An Investigation into the Influence of Suspended Glass Particles on Bubble Diameter, Gas Holdup, and Interfacial Area in an Agitated Tank

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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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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 \( a = 6 \frac{0G}{D_B} \).

Consistently, experimental results show significant decreases in bubble diameter, gas holdup and correspondingly a decrease in interfacial area with the initial addition of 25 \( \mu \)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 μm, 200 μm) 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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# TABLE OF CONTENTS

| TITLE PAGE | PAGE NO. |
|------------|----------|
|            |          |

| ABSTRACT | ii |
|----------|----|
| ACKNOWLEDGEMENT | v |
| TABLE OF CONTENTS | vii |
| NOMENCLATURE | viii |
| LIST OF TABLES | x |
| LIST OF FIGURES | xii |

## CHAPTER

| I. INTRODUCTION | 1 |
|-----------------|---|
| II. LITERATURE SURVEY | 7 |
| III. EXPERIMENTAL APPARATUS AND PROCEDURES | 18 |
| IV. EXPERIMENTAL RESULTS | 31 |
| V. DISCUSSION OF RESULTS | 46 |
| VI. SUMMARY AND CONCLUSION | 58 |

| APPENDIX | 60 |
|----------|---|
| BIBLIOGRAPHY | 95 |
| Symbol | Description |
|--------|-------------|
| 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, Ft-lb\(_F\)/sec |
| \(P_G\) | mechanical power transmitted by the agitator in an aerated medium, Ft-lb\(_F\)/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

$\mu_G$ dynamic viscosity of the gas, cp

$\mu_L$ dynamic viscosity of the liquid, cp

$\rho_G$ mass density of the gas, gm/cc

$\rho_L$ mass density of the liquid, gm/cc

$\sigma_L$ liquid surface tension, dynes/cm

$\phi_G$ overall gas holdup, volume fraction of gas

$\phi$ local gas holdup, point volume fraction of gas
LIST OF TABLES

| TABLE NO. | DESCRIPTION | PAGE NO. |
|-----------|-------------|----------|
| 1         | Effect of 25\(\mu\)m glass particles on local gas holdup with increasing solids concentration at \(N = 150\) RPM. | 32       |
| 2         | Effect of 25\(\mu\)m glass particles on bubble diameter with increasing solids concentration at \(N = 150\) RPM. | 33       |
| 3         | Effect of 25\(\mu\)m glass particles on local gas holdup with increasing solids concentration at \(N = 200\) RPM. | 35       |
| 4         | Effect of 25\(\mu\)m glass particles on bubble diameter with increasing solids concentration at \(N = 200\) RPM. | 36       |
| 5         | Effect of 25\(\mu\)m glass particles on local gas holdup with increasing solids concentration at \(N = 250\) RPM. | 37       |
| 6         | Effect of 25\(\mu\)m glass particles on bubble diameter with increasing solids concentration at \(N = 250\) RPM. | 38       |
| 7         | Effect of 70\(\mu\)m glass particles on local gas holdup and bubble diameter with increasing solids concentration at \(N = 200\) RPM. | 40       |
| 8         | Effect of 70\(\mu\)m glass particles on local gas holdup and bubble diameter with increasing solids concentration at \(N = 250\) RPM. | 41       |
| 9         | Effect of 200\(\mu\)m glass particles on local gas holdup and bubble diameter with increasing solids concentration at \(N = 250\) RPM. | 43       |
| 10        | Literature comparisons. | 57       |
| TABLE NO. | PAGE NO. | Description |
|-----------|----------|-------------|
| A1 -      | 70       | Local distribution of bubble diameter, gas holdup, and interfacial area in an air-water dispersion (HA = T/2). |
| A2 -      | 73       | Local distribution of bubble diameter, gas holdup, and interfacial area in an air-water-solid (25 μm) system at 0.3 wt percent (HA = T/2). |
| A3 -      | 76       | Local distribution of bubble diameter, gas holdup and interfacial area in an air-water-solid (25 μm) system at 0.6 wt percent (HA = T/2). |
| A4 -      | 79       | Local distribution of bubble diameter, gas holdup, and interfacial area in an air-water-solid (25 μm) system at 0.6 wt percent for the upper impeller region (HA = T/2). |
| A5 -      | 81       | Local distribution of bubble diameter, gas holdup, and interfacial area in an air-water-solid (25 μm) system at 1.2 wt percent (HA = T/2). |
| A6 -      | 84       | Local distribution of bubble diameter, gas holdup, and interfacial area in an air-water solid (70 μm) system at 0.3 wt percent (HA = T/4). |
| A7 -      | 86       | Local distribution of bubble diameter, gas holdup, and interfacial area in an air-water-solid (70 μm) system at 1.2 wt percent (HA = T/4). |
| A8 -      | 88       | Local distribution of bubble diameter, gas holdup, and interfacial area in an air-water dispersion (HA = T/4). |
| A9 -      | 90       | Local distribution of bubble diameter, gas holdup, and interfacial area in an air-water-solid (200 μm) system at 0.3 wt percent (HA = T/4). |
| A10 -     | 91       | Local distribution of bubble diameter, gas holdup, and interfacial area in an air-water-solid (200 μm) system at 1.2 wt percent (HA = T/4). |
| A11 -     | 92       | Local distribution of bubble diameter, gas holdup, and interfacial area in an air-water dispersion at a higher gas rate of 3CFM (HA = T/2). |
# LIST OF FIGURES

| FIGURE NO. | DESCRIPTION                                                                 | PAGE NO. |
|------------|------------------------------------------------------------------------------|----------|
| 1          | Power of Agitation From Calderbank (1958).                                  | 15       |
| 2          | The relation between the observed two phase flow and the power consumption.  | 17       |
| 3          | The gassed power curves for different impeller speeds. From Warmoeskerken (1982). | 17       |
| 4          | Flow Diagram of Experimental Apparatus.                                    | 19       |
| 5          | Tank schematic                                                              | 21       |
| 6          | Spectra Physics Model 155 He-Ne Laser.                                     | 23       |
| 7          | Photocell biasing and operational amplifier circuitry.                     | 25       |
| 8          | Flow patterns in a mixing tank.                                            | 27       |
| 9          | Sampling locations.                                                         | 30       |
| FIGURE NO. | Description                                                                 | PAGE NO. |
|------------|-----------------------------------------------------------------------------|----------|
| A1         | Bubble diameter versus local gas holdup at N = 200 RPM, Ø > .04, locations 1-18 | 62       |
| A2         | Bubble diameter versus local gas holdup at N = 250 RPM, Ø > .04, locations 1-18. | 63       |
| A3         | Bubble diameter versus local gas holdup at N = 200 RPM, Ø > .04, upper impeller region, locations 7-18 | 64       |
| A4         | Bubble diameter versus local gas holdup at N = 250 RPM, Ø > .04, upper impeller region, locations 7-18. | 65       |
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 SO₂ 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 CO₂ 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 Parkas (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 $\text{CO}_2$ 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 $\mu$m. 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 \( a = \frac{6 \, \Omega G}{DB} \). 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 $K_La$ (Yoshida and Miura 1963, Robinson and Wilke 1974), interfacial area (Calderbank 1958, Sridhar and Potter 1980, Westerptterp 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:

$$D_B = \frac{60G}{a}$$

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:

$$D_B = 1.90 \left( \frac{\sigma}{(\rho_g V)^{0.4} \rho_L^{0.2}} \right) \phi^{0.65} \left( \frac{\mu_g}{\mu_L} \right)^{0.25}$$

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:

$$D_B = 4.15 \left( \frac{\sigma}{(\rho_g V)^{0.4} \rho_L^{0.2}} \right) \phi^{0.5} + 0.09 \text{ cm}$$
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 $\theta$. They presented their results in the form:

$$D_B = N^{-y_1} D^{-y_2}$$

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 $0.33\text{ mm}$ diameter by $3\text{ mm}$ 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 $\varnothing$ 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 $\varnothing$.

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

$$
\varnothing_G = \left( \frac{V_S \varnothing_G}{V_t} \right) + 0.0216 \left[ \frac{\left( \frac{\rho_G}{\rho_L} \right)^{0.4}}{\sigma_L^{0.6}} \right] \left( \frac{V_S}{V_t} \right)^{0.5}
$$

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 \( \text{CO}_2 \) 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
(dp < 0.42 \mu m) and 45% particles of slightly larger size (dp \approx 0.42 - 3.0 \mu 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), Westerpterp 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 $5\ell$ and $100\ell$, two correlations of the gassed power to ungassed power ratio ($PG/PO$) and the dimensionless aeration number, $NA$ in a dispersion of air in water, ethanol or glycol (see Figure 1).

$$PG/PO = 1-12.6 \ NA \quad NA < 0.03$$
$$PG/PO = 0.62-1.85 \ NA \quad NA > 0.035$$

Warmoeskerken et al (1982) measured for different impeller speeds the power ratio $PG/PO$ 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).
Experimental 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 75 l 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
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 25μm GLASS PARTICLES, \( H_A = \frac{T}{2} \)

For 70μm, 200μm GLASS PARTICLES, \( H_A = \frac{T}{4} \)

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 (do = 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/μm, 70/μm, and 200/μm 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 FT^3/MIN except for one gas-liquid study which is performed at 3.0 FT^3/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 (~ intensity of .025 watts/cm^2). The light from the laser is bright red with a wave length of 632.8 nanometers. The laser beam (beam diameter ~ .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 x 2.7 mm). The photodiode is
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 5648B 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
FIG. 7: Photocell biasing and operational amplifier circuitry.

\[ V_o = \left(-\frac{R_2}{R_1}\right) V_1 \]
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 25μm glass bead runs.

For the heavier, denser solids (70μm, 200μm) 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.
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\(\mu\)m Glass Particles

The effect of increasing solid concentration of 25\(\mu\)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 (0.3, 0.6, 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 25.4 μm glass particles on local gas holdup with increasing solids concentration (wt percent).

| ROW | LOC | 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 | 0.066 |
| 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 | 0.026 |
| 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 25μm glass particles on bubble diameter with increasing solids concentration (wt percent).

HA = T/2  HL = 45.72 CM  Q = 1.7 CFM
N = 150 RPM  PG = 2.71 FT-LBF/SEC

| BCW | LOC | 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| 0.33| 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 = 6G/DB = 0.187  0.144  0.125  0.138

NOTE: CALDERBANK PREDICTS

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, $\theta = 0.152$ for 0% then decreases with the 
initial addition of solids ($\theta = 0.0711 \times 0.3$ wt %). Loca-
tions 2-6 has so little gas fractions collected that no 
trend is possible except to say that the impeller is flood-
ed. Then at locations 7, 13, the decrease in local gas 
holdup is more evident with solid addition.

Table 3, 4 introduces $\theta$ 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 $\mu$m glass particles on local gas 
holdup and bubble diameter with increasing solids concentra-
tion, 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
| BGW | LOC | $\phi$ | $\phi_3$ | $\phi_6$ | $\phi_12$ |
|-----|-----|--------|---------|---------|-----------|
| 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     |

$\phi = 0.067 \quad 0.059 \quad 0.059 \quad 0.058$

$\phi_G = \phi / 2 = 0.033 \quad 0.0295 \quad 0.0295 \quad 0.0290$
TABLE 4  Effect of 25\(\mu\)m glass particles on bubble diameter with increasing solids concentration (wt percent).

\[\text{HA} = \frac{T}{2}, \quad \text{HL} = 45.72 \text{ CM}, \quad Q = 1.7 \text{ CFM}\]
\[N = 200 \text{ RPM}, \quad \text{PG} = 5.72 \text{ FT-LBF/SEC}\]

| ROW | LOC | 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 |

\[DB= 0.514 0.487 0.472 0.470\]

\[a=6\bar{G}/DB= 0.391 0.363 0.375 0.370\]

**NOTE:** CALDERBANK PREDICTS
\[\bar{G} = 0.027\]
\[DB = 0.632 \text{ CM}\]
\[a = 0.255 \text{ CM}^{-1}\]
TABLE 5  Effect of 25\mu m glass particles on local gas holdup with increasing solids concentration (wt percent).

| B/C | LOC | 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  | 0.055 | 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 |

ϕ = 0.070  0.059  0.062  0.061

ϕG=ϕ/2= 0.035  0.0295  0.031  0.0305
### TABLE 6  Effect of 25µm glass particles on bubble diameter with increasing solids concentration (wt percent).

HA= T/2  \[ 45.72 \text{ CM} \]  Q= 1.7 CFM
N= 250 RPM  PG= 10.26 FT-LEF/SEC

| ROW | LOC | 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=6G/DB=  

| 0.434 | 0.382 | 0.422 | 0.414 |

**NOTE:** CALDERBANK PREDICTS  
\( G= 0.029 \)  
\( DB= 0.512 \text{ CM} \)  
\( a= 0.339 \text{ CM}^{-1} \)
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.

Table 7 summarizes experimental data points for the effect of 70 \( \mu \)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 \( \mu \)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 70μm 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 = 200 RPM  PG = 5.72 FT-LBF/SEC

| ROW | LOC | 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 μm glass particles on local gas holdup and bubble diameter with increasing concentration. (wt percent).

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

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

Table 9 summarizes experimental results of adding 200 μm 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%, 0 = 5.1%, @ 0.3% 0 = 5.4%, and 1.2%, 0 = 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 μm and 70 μm glass particles) with the gassed power number, some intriguing correlations were developed which were very
### TABLE 9 Effect of 200 µm 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 | \( \phi \) | **DB** |
|-----|-----|-------|-------|
| 7   | 7   | 0.075 | 0.51  |
| 8   | 8   | 0.069 | 0.52  |
| 9   | 9   | 0.043 | 0.49  |
| 10  | 10  | 0.076 | 0.50  |
| 11  | 11  | 0.041 | 0.39  |
| 12  | 12  | 0.075 | 0.40  |
| 13  | 13  | 0.063 | 0.50  |
| 14  | 14  | 0.035 | 0.42  |
| 15  | 15  | 0.011 | 0.36  |
| 16  | 16  | 0.046 | 0.45  |
| 17  | 17  | 0.023 | 0.40  |
| 18  | 18  | 0.060 | 0.40  |
| 19  | 19  | * 0.084 | * 0.51 |
| 20  | 20  | * 0.046 | * 0.43 |
| 21  | 21  | * 0.025 | * 0.38 |
| 22  | 22  | * 0.067 | * 0.45 |
| 23  | 23  | * 0.026 | * 0.42 |
| 24  | 24  | * 0.050 | * 0.45 |
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:

\[ D_B = 2.7 \theta^{0.468} P_G^{-.212} \]

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 \( \theta \) 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 coalescing. 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:

\[ D_B = 3.11 \theta^{0.479} \rho_{G}^{-0.274} \]

Again, only local gas holdup values greater than 0.04 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:

\[ D_B = 3.41 \theta^{0.5} \rho_{G}^{-0.29} \]

The gassed power exponent was -0.29 versus the exponent of -0.4 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 μm 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% 0, >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 μm 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 CO₂ in aqueous sodium carbonate-bicarbonate solutions with CaCO₃ 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:

\[ D_B \propto \theta^{0.5} P_G^{-0.29} \]

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, $u^2(d) = C(\varepsilon d)^{2/3}$ thus combining those two equations
Therefore, in a stirred tank
\[ \frac{c_i \rho \varepsilon^{2/3} d^{8/3}}{A(h_0)} = \text{constant} \]

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
\[ N \left( \frac{PE}{V} \right) \propto N^3, N \propto \frac{PE}{V}^{-0.33} \]. From this fact, the bubble diameters can be interpreted in terms of either agitator speed or energy dissipation rate.

Breakage region: \[ D_B \propto N^{-6/5} \quad \text{or} \quad D_B \propto \left( \frac{PE}{V} \right)^{-40} \]

Coalescence region: \[ D_B \propto N^{-3/4} \quad \text{or} \quad D_B \propto \left( \frac{PE}{V} \right)^{-25} \]

As discussed before, we suspect that our system behaves similar to a coalesing 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\(\mu\)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 m, 200 \mu 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 extend 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 \( PG^{-0.29}(N^{-0.87}) \) also \( PG^{-0.21} \) 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 $0.5$ 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:

$$D_B \propto \phi^6 P_{\infty}^{0.4}$$  Calderbank

$$D_B \propto \phi^6 P_{\infty}^{0.5 - 0.29}$$  Randall

A comparison of this relationship to our results re-
flect a difference in the gassed power exponent, $PG^{-0.4}$. We suspect that one may expect an exponent between $-0.25$ and $-0.4$ for the overall bubble size.

For a summary of the literature comparisons, see Table 10.
### Table 10 - Literature Comparisons

| System                  | Exponent | References                      |
|-------------------------|----------|---------------------------------|
| Liquid                  | Gas      | $\delta G$, $P_G$               |
| 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                   | Randall¹ (1985)   |
|                         |          | 0.479, -0.274                   | Randall²          |
|                         |          | 0.5, -0.290                     | Randall³          |

**Notes:**
1. Locations 1-18 Absolute error = 9.3%
2. Locations 7-18 Absolute error = 9.2%
3. Force fit of $\delta G$ 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 μm 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 consis-
tent with the findings of Calderbank for air-water
systems ($\theta_G^{-.5}$). The mechanical gassed power exponent
is lower than the one for Calderbank (-.4 vs. -.29)
but we suspect an exponent of -.25 and -.4 for corre-
lating 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:

$$D_B = 2.7 \phi^{0.468} \phi^{0.212}$$

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.

$$D_B = 3.11 \phi^{0.479} \phi^{0.274}$$

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 Versus Local Gas Holdup at N = 200 RPM, \( \phi > 0.04 \), Locations 1-18.
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, $\phi > 0.04$ Upper Impeller Regions, Locations, 7–18.
Interfacial 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, \( \phi_G \), 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:

\[ V_G = \frac{\pi D_B^3}{6} \]

therefore

\[ a = \frac{6 \phi_G}{D_B} \]
Mean Bubble Diameter

\[
\bar{D_B} = \frac{\varepsilon \pi D_B^3}{\varepsilon \pi D_B^2} = \frac{\varepsilon \pi D_B}{\varepsilon \pi}
\]

where \( \varepsilon \pi D_B = \left(\frac{\varphi V}{\pi D_B^3}\right) D_B + \ldots = \frac{6 \varphi V}{\pi D_B^2} + \ldots \)

and \( \varepsilon \pi = \frac{6 \varphi V}{\pi D_B^3} \)

therefore \( \bar{D_B} = \frac{\varphi}{D_B^2} + \ldots \)

Gas Holdup

Local gas holdup measurements were calculated based on this equation.

\[
\varphi = \frac{V_G}{V_G + V_L}
\]

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.
### APPENDIX III

**RAW AND CALCULATED DATA**

| Value 1 | Value 2 | Value 3 |
|---------|---------|---------|
| 0.127   | 0.254   | 0.381   |
| 0.168   | 0.306   | 0.439   |
| 0.211   | 0.357   | 0.497   |
| 0.264   | 0.415   | 0.579   |
| 0.326   | 0.481   | 0.671   |
| 0.397   | 0.553   | 0.778   |
| 0.480   | 0.632   | 0.902   |
| 0.571   | 0.719   | 1.045   |
| 0.680   | 0.812   | 1.193   |
| 0.800   | 0.898   | 1.347   |
| 0.933   | 0.996   | 1.505   |
| 1.082   | 1.157   | 1.661   |
| 1.248   | 1.245   | 1.818   |
| 1.428   | 1.387   | 2.055   |
| 1.620   | 1.565   | 2.339   |
| 1.826   | 1.777   | 2.635   |
| 2.046   | 1.993   | 2.957   |
| 2.281   | 2.221   | 3.300   |
| 2.531   | 2.465   | 3.657   |
| 2.795   | 2.765   | 4.040   |
| 3.079   | 3.079   | 4.444   |
| 3.404   | 3.404   | 4.865   |
| 3.756   | 3.756   | 5.300   |
| 4.133   | 4.133   | 5.749   |
| 4.534   | 4.534   | 6.218   |
| 4.955   | 4.955   | 6.699   |
| 5.410   | 5.410   | 7.201   |
| 5.889   | 5.889   | 7.723   |
| 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   |
| 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 |
| ROW | LOC | N (RPM) | Q (CFM) | DB (CM) | $\phi$ | $a$ (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         |
(Table A2 Continued)

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
| 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 | 0.519 | 0.059 | 0.773 |
| 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 | 250 | 1.7 | 0.498 | 0.046 | 0.661 |
| 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 | 0.341 | 0.003 | 0.060 |
| 65 | 11 | 150 | 1.7 | 0.313 | 0.002 | 0.046 |
| 66 | 11 | 200 | 1.7 | 0.444 | 0.057 | 0.777 |
| 67 | 11 | 200 | 1.7 | 0.479 | 0.058 | 0.733 |
| 68 | 11 | 250 | 1.7 | 0.391 | 0.061 | 0.941 |
| 69 | 11 | 250 | 1.7 | 0.443 | 0.058 | 0.791 |
| 70 | 12 | 150 | 1.7 | 0.386 | 0.009 | 0.154 |
| 71 | 12 | 150 | 1.7 | 0.418 | 0.012 | 0.173 |
| 72 | 12 | 200 | 1.7 | 0.491 | 0.076 | 0.936 |
| 73 | 12 | 200 | 1.7 | 0.457 | 0.070 | 0.930 |
| 74 | 12 | 200 | 1.7 | 0.450 | 0.059 | 0.791 |
| 75 | 12 | 250 | 1.7 | 0.437 | 0.061 | 0.836 |
| 76 | 12 | 250 | 1.7 | 0.501 | 0.100 | 1.196 |
| 77 | 13 | 150 | 1.7 | 0.512 | 0.101 | 1.188 |
| 78 | 13 | 150 | 1.7 | 0.480 | 0.059 | 0.736 |
| 79 | 13 | 200 | 1.7 | 0.451 | 0.069 | 0.926 |
| 80 | 13 | 200 | 1.7 | * | * | * |

Table continued...
| 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 | * | 0.002 | 0.044 |
| 89 | 15 | 150 | 1.7 | 0.283 | 0.042 | 0.649 |
| 90 | 15 | 200 | 1.7 | 0.390 | 0.035 | 0.510 |
| 91 | 15 | 200 | 1.7 | 0.413 | 0.049 | 0.726 |
| 92 | 15 | 250 | 1.7 | 0.405 | 0.044 | 0.686 |
| 93 | 15 | 250 | 1.7 | 0.387 | 0.023 | 0.213 |
| 94 | 16 | 150 | 1.7 | 0.653 | 0.018 | 0.238 |
| 95 | 16 | 150 | 1.7 | 0.471 | 0.018 | 0.733 |
| 96 | 16 | 200 | 1.7 | 0.598 | 0.073 | 0.736 |
| 97 | 16 | 200 | 1.7 | 0.577 | 0.069 | 0.893 |
| 98 | 16 | 250 | 1.7 | 0.467 | 0.093 | 1.175 |
| 99 | 16 | 250 | 1.7 | 0.475 | 0.009 | 0.126 |
| 100 | 17 | 150 | 1.7 | 0.442 | 0.122 | 0.663 |
| 101 | 17 | 150 | 1.7 | 0.592 | 0.056 | 0.692 |
| 102 | 17 | 200 | 1.7 | 0.507 | 0.065 | 0.878 |
| 103 | 17 | 200 | 1.7 | 0.568 | 0.068 | 0.793 |
| 104 | 17 | 250 | 1.7 | 0.466 | 0.010 | 0.139 |
| 105 | 17 | 250 | 1.7 | 0.506 | 0.009 | 0.172 |
| 106 | 18 | 150 | 1.7 | 0.468 | 0.071 | 0.853 |
| 107 | 18 | 150 | 1.7 | 0.324 | 0.065 | 0.775 |
| 108 | 18 | 200 | 1.7 | 0.509 | 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(CPM) | DB(CM) | β  | a(CH-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 | 0.000   |
| 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| 200| 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| 0.485| 0.065| 0.901|
### TABLE A4

**SYSTEM:** AIR-WATER-SOLID  
**SOLID TYPE:** 254μM GLASS PARTICLES  
**CONCENTRATION:** 0.6 wt PERCENT  
**NOTE:** RERUN OF UPPER REGION

| ROW | LCC | N(BPM) | Q(CFM) | DB(CM) | $\phi$ | $a$ (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:** 25/48 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 | 0.430 | 0.052 | 0.728 |
|51 | 9 | 200 | 1.7 | 0.457 | 0.059 | 0.787 |
|52 | 9 | 200 | 1.7 | 0.545 | 0.080 | 0.882 |
|53 | 9 | 250 | 1.7 | 0.451 | 0.083 | 1.110 |
|54 | 9 | 250 | 1.7 | 0.335 | 0.004 | 0.087 |
|55 | 10 | 150 | 1.7 | 0.332 | 0.006 | 0.114 |
|56 | 10 | 150 | 1.7 | 0.586 | 0.112 | 1.150 |
|57 | 10 | 200 | 1.7 | 0.569 | 0.120 | 1.272 |
|58 | 10 | 250 | 1.7 | 0.475 | 0.076 | 0.968 |
|59 | 10 | 250 | 1.7 | 0.517 | 0.090 | 1.052 |
|60 | 10 | 250 | 1.7 | 0.413 | 0.003 | 0.044 |
|61 | 11 | 150 | 1.7 | 0.307 | 0.002 | 0.056 |
|62 | 11 | 200 | 1.7 | 0.554 | 0.062 | 0.680 |
|63 | 11 | 200 | 1.7 | 0.526 | 0.068 | 0.784 |
|64 | 11 | 200 | 1.7 | 0.332 | 0.004 | 0.087 |
|65 | 11 | 250 | 1.7 | 0.465 | 0.069 | 0.898 |
|66 | 11 | 250 | 1.7 | 0.564 | 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:** 70/40 GLASS PARTICLES
**CONCENTRATION:** 0.3 WT PERCENT

| ROW | LOC | N (RPM) | Q (CFM) | DB (CM) | $\phi$ | 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        |
(Table A6 Continued)

|   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|
| 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|   |   |
| 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 | 0.999   |
| 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) | Ø   | 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 | 0.979    |
| 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    |
(Table A8 Continued)

|    |   |   |   |   |   |   |
|----|---|---|---|---|---|---|
| 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 |
| 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:** 200μM GLASS PARTICLES  
**CONCENTRATION:** 1.2 WT PERCENT

| ROW | LOC | N (RPM) | Q (CFM) | DB (CM) | θ | 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   |
| ROW | LOC | N(RPM) | Q(CFM) | $\varphi$ | 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 |
| 4 | 6 | 250 | 3 | 0.424 | 0.0665 |
| 1 | 7 | 150 | 3 | 0.600 | 0.150 |
| 2 | 7 | 150 | 3 | 0.585 | 0.142 |
| 3 | 7 | 200 | 3 | 0.655 | 0.179 |
| 4 | 7 | 200 | 3 | 0.650 | 0.181 |
| 5 | 7 | 250 | 3 | 0.515 | 0.086 |
| 6 | 7 | 250 | 3 | 0.498 | 0.084 |
| 1 | 8 | 150 | 3 | 0.430 | 0.021 |
| 2 | 8 | 150 | 3 | 0.430 | 0.022 |
| 3 | 8 | 150 | 3 | 0.459 | 0.023 |
| 4 | 8 | 200 | 3 | 0.482 | 0.046 |
| 5 | 8 | 200 | 3 | 0.437 | 0.043 |
| 6 | 8 | 250 | 3 | 0.554 | 0.124 |
| 7 | 8 | 250 | 3 | 0.495 | 0.123 |
| 1 | 9 | 150 | 3 | 0.495 | 0.002 |
| 2 | 9 | 150 | 3 | 0.617 | 0.003 |
| 3 | 9 | 200 | 3 | 0.417 | 0.016 |
| 4 | 9 | 200 | 3 | 0.337 | 0.015 |
| 5 | 9 | 250 | 3 | 0.459 | 0.107 |
| 6 | 9 | 250 | 3 | 0.494 | 0.101 |
| 1 | 10 | 150 | 3 | 0.471 | 0.032 |
| 2 | 10 | 150 | 3 | 0.569 | 0.029 |
| 3 | 10 | 200 | 3 | 0.477 | 0.056 |
| 4 | 10 | 200 | 3 | 0.465 | 0.060 |
| 5 | 10 | 250 | 3 | 0.503 | 0.124 |
| 6 | 10 | 250 | 3 | 0.480 | 0.112 |
| 1 | 11 | 150 | 3 | 0.239 | 0.000 |
| 2 | 11 | 150 | 3 | 0.000 | 0.000 |
| 3 | 11 | 200 | 3 | 0.297 | 0.012 |
| 4 | 11 | 200 | 3 | 0.277 | 0.010 |
| 5 | 11 | 250 | 3 | 0.544 | 0.123 |
| 6 | 11 | 250 | 3 | 0.478 | 0.117 |
| 1 | 12 | 150 | 3 | 0.468 | 0.003 |
| 2 | 12 | 200 | 3 | 0.553 | 0.075 |
| 3 | 12 | 250 | 3 | 0.535 | 0.118 |
| 4 | 12 | 250 | 3 | 0.674 | 0.123 |
| 1 | 13 | 150 | 3 | 0.618 | 0.188 |

(Table All Continued)
|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
| 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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