250	1.7	0.490	0.074	0.914
15	2	250	1.7	0.475	0.077	0.981
16	3	150	1.7	0.377	0.024	0.395
17	3	150	1.7	0.409	0.026	0.391
18	3	200	1.7	0.449	0.066	0.888
19	3	200	1.7	0.516	0.061	0.709
20	3	250	1.7	0.448	0.063	0.848
21	3	250	1.7	0.484	0.070	0.874
22	3	250	1.7	0.454	0.076	1.003
23	4	150	1.7	0.413	0.022	0.325
24	4	150	1.7	0.389	0.015	0.238
25	4	200	1.7	0.481	0.053	0.666
26	4	200	1.7	0.667	0.074	0.667
27	4	250	1.7	0.402	0.028	0.424
28	4	250	1.7	0.389	0.042	0.650
29	5	150	1.7	*	*	*
30	5	200	1.7	0.604	0.036	0.357
31	5	200	1.7	0.675	0.040	0.357
32	5	250	1.7	0.458	0.038	0.508
33	5	250	1.7	0.562	0.041	0.445
34	6	150	1.7	0.424	0.001	0.024

35	6	200	1.7	0.619	0.059	0.578
36	6	200	1.7	0.553	0.061	0.671
37	6	250	1.7	0.536	0.064	0.721
38	6	250	1.7	*	0.059	*
39	7	150	1.7	0.418	0.074	1.073
40	7	150	1.7	0.506	0.077	0.913
41	7	200	1.7	0.481	0.036	0.452
42	7	200	1.7	0.426	0.036	0.520
43	7	250	1.7	0.469	0.056	0.715
44	7	250	1.7	0.465	0.052	0.677
45	8	150	1.7	0.381	0.023	0.367
46	8	150	1.7	0.379	0.019	0.313
47	8	200	1.7	0.459	0.048	0.638
48	8	200	1.7	0.472	0.055	0.701
49	8	250	1.7	0.422	0.054	0.779
50	8	250	1.7	0.497	0.057	0.699
51	9	150	1.7	0.451	0.002	0.037
52	9	150	1.7	0.429	0.002	0.034
53	9	200	1.7	0.453	0.043	0.578
54	9	200	1.7	0.448	0.046	0.616
55	9	200	1.7	0.498	0.046	0.561
56	9	250	1.7	0.439	0.077	1.055
57	9	250	1.7	0.469	0.066	0.853
58	10	150	1.7	0.400	0.018	0.275
59	10	150	1.7	0.463	0.016	0.215
60	10	200	1.7	0.530	0.080	0.913
61	10	200	1.7	0.593	0.081	0.823
62	10	250	1.7	0.446	0.058	0.791
63	10	250	1.7	0.398	0.058	0.878
64	11	150	1.7	*	*	*
65	11	150	1.7	0.341	0.003	0.060
66	11	150	1.7	0.313	0.002	0.046
67	11	200	1.7	0.444	0.057	0.777
68	11	200	1.7	0.479	0.058	0.733
69	11	250	1.7	0.391	0.061	0.941
70	11	250	1.7	0.443	0.058	0.791
71	12	150	1.7	0.386	0.009	0.154
72	12	150	1.7	0.418	0.012	0.173
73	12	200	1.7	0.491	0.076	0.936
74	12	200	1.7	0.457	0.070	0.930
75	12	250	1.7	0.450	0.059	0.791
76	12	250	1.7	0.437	0.061	0.836
77	13	150	1.7	0.501	0.100	1.196
78	13	150	1.7	0.512	0.101	1.188
79	13	200	1.7	0.480	0.059	0.736
80	13	200	1.7	0.451	0.069	0.926

81	13	250	1.7	0.473	0.072	0.917
82	13	250	1.7	0.453	0.075	0.996
83	14	150	1.7	0.431	0.035	0.499
84	14	150	1.7	0.420	0.033	0.479
85	14	200	1.7	0.427	0.056	0.796
86	14	200	1.7	0.461	0.059	0.767
87	14	250	1.7	0.568	0.064	0.678
88	15	150	1.7	*	*	*
89	15	150	1.7	0.283	0.002	0.044
90	15	200	1.7	0.390	0.042	0.649
91	15	200	1.7	0.413	0.035	0.510
92	15	250	1.7	0.405	0.049	0.726
93	15	250	1.7	0.387	0.044	0.686
94	16	150	1.7	0.653	0.023	0.213
95	16	150	1.7	0.471	0.018	0.238
96	16	200	1.7	0.598	0.073	0.733
97	16	200	1.7	0.577	0.070	0.736
98	16	250	1.7	0.467	0.069	0.893
99	16	250	1.7	0.475	0.093	1.175
100	17	150	1.7	0.442	0.009	0.126
101	17	150	1.7	0.592	0.012	0.121
102	17	200	1.7	0.507	0.056	0.663
103	17	200	1.7	0.568	0.065	0.692
104	17	250	1.7	0.466	0.068	0.878
105	17	250	1.7	0.506	0.067	0.793
106	18	150	1.7	0.468	0.010	0.139
107	18	150	1.7	0.324	0.009	0.172
108	18	200	1.7	0.500	0.071	0.853
109	18	200	1.7	0.509	0.065	0.775
110	18	250	1.7	0.477	0.069	0.874

TABLE A3

SYSTEM: AIR-WATER-SOLID
 SOLID TYPE: 254M GLASS PARTICLES
 CONCENTRATION: 0.6 WT PERCENT

ROW	LOC	N (RPM)	Q (CFM)	DB (CM)	θ	a (CM-1)
1	1	150	1.7	0.678	0.226	2.002
2	1	150	1.7	0.745	0.237	1.910
3	1	200	1.7	*	*	*
4	1	200	1.7	*	*	*
5	1	250	1.7	0.673	0.006	0.053
6	1	250	1.7	0.573	0.006	0.068
7	2	150	1.7	0.361	0.001	0.026
8	2	150	1.7	0.390	0.005	0.085
9	2	200	1.7	0.530	0.061	0.697
10	2	200	1.7	0.518	0.061	0.715
11	2	250	1.7	0.599	0.058	0.585
12	2	250	1.7	0.559	0.063	0.681
13	3	150	1.7	*	*	*
14	3	150	1.7	0.332	0.002	0.041
15	3	200	1.7	0.318	0.008	0.155
16	3	200	1.7	0.552	0.046	0.499
17	3	250	1.7	0.547	0.065	0.721
18	3	250	1.7	0.550	0.064	0.703
19	4	150	1.7	0.566	0.025	0.274
20	4	150	1.7	0.510	0.022	0.265
21	4	200	1.7	0.680	0.105	0.927
22	4	200	1.7	0.628	0.122	1.168
23	4	250	1.7	0.544	0.053	0.592
24	4	250	1.7	0.632	0.053	0.509
25	5	150	1.7	0.262	0.000	0.017
26	5	150	1.7	0.000	0.000	*
27	5	200	1.7	0.388	0.044	0.692
28	5	200	1.7	0.399	0.039	0.587
29	5	250	1.7	0.400	0.058	0.873
30	5	250	1.7	0.405	0.050	0.748
31	6	150	1.7	*	*	*
32	6	150	1.7	*	*	*
33	6	200	1.7	0.673	0.060	0.538
34	6	200	1.7	0.390	0.058	0.893

35	6	250	1.7	0.443	0.067	0.913
36	6	250	1.7	0.432	0.056	0.789
37	7	150	1.7	0.489	0.036	0.446
38	7	150	1.7	0.443	0.028	0.387
39	7	200	1.7	0.533	0.074	0.837
40	7	200	1.7	0.485	0.075	0.929
41	7	250	1.7	0.367	0.055	0.905
42	7	250	1.7	0.444	0.056	0.757
43	8	150	1.7	0.422	0.006	0.098
44	8	150	1.7	0.390	0.006	0.100
45	8	200	1.7	0.493	0.077	0.941
46	8	200	1.7	0.546	0.067	0.741
47	8	250	1.7	0.444	0.064	0.876
48	8	250	1.7	0.442	0.053	0.724
49	9	150	1.7	*	*	*
50	9	150	1.7	*	*	*
51	9	200	1.7	0.416	0.061	0.889
52	9	200	1.7	0.420	0.054	0.781
53	9	250	1.7	0.465	0.097	1.252
54	9	250	1.7	0.485	0.099	1.235
55	10	150	1.7	0.486	0.005	0.063
56	10	150	1.7	0.294	0.007	0.159
57	10	200	1.7	0.490	0.082	1.007
58	10	200	1.7	0.491	0.084	1.027
59	10	250	1.7	0.465	0.070	0.910
60	10	250	1.7	0.466	0.074	0.952
61	11	150	1.7	0.489	0.011	0.144
62	11	150	1.7	0.506	0.011	0.132
63	11	200	1.7	0.622	0.063	0.611
64	11	200	1.7	0.663	0.074	0.674
65	11	250	1.7	0.581	0.068	0.705
66	11	250	1.7	0.601	0.057	0.573
67	12	150	1.7	0.478	0.003	0.049
68	12	150	1.7	0.426	0.003	0.055
69	12	200	1.7	0.456	0.065	0.864
70	12	200	1.7	0.528	0.056	0.639
71	12	250	1.7	0.435	0.074	1.023
72	12	250	1.7	0.428	0.080	1.131
73	13	150	1.7	0.586	0.065	0.668
74	13	150	1.7	0.502	0.056	0.672
75	13	200	1.7	0.481	0.067	0.836
76	13	200	1.7	0.505	0.070	0.833
77	13	250	1.7	0.445	0.054	0.736
78	13	250	1.7	0.468	0.054	0.692
79	14	150	1.7	0.337	0.016	0.285
80	14	150	1.7	0.424	0.018	0.264

81	14	200	1.7	0.430	0.045	0.633
82	14	200	1.7	0.443	0.051	0.699
83	14	250	1.7	0.486	0.062	0.768
84	14	250	1.7	0.426	0.057	0.801
85	15	150	1.7	0.212	0.001	0.056
86	15	150	1.7	0.329	0.002	0.051
87	15	200	1.7	0.392	0.035	0.545
88	15	200	1.7	0.394	0.029	0.453
89	15	250	1.7	0.456	0.039	0.517
90	15	250	1.7	0.369	0.032	0.525
91	16	150	1.7	0.855	0.024	0.173
92	16	150	1.7	0.572	0.035	0.374
93	16	200	1.7	0.476	0.080	1.016
94	16	200	1.7	0.488	0.072	0.892
95	16	250	1.7	0.404	0.082	1.230
96	16	250	1.7	0.387	0.071	1.108
97	17	150	1.7	0.369	0.004	0.079
98	17	150	1.7	0.348	0.005	0.100
99	17	200	1.7	0.455	0.047	0.619
100	17	200	1.7	0.373	0.054	0.878
101	17	250	1.7	0.378	0.069	1.103
102	17	250	1.7	0.398	0.072	1.088
103	18	150	1.7	0.324	0.008	0.156
104	18	150	1.7	0.311	0.005	0.112
105	18	200	1.7	0.420	0.058	0.828
106	18	200	1.7	0.424	0.050	0.711
107	18	250	1.7	0.396	0.065	0.992
108	18	250	1.7	0.435	0.065	0.901

TABLE A4

SYSTEM: AIR-WATER-SOLID
 SOLID TYPE: 25 μ M GLASS PARTICLES
 CONCENTRATION: 0.6 WT PERCENT
 NOTE: RERUN OF UPPER REGION

ROW	LCC	N(RFM)	O(CFM)	DB(CM)	ϕ	a(CM-1)
1	8	250	1.7	0.463	0.0560	0.725
2	8	250	1.7	0.406	0.0567	0.836
3	8	200	1.7	0.436	0.0417	0.574
4	8	200	1.7	0.519	0.0454	0.525
5	9	250	1.7	0.469	0.0547	0.699
6	9	250	1.7	0.420	0.0790	1.127
7	9	200	1.7	0.380	0.0435	0.685
8	9	200	1.7	0.401	0.0465	0.696
9	10	250	1.7	0.466	0.0709	0.912
10	10	250	1.7	0.410	0.0747	1.092
11	10	200	1.7	0.486	0.0624	0.769
12	10	200	1.7	0.472	0.0578	0.735
13	11	250	1.7	0.455	0.0653	0.861
14	11	250	1.7	0.462	0.0632	0.820
15	11	200	1.7	0.401	0.0404	0.603
16	11	200	1.7	0.459	0.0386	0.504
17	12	250	1.7	0.638	0.0705	0.662
18	12	250	1.7	0.553	0.0735	0.797
19	12	200	1.7	0.466	0.0559	0.719
20	12	200	1.7	0.560	0.0586	0.627
21	14	250	1.7	0.452	0.0551	0.731
22	14	250	1.7	0.412	0.0558	0.812
23	14	200	1.7	0.432	0.0356	0.494
24	14	200	1.7	0.441	0.0407	0.552
25	15	250	1.7	0.402	0.0423	0.632
26	15	250	1.7	0.452	0.0475	0.630
27	15	200	1.7	0.380	0.0319	0.503
28	15	200	1.7	0.469	0.0298	0.380
29	16	250	1.7	0.418	0.0706	1.012
30	16	250	1.7	0.450	0.0705	0.940
31	16	200	1.7	0.459	0.0726	0.949
32	16	200	1.7	0.460	0.0734	0.958
33	17	250	1.7	0.429	0.0532	0.744

34	17	250	1.7	0.477	0.0628	0.789
35	17	200	1.7	0.424	0.0451	0.638
36	17	200	1.7	0.425	0.0395	0.558
37	18	250	1.7	0.423	0.0546	0.774
38	18	250	1.7	0.364	0.0413	0.680
39	18	200	1.7	0.522	0.0516	0.593
40	18	200	1.7	0.436	0.0464	0.637

TABLE A5

SYSTEM: AIR-WATER-SOLID
 SOLID TYPE: 254M GLASS PARTICLES
 CONCENTRATION: 1.2 WT PERCENT

ROW	LOC	N(RPM)	Q(CFM)	DB(CM)	0	a(CM-1)
1	1	150	1.7	0.617	0.213	2.072
2	1	150	1.7	0.693	0.216	1.873
3	1	200	1.7	0.473	0.002	0.026
4	1	200	1.7	0.539	0.003	0.041
5	1	250	1.7	0.331	0.008	0.160
6	1	250	1.7	0.396	0.014	0.217
7	2	150	1.7	0.326	0.000	0.017
8	2	150	1.7	*	*	*
9	2	200	1.7	0.449	0.086	1.153
10	2	200	1.7	0.441	0.079	1.083
11	2	250	1.7	0.468	0.066	0.853
12	2	250	1.7	0.461	0.065	0.846
13	3	150	1.7	*	*	*
14	3	150	1.7	*	*	*
15	3	200	1.7	0.424	0.043	0.619
16	3	200	1.7	0.415	0.040	0.583
17	3	250	1.7	0.415	0.063	0.915
18	3	250	1.7	0.412	0.061	0.895
19	4	150	1.7	*	*	*
20	4	150	1.7	*	*	*
21	4	200	1.7	0.454	0.074	0.977
22	4	200	1.7	0.546	0.084	0.926
23	4	250	1.7	0.474	0.070	0.887
24	4	250	1.7	0.537	0.070	0.787
25	5	150	1.7	*	*	*
26	5	150	1.7	*	*	*
27	5	200	1.7	0.413	0.043	0.627
28	5	200	1.7	0.443	0.040	0.544
29	5	250	1.7	0.450	0.053	0.717
30	5	250	1.7	0.431	0.050	0.699
31	6	150	1.7	*	*	*
32	6	150	1.7	*	*	*
33	6	200	1.7	0.430	0.039	0.549
34	6	200	1.7	0.416	0.038	0.557

35	6	250	1.7	0.484	0.049	0.609
36	6	250	1.7	0.413	0.046	0.668
37	7	150	1.7	0.578	0.079	0.828
38	7	150	1.7	0.531	0.083	0.937
39	7	200	1.7	0.405	0.034	0.509
40	7	200	1.7	0.430	0.037	0.517
41	7	250	1.7	0.378	0.053	0.844
42	7	250	1.7	0.345	0.050	0.878
43	8	150	1.7	0.262	0.003	0.087
44	8	150	1.7	0.222	0.002	0.057
45	8	200	1.7	0.422	0.030	0.436
46	8	200	1.7	0.625	0.089	0.858
47	8	250	1.7	0.422	0.045	0.643
48	8	250	1.7	0.525	0.057	0.654
49	9	150	1.7	0.315	0.002	0.039
50	9	150	1.7	*	*	*
51	9	200	1.7	0.430	0.052	0.728
52	9	200	1.7	0.457	0.059	0.787
53	9	250	1.7	0.545	0.080	0.882
54	9	250	1.7	0.451	0.083	1.110
55	10	150	1.7	0.335	0.004	0.087
56	10	150	1.7	0.332	0.006	0.114
57	10	200	1.7	0.586	0.112	1.150
58	10	200	1.7	0.569	0.120	1.272
59	10	250	1.7	0.475	0.076	0.968
60	10	250	1.7	0.517	0.090	1.052
61	11	150	1.7	0.413	0.003	0.044
62	11	150	1.7	0.317	0.002	0.056
63	11	200	1.7	0.554	0.062	0.680
64	11	200	1.7	0.526	0.068	0.784
65	11	250	1.7	0.465	0.069	0.898
66	11	250	1.7	0.464	0.076	0.984
67	12	150	1.7	0.238	0.002	0.053
68	12	150	1.7	0.367	0.001	0.025
69	12	200	1.7	0.491	0.065	0.795
70	12	200	1.7	0.486	0.067	0.837
71	12	250	1.7	0.537	0.080	0.894
72	12	250	1.7	0.502	0.083	0.997
73	13	150	1.7	0.612	0.084	0.831
74	13	150	1.7	0.559	0.069	0.743
75	13	200	1.7	0.454	0.065	0.864
76	13	200	1.7	0.515	0.071	0.835
77	13	250	1.7	0.417	0.076	1.093
78	13	250	1.7	0.420	0.072	1.036
79	14	150	1.7	0.374	0.020	0.326
80	14	150	1.7	0.486	0.016	0.205

(Table A5 Continued)

81	14	200	1.7	0.372	0.039	0.642
82	14	200	1.7	0.439	0.042	0.586
83	14	250	1.7	0.404	0.056	0.844
84	14	250	1.7	0.408	0.057	0.845
85	15	150	1.7	*	*	*
86	15	150	1.7	*	*	*
87	15	200	1.7	0.375	0.012	0.198
88	15	200	1.7	0.332	0.017	0.311
89	15	250	1.7	0.348	0.034	0.592
90	15	250	1.7	0.339	0.030	0.536
91	16	150	1.7	0.742	0.037	0.301
92	16	150	1.7	0.639	0.043	0.406
93	16	200	1.7	1.002	0.103	0.621
94	16	200	1.7	0.863	0.109	0.762
95	16	250	1.7	0.633	0.078	0.745
96	16	250	1.7	0.648	0.074	0.685
97	17	150	1.7	*	*	*
98	17	150	1.7	*	*	*
99	17	200	1.7	0.539	0.054	0.611
100	17	200	1.7	0.428	0.046	0.650
101	17	250	1.7	0.462	0.043	0.563
102	17	250	1.7	0.508	0.047	0.565
103	18	150	1.7	0.300	0.002	0.044
104	18	150	1.7	0.436	0.004	0.055
105	18	200	1.7	0.509	0.066	0.785
106	18	200	1.7	0.438	0.068	0.935
107	18	250	1.7	0.433	0.068	0.947
108	18	250	1.7	0.447	0.063	0.852

TABLE A6

SYSTEM: AIR-WATER-SOLID
 SOLID TYPE: 70 μ M GLASS PARTICLES
 CONCENTRATION: 0.3 WT PERCENT

ROW	LOC	N (RPM)	Q (CFM)	DB (CM)	ϕ	a (CM-1)
1	7	200	1.7	0.575	0.0735	0.767
2	7	200	1.7	0.581	0.0710	0.733
3	7	250	1.7	0.635	0.0674	0.637
4	7	250	1.7	0.611	0.0661	0.648
5	8	200	1.7	0.486	0.0584	0.720
6	8	200	1.7	0.519	0.0576	0.665
7	8	250	1.7	0.498	0.0535	0.645
8	8	250	1.7	0.505	0.0554	0.658
9	9	200	1.7	0.404	0.0259	0.385
10	9	200	1.7	0.380	0.0311	0.490
11	9	250	1.7	0.378	0.0310	0.492
12	9	250	1.7	0.300	0.0315	0.629
13	10	200	1.7	0.433	0.0518	0.716
14	10	200	1.7	0.537	0.0548	0.612
15	10	250	1.7	0.572	0.0729	0.764
16	10	250	1.7	0.540	0.0774	0.859
17	11	200	1.7	0.420	0.0294	0.420
18	11	200	1.7	0.486	0.0315	0.389
19	11	250	1.7	0.495	0.0554	0.671
20	11	250	1.7	0.536	0.0495	0.553
21	12	200	1.7	0.401	0.0389	0.582
22	12	200	1.7	0.390	0.0386	0.593
23	12	250	1.7	0.409	0.0705	1.033
24	12	250	1.7	0.396	0.0675	1.022
25	13	200	1.7	0.521	0.0590	0.679
26	13	200	1.7	0.491	0.0606	0.740
27	13	250	1.7	0.470	0.0564	0.719
28	13	250	1.7	0.426	0.0627	0.882
29	14	200	1.7	0.412	0.0311	0.452
30	14	200	1.7	0.486	0.0374	0.462
31	14	250	1.7	0.360	0.0407	0.677
32	14	250	1.7	0.428	0.0433	0.606
33	15	200	1.7	0.342	0.0083	0.146
34	15	200	1.7	0.328	0.0081	0.149

35	15	250	1.7	0.410	0.0131	0.191
36	15	250	1.7	0.275	0.0118	0.258
37	16	200	1.7	0.388	0.0419	0.647
38	16	200	1.7	0.454	0.0480	0.633
39	16	250	1.7	0.430	0.0623	0.868
40	16	250	1.7	0.395	0.0582	0.885
41	17	200	1.7	0.402	0.0149	0.223
42	17	200	1.7	0.387	0.0118	0.183
43	17	250	1.7	0.466	0.0332	0.427
44	17	250	1.7	0.401	0.0315	0.470
45	18	200	1.7	0.405	0.0421	0.623
46	18	200	1.7	0.411	0.0349	0.509
47	18	250	1.7	0.414	0.0709	1.026
48	18	250	1.7	0.387	0.0732	1.134

TABLE A7

SYSTEM: AIR-WATER-SOLID
 SOLID TYPE: 70 μ M GLASS PARTICLES
 CONCENTRATION: 1.2 WT PERCENT

ROW	LOC	N (RPM)	Q (CFM)	DB (CM)	ϕ	a (CM-1)
1	7	200	1.7	0.622	0.0368	0.933
2	7	200	1.7	0.572	0.0867	0.909
3	7	250	1.7	0.517	0.0696	0.807
4	7	250	1.7	0.553	0.0716	0.776
5	8	200	1.7	0.603	0.0825	0.820
6	8	200	1.7	0.516	0.0670	0.779
7	8	250	1.7	0.561	0.0758	0.811
8	8	250	1.7	0.559	0.0722	0.774
9	9	200	1.7	0.415	0.0375	0.542
10	9	200	1.7	0.444	0.0357	0.482
11	9	250	1.7	0.402	0.0483	0.721
12	9	250	1.7	0.421	0.0586	0.834
13	10	200	1.7	0.451	0.0577	0.766
14	10	200	1.7	0.494	0.0610	0.741
15	10	250	1.7	0.526	0.0894	1.020
16	10	250	1.7	0.501	0.0774	0.925
17	11	200	1.7	0.353	0.0298	0.506
18	11	200	1.7	0.393	0.0252	0.385
19	11	250	1.7	0.375	0.0508	0.812
20	11	250	1.7	0.385	0.0476	0.741
21	12	200	1.7	0.469	0.0472	0.603
22	12	200	1.7	0.424	0.0443	0.626
23	12	250	1.7	0.437	0.0782	1.073
24	12	250	1.7	0.398	0.0736	1.109
25	12	250	1.7	0.418	0.0773	1.109
26	13	200	1.7	0.676	0.0738	0.655
27	13	200	1.7	0.619	0.0713	0.691
28	13	250	1.7	0.571	0.0713	0.748
29	13	250	1.7	0.579	0.0770	0.798
30	14	200	1.7	0.510	0.0366	0.431
31	14	200	1.7	0.486	0.0366	0.452
32	14	250	1.7	0.484	0.0468	0.579
33	14	250	1.7	0.557	0.0499	0.537
34	15	200	1.7	0.390	0.0217	0.334

(Table A7 Continued)

35	15	200	1.7	0.436	0.0201	0.276
36	15	250	1.7	0.479	0.0310	0.389
37	15	250	1.7	0.404	0.0285	0.423
38	16	200	1.7	0.462	0.0454	0.590
39	16	200	1.7	0.469	0.0490	0.627
40	16	250	1.7	0.503	0.0683	0.814
41	16	250	1.7	0.474	0.0631	0.799
42	17	200	1.7	0.421	0.0176	0.251
43	17	200	1.7	0.426	0.0158	0.222
44	17	250	1.7	0.415	0.0282	0.407
45	17	250	1.7	0.436	0.0298	0.410
46	18	200	1.7	0.400	0.0245	0.367
47	18	200	1.7	0.376	0.0250	0.399
48	18	250	1.7	0.436	0.0619	0.851
49	18	250	1.7	0.462	0.0632	0.820

TABLE A8

SYSTEM: AIR-WATER

ROW	LOC	N (RPM)	Q (CFM)	DB (CM)	ϕ	a (CM-1)
1	7	200	1.7	0.558	0.0920	0.988
2	7	200	1.7	0.544	0.0876	0.966
3	7	250	1.7	0.530	0.0705	0.797
4	7	250	1.7	0.487	0.0790	0.972
5	8	200	1.7	0.566	0.0574	0.608
6	8	200	1.7	0.496	0.0616	0.744
7	8	250	1.7	0.486	0.0637	0.786
8	8	250	1.7	0.553	0.0729	0.791
9	9	200	1.7	0.403	0.0358	0.532
10	9	200	1.7	0.448	0.0314	0.420
11	9	250	1.7	0.493	0.0479	0.582
12	9	250	1.7	0.486	0.0376	0.464
13	10	200	1.7	0.443	0.0388	0.526
14	10	200	1.7	0.476	0.0459	0.578
15	10	250	1.7	0.462	0.0779	1.011
16	10	250	1.7	0.488	0.0733	0.901
17	11	200	1.7	0.373	0.0265	0.426
18	11	200	1.7	0.350	0.0272	0.467
19	11	250	1.7	0.381	0.0387	0.608
20	11	250	1.7	0.400	0.0443	0.663
21	12	200	1.7	0.438	0.0357	0.488
22	12	200	1.7	0.406	0.0349	0.515
23	12	250	1.7	0.392	0.0748	1.144
24	12	250	1.7	0.396	0.0757	1.146
25	13	200	1.7	0.485	0.0672	0.830
26	13	200	1.7	0.503	0.0660	0.787
27	13	250	1.7	0.508	0.0585	0.691
28	13	250	1.7	0.500	0.0662	0.794
29	14	200	1.7	0.426	0.0297	0.418
30	14	200	1.7	0.418	0.0323	0.463
31	14	250	1.7	0.406	0.0344	0.509
32	14	250	1.7	0.442	0.0366	0.497
33	15	200	1.7	0.346	0.0103	0.179
34	15	200	1.7	0.420	0.0135	0.192

35	15	250	1.7	0.347	0.0100	0.173
36	15	250	1.7	0.362	0.0107	0.178
37	16	200	1.7	0.391	0.0251	0.386
38	16	200	1.7	0.375	0.0275	0.440
39	16	250	1.7	0.447	0.0460	0.617
40	16	250	1.7	0.461	0.0460	0.599
41	17	200	1.7	0.429	0.0121	0.169
42	17	200	1.7	0.419	0.0121	0.173
43	17	250	1.7	0.390	0.0211	0.325
44	17	250	1.7	0.411	0.0250	0.365
45	18	200	1.7	0.383	0.0248	0.388
46	18	200	1.7	0.414	0.0284	0.411
47	18	250	1.7	0.391	0.0613	0.941
48	18	250	1.7	0.411	0.0590	0.861

TABLE A9

SYSTEM: AIR-WATER-SOLID
 SOLID TYPE: 200 μ M GLASS PARTICLES
 CONCENTRATION: 0.3 WT PERCENT

ROW	LOC	N (RPM)	Q (CFM)	DB (CM)	ϕ	a (CM-1)
1	7	250	1.7	0.494	0.0718	0.871
2	7	250	1.7	0.521	0.0847	0.975
3	8	250	1.7	0.471	0.0700	0.890
4	8	250	1.7	0.515	0.0643	0.748
5	9	250	1.7	0.480	0.0467	0.583
6	9	250	1.7	0.511	0.0475	0.558
7	10	250	1.7	0.501	0.0786	0.941
8	10	250	1.7	0.476	0.0714	0.898
9	11	250	1.7	0.649	0.0353	0.326
10	11	250	1.7	0.507	0.0367	0.434
11	12	250	1.7	0.440	0.0666	0.909
12	12	250	1.7	0.400	0.0679	1.018
13	12	250	1.7	0.476	0.0888	1.119
14	13	250	1.7	0.440	0.0593	0.807
15	13	250	1.7	0.477	0.0597	0.751
16	14	250	1.7	0.403	0.0336	0.500
17	14	250	1.7	0.444	0.0374	0.504
18	15	250	1.7	0.347	0.0095	0.164
19	15	250	1.7	0.383	0.0116	0.181
20	16	250	1.7	0.497	0.0788	0.951
21	16	250	1.7	0.487	0.0658	0.810
22	17	250	1.7	0.385	0.0187	0.291
23	17	250	1.7	0.405	0.0219	0.325
24	18	250	1.7	0.412	0.0674	0.982
25	18	250	1.7	0.448	0.0683	0.914
26	19	250	1.7	0.482	0.0783	0.974
27	19	250	1.7	0.507	0.0848	1.002
28	19	250	1.7	0.524	0.0891	1.020
29	20	250	1.7	0.433	0.0470	0.650
30	20	250	1.7	0.429	0.0463	0.646
31	21	250	1.7	0.360	0.0265	0.441
32	21	250	1.7	0.390	0.0252	0.388
33	22	250	1.7	0.434	0.0709	0.980
34	22	250	1.7	0.461	0.0649	0.843
35	23	250	1.7	0.441	0.0263	0.358
36	23	250	1.7	0.396	0.0256	0.387
37	24	250	1.7	0.452	0.0531	0.705
38	24	250	1.7	0.444	0.0484	0.653

TABLE A10

SYSTEM: AIR-WATER-SOLID
 SOLID TYPE: 200 μ M GLASS PARTICLES
 CONCENTRATION: 1.2 WT PERCENT

ROW	LOC	N(RPM)	Q(CFM)	DB(CM)	ϕ	a(CM-1)
1	7	250	1.7	0.481	0.083	1.045
2	7	250	1.7	0.560	0.100	1.072
3	8	250	1.7	0.505	0.059	0.711
4	8	250	1.7	0.474	0.069	0.876
5	9	250	1.7	0.457	0.059	0.785
6	9	250	1.7	0.506	0.063	0.747
7	10	250	1.7	0.549	0.076	0.837
8	10	250	1.7	0.522	0.082	0.942
9	11	250	1.7	0.584	0.058	0.595
10	11	250	1.7	0.616	0.055	0.539
11	12	250	1.7	0.411	0.068	0.996
12	12	250	1.7	0.398	0.063	0.964
13	13	250	1.7	0.578	0.100	1.043
14	13	250	1.7	0.591	0.085	0.871
15	14	250	1.7	0.523	0.057	0.663
16	14	250	1.7	0.542	0.061	0.684
17	15	250	1.7	0.469	0.037	0.479
18	15	250	1.7	0.414	0.021	0.314
19	16	250	1.7	0.421	0.074	1.066
20	16	250	1.7	0.449	0.072	0.971
21	17	250	1.7	0.444	0.027	0.366
22	17	250	1.7	0.447	0.030	0.411
23	18	250	1.7	0.409	0.047	0.689
24	18	250	1.7	0.480	0.059	0.748
25	19	250	1.7	0.486	0.088	1.085
26	19	250	1.7	0.477	0.091	1.153
27	20	250	1.7	0.443	0.056	0.764
28	20	250	1.7	0.429	0.054	0.758
29	21	250	1.7	0.438	0.027	0.378
30	21	250	1.7	0.369	0.022	0.361
31	22	250	1.7	0.454	0.067	0.888
32	22	250	1.7	0.498	0.066	0.796
33	23	250	1.7	0.398	0.023	0.347
34	23	250	1.7	0.379	0.025	0.396
35	24	250	1.7	0.405	0.041	0.611
36	24	250	1.7	0.392	0.038	0.585

TABLE A 11

SYSTEM: AIR-WATER

ROW	LOC	N(RPM)	Q(CFM)	ϕ	DB(CM)	a(CM-1)
1	1	150	3	0.483	0.197	2.455
2	1	150	3	0.536	0.216	2.420
3	1	150	3	0.493	0.196	2.386
4	1	200	3	0.511	0.193	2.270
5	1	200	3	0.526	0.203	2.325
6	1	250	3	0.308	0.013	0.265
7	1	250	3	0.408	0.013	0.196
8	1	250	3	0.391	0.014	0.223
1	2	150	3	0.367	0.047	0.773
2	2	150	3	0.400	0.051	0.773
3	2	200	3	0.405	0.077	1.142
4	2	200	3	0.360	0.078	1.314
5	2	200	3	0.468	0.072	0.933
6	2	250	3	0.434	0.025	0.355
7	2	250	3	0.438	0.026	0.363
1	3	150	3	*	*	*
2	3	200	3	*	*	*
3	3	250	3	0.442	0.092	1.248
4	3	250	3	0.494	0.095	1.153
1	4	150	3	0.529	0.012	0.1416
2	4	150	3	0.511	0.011	0.1395
3	4	200	3	0.451	0.023	0.3075
4	4	200	3	0.401	0.021	0.3142
5	4	250	3	0.437	0.096	1.3181
6	4	250	3	0.476	0.103	1.2990
1	5	*	3	*	*	*
2	5	200	3	*	*	*
3	5	250	3	0.392	0.064	0.989
4	5	250	3	0.395	0.061	0.937

1	6	150	3	*	*	*
2	6	200	3	*	*	*
3	6	250	3	0.427	0.0743	1.044
4	6	250	3	0.424	0.0665	0.940
1	7	150	3	0.600	0.150	1.503
2	7	150	3	0.585	0.142	1.457
3	7	200	3	0.655	0.179	1.644
4	7	200	3	0.650	0.181	1.674
5	7	250	3	0.515	0.086	1.009
6	7	250	3	0.498	0.084	1.016
1	8	150	3	0.430	0.021	0.294
2	8	150	3	0.430	0.022	0.318
3	8	150	3	0.459	0.023	0.308
4	8	200	3	0.482	0.046	0.578
5	8	200	3	0.437	0.043	0.591
6	8	250	3	0.554	0.124	1.344
7	8	250	3	0.495	0.123	1.492
1	9	150	3	0.495	0.002	0.034
2	9	150	3	0.617	0.003	0.032
3	9	200	3	0.417	0.016	0.239
4	9	200	3	0.337	0.015	0.284
5	9	250	3	0.459	0.107	1.407
6	9	250	3	0.494	0.101	1.231
1	10	150	3	0.471	0.032	0.416
2	10	150	3	0.569	0.029	0.315
3	10	200	3	0.477	0.056	0.713
4	10	200	3	0.465	0.060	0.778
5	10	250	3	0.503	0.124	1.481
6	10	250	3	0.480	0.112	1.404
1	11	150	3	0.239	0.000	0.008
2	11	150	3	0.000	0.000	*
3	11	200	3	0.297	0.012	0.248
4	11	200	3	0.277	0.010	0.229
5	11	250	3	0.544	0.123	1.359
6	11	250	3	0.478	0.117	1.469
1	12	150	3	0.468	0.003	0.038
2	12	200	3	0.553	0.075	0.820
3	12	250	3	0.535	0.118	1.330
4	12	250	3	0.674	0.123	1.095
1	13	150	3	0.618	0.188	1.831

2	13	200	3	0.508	0.101	1.196
3	13	250	3	0.559	0.106	1.137
4	13	250	3	0.538	0.115	1.284
1	14	150	3	0.653	0.071	0.659
2	14	200	3	0.429	0.082	1.153
3	14	250	3	0.528	0.127	1.442
4	14	250	3	0.540	0.138	1.538
1	15	150	3	0.399	0.012	0.192
2	15	200	3	0.376	0.030	0.493
3	15	250	3	0.472	0.139	1.769
4	15	250	3	0.458	0.137	1.799
1	16	150	3	0.392	0.035	0.547
2	16	200	3	0.446	0.060	0.809
3	16	250	3	0.450	0.114	1.527
4	16	250	3	0.385	0.126	1.973
1	17	150	3	0.373	0.009	0.159
2	17	200	3	0.564	0.061	0.658
3	17	250	3	0.518	0.072	0.842
4	17	250	3	0.455	0.073	0.970
1	18	150	3	0.407	0.006	0.093
2	18	200	3	0.326	0.027	0.509
3	18	250	3	0.462	0.085	1.105
4	18	250	3	0.435	0.077	1.062

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