OPTIMIZATION OF AIR-INJECTION SPARGERS FOR COLUMN FLOTATION APPLICATIONS

Viviana Ramirez Coterio

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Gerald H. Luttrell, Chair
Greg T. Adel
Michael Mankosa

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ABSTRACT

Column flotation cells have become the most popular machine design for industrial applications that require high purity concentrates. The superior metallurgical performance of column cells can be largely attributed to their unique geometry which readily accommodates the use of froth washing systems. This unique feature allows column cells to provide impressive levels of metallurgical performance closely approaching the ultimate separation curve predicted using flotation release analysis. Another very important feature of column cells is the gas sparging system. Unfortunately, field studies suggest that gas injector systems are not always optimized. Two possible reasons for this unfavorable status are (i) improper design of the sparging system and (ii) poor operation practices employed by plant operators. In light of these issues, an experimental study was performed to develop a better understanding of the effects of various design and operating variables on the performance of a commercial gas sparging system. The data collected from this work was used to develop operational guidelines that plant operators can employ to improve column performance and to correct flaws in the design of their gas sparging systems.

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GENERAL AUDIENCE ABSTRACT

Column flotation cells have become the most popular separation device designed for industrial applications requiring the concentration of wanted or unwanted mineral from the rest material in a pulp. To achieve separation, an air sparging device is required to produce bubbles in the flotation cell. In column flotation operations sparging devices generate small bubbles into the cell to carry the desired mineral to the surface for later recovery and processing. However, field studies suggest that air injector systems are not always optimized. Reasons contributing to the lack of optimization are: (i) ineffective internal design of the sparging system, and (ii) poor operation techniques by the industrial processing plants.

The objective of this present study is to better understand sparging performance into the column cell and how to optimize sparging systems more effectively. To achieve this end, data for gas-water injection rate, froth addition, and inlet-pressure are collected and analyzed. Based on the data collected and its analysis, a guideline to better operational practices that plant operators can employ to improve column performance was developed. Furthermore, the correction of flaws in the design of the sparging devices was possible translating in an improvement in bubble generation inside the flotation cell.

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1. INTRODUCTION

1.1 Preamble

Column flotation is a separation method that was born within the mining industry for the recovery of fine particles, normally less than 100 microns in diameter. This process is now employed in several industries, e.g., in the civil industry for soil recovery and wastewater treatment, in the paper recycling industry for paper deinking, and in the petrochemical industry for oil-water separation. In the mining industry, column flotation is well suited because this technology offers better efficiency than others technologies in the selective separation of particles. The high selectivity is attributed to the employment of wash water that is added to the top of the column to reduce the hydraulic entrainment of fine hydrophilic particles. Column flotation machines make use of a variety of gas aeration systems for bubble generation. As stated by Rubinstein (1995), optimal performance of the aerator system is imperative as this is responsible for bubble generation. The bubble size generated by the aerator system is considered to be one of the most important parameters affecting column flotation performance. However, few aerator systems offer the possibility to monitor, control, and even less, predict the bubble size generated within the column. This unfavorable situation can create a number of issues within the column operation, including poorer concentrate grade and lower recovery, among others.

A basic understanding of column flotation operation is essential in order to recognize the critical function of the gas sparging system. A column flotation cell is basically a cylindrical vessel with a large height-to diameter ratio. Gas is introduced near the bottom of the cell through a gas distributor system. The dispersed bubbles rise in countercurrent fashion to the downward flow of feed slurry. Through the introduction of gas into the pulp, air bubbles selectively adhere to naturally or chemically altered hydrophobic particles. The bubbles carry these hydrophobic particles to the surface where they are recovered as a froth phase. The remaining hydrophilic particles stay in the pulp phase and are removed as a tailings stream through a discharge valve located at the very bottom of the column. As mentioned before, the use of wash water at the top of the column improves selectivity by washing undesirable material that may get hydraulically entrained into the froth phase.

A mayor constraint on column flotation capacity is froth overloading. The carrying capacity of the froth depends on the bubble surface area available for bubble-particle attachment. The bubble surface area, and hence carrying capacity, can be increased by reducing the average size of bubbles for a given gas flow rate. Efficient and proper air sparging performance is vital to the success of column flotation operation as an increase in bubble size decreases gas holdup or gas volume in the flotation pulp, thus decreasing the probability of bubble-particle collision and attachment. The introduction of finer bubbles to the cell also improves flotation kinetics and increases the total bubble surface area flux (Laskowski, 2001). Based on this concept, it can be said that spargers become the most important device for column flotation operations; therefore, without burping or surging, they should produce the maximum rate of bubble surface area throughout the column (Kohmuench, Mankosa, Wyslouzil, & Luttrell, 2009). This objective can be achieved by controlling the gas dispersion performance of the sparger, which is heavily dependent on the proper balance of gas and water flows and the design of the sparger.

Among the available aeration systems to be employed in column flotation operations, the market offers both static and dynamic sparging systems. In the static sparging system category, porous bubblers are widely used in several industries. However, due to plugging problems, porous bubbles often cannot be employed in mineral processing operations due to plugging issues. In the mining industry, porous spargers are therefore usually confined to laboratory testing or pilot plant evaluations. In the dynamic sparging system category, the market offers several options including jetting, Microcel and CavTube spargers. These three types of sparging systems are widely employed and accepted in the mining industry for column flotation operations due to their high efficiency, low cost and reliability, to name a few advantages. Moreover research has shown that dynamic spargers, which employ high energy dissipation to disperse gas within the column, are the most suitable devices for the control and prediction of bubble size in column operations.

1.2 Problem Statement

The performance of column flotation is strongly influenced by the effectiveness of the gas sparging system. Unfortunately, field studies suggest that gas injector systems used for column sparging are not always optimized. This unfavorable condition can create a number of issues within the concentrator, including lower recoveries, poorer metallurgical upgrading, decreased capacities, increased circulating loads, higher reagent consumption and inefficient energy usage. In order to avoid these problems and to obtain an optimal level of performance, the sparging system must be properly designed, installed, operated, and maintained. An effective sparging system should create small and uniform bubbles throughout the column (Yoon and Luttrell, 1989).

The present study is focused on the evaluation and optimization of the very popular “SlamJet” gas sparger manufactured by the Eriez Flotation Division (EDF). Field studies suggest that this type of gas injector system is often not fully optimized, which can translate into poor column performance. Therefore, in order to have peak column performance, the sparging system must to be properly designed and well operated. In terms of design, this level of performance requires the upfront selection of the proper number of sparger nozzles, the best choice of nozzle diameters, and the best sparger distribution pattern across the column cross-sectional area. Because in the manufacturing industry there is uncertainty as to how to design a sparging system that can bring optimum results to the mineral processing operations, this study focused on the development of guidelines that can be adapted by plant operators to improve sparging system performance and, at the same time, can positively impact column performance in terms of throughput capacity and separation efficiency. The techniques and modifications proposed from this work can also be used to improve future designs of gas injector sparging systems.

1.3 Objectives

The main objective of this project is to review the important criteria that govern sparging system operation. The investigation also reviews how the design of these sparging systems can influence column flotation performance. This study primarily focuses on one type of gas dispersion system, the SlamJet® sparger, which has shown increased popularity in the mining industry for mineral processing applications. The SlamJet® sparger, which is manufactured by the Eriez Flotation Division, operates by passing compressed gas (and often a small amount of water) through a small discharge nozzle. Fluid turbulence created by the exiting gas (and water if used) disperses and distributes small bubbles into the flotation pulp.

The main aims of this study are:

- To collect data required to improve sparging systems designs.
- To determine gas/water flow rates, inlet pressure, frother addition and frother type for optimum sparging system operation.
- To better understand the performance of jetting-type sparger systems in column flotation.

1.4 Literature Review

1.4.1 Froth Flotation

Froth flotation is a physical method that relies on the naturally or chemically altered hydrophobicity of certain minerals. This method is used to selectively separate valuable minerals from unwanted gangue. In the mining industry, froth flotation is typically used as the last stage of the mineral recovery/concentration system. It is used to recover or upgrade materials that conventional gravity or magnetic separators cannot recover due to the very fine particle size. Froth flotation allows the economic recovery of valuable minerals from low-grade ores that were not possible to obtain decades ago.

Froth flotation cannot be possible without the introduction of air bubbles into the flotation pulp. The froth flotation concept relies on the ability of air bubbles to adhere to hydrophobic mineral surfaces. The bubble-particle aggregates rise to the surface of the flotation pulp where they are later skimmed off as froth to make the separation. The remaining unwanted material is then evacuated from the flotation machine as a tailing stream. Froth flotation methods can also be employed to recover naturally hydrophilic minerals. This is possible by altering the mineral particle surface from hydrophilic to hydrophobic through chemical treatment so that air bubbles can attach to the mineral and the separation can take place. The ability to change the mineral/material surface through chemical treatment expanded the use of froth flotation in the mining industry and also into new non-mining industries including water treatment, deinking of paper, removal of organic contaminants in the dairy and beer industries, the remediation of contaminated soils in the civil field, as well as other industries (Kantarcia, Borakb and Ulgen, 2004). To increase hydrophobicity, or make a hydrophilic mineral hydrophobic, fatty acids and oils were first employed as reagents during the early years of flotation technology development. Now, a wide range of chemicals, including collectors, frothers, activators, depressants, and pH regulators, are commonly used as a complement to enable the flotation process and to increase the recoverability of valuable materials.

In 1869, William Haynes introduced the concept of flotation to separate sulfides from gangue using oils. This process was called *bulk oil flotation*. The separation was possible by bubbles generated through three different methods: (i) the entrainment of air during mixing, (ii) the reduction of pressure to generate bubbles, and (iii) the addition of sulfuric acid to create carbon dioxide bubbles (Fuerstenau, Jameson and Yoon, 2007). Later, in 1877, the Bessel brothers patented what is known today as froth flotation to concentrate graphite minerals. They innovated the industry by using nonpolar oils and by generating bubbles through the buoyancy of water to raise graphite flakes to the surface. In 1896, Frank Elmore, in conjunction with his brother Stanley and father William, developed, commercialized, and installed the first industrial-sized flotation process to concentrate sulfide minerals in The Glasdir copper mine in North

Wales. The process patented by Frank in 1989 was not froth flotation, but it used oil to agglomerate pulverized sulfides and bring them to the surface by buoyancy (Fuerstenau et al., 2007). Although Frank's technology successfully improved the separation of sulfides from non-sulfides, new research realized the importance of bubbles in the froth flotation process. Therefore, the flotation process was independently reinvented in other places, especially in Australia at the beginning of 1900. Some of the new Australian inventors were Charles Vincent and Guilleame Daniel Delprat.

Further improvements in the flotation process were accomplished throughout history, but two flotation methods are very well established in the mining industry today for mineral processing: the conventional mechanical cell and the column cell.

1.4.1.1 Conventional Mechanical Cell

The conventional mechanical flotation cell consists of a tank equipped with an impeller and stator mechanism. The rotating impeller is located in the lower part of the cell or tank. The air required to generate bubbles is introduced through a small-diameter orifice near the impeller or through an orifice inside of the impeller (Rubinstein, 1995). In the flotation cell, three distinct zones are observed during operation: (I) the turbulent zone, (II) the quiescent zone, and (III) the froth zone. According to Miskovic (2011), "*the rotating action of the impeller in the turbulent zone (I) provides the energy necessary to keep particles in suspension, enables the generation of small bubbles, and maintains the hydrodynamic conditions needed for efficient bubble-particle interaction*" (Miskovic, 2011). In Zone II, entrained gangue particles are separated or liberated from the aggregates. In addition, Zone II helps to maintain the froth in a stable state. Zone (III) is the cleaning zone of the process; it is the zone were valuable material is skimmed off. These three zones can be more clearly appreciated in Figure 1.1.

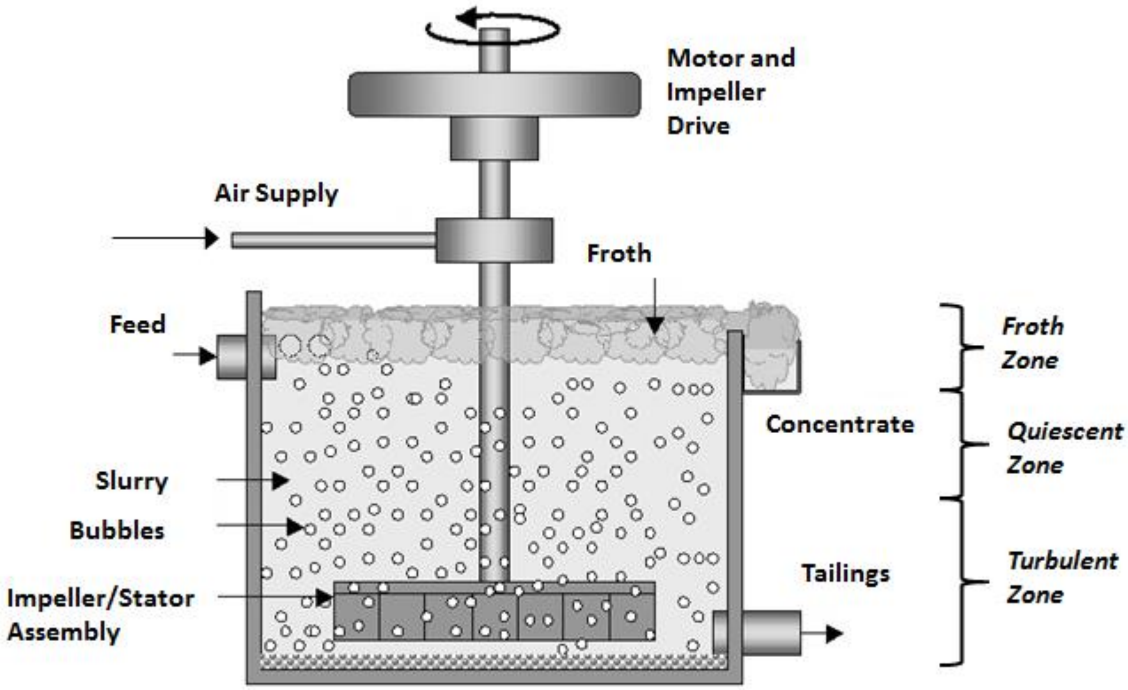


Figure 1.1 Flotation cell with its main components and zones

Because conventional mechanical flotation cells present low selectivity of valuable material and entrainment of slimes (Rubinstein, 1995), it is necessary for these cells to be configured in multi-stage circuits often consisting of “rougher,” “scavenger,” and “cleaner” cells. Rougher, scavenger, and cleaner flotation circuits can be arranged in different configurations, as shown in the example in Figure 1.2. From the previous explanation, it can be deduced that the use of conventional mechanical cells requires higher capital and operational costs and more maintenance due to wear and tear of the impeller that can become clogged by coarse particles. Banks of conventional cells can also consume up to 3 to 4 times more floor space in the plant due to the multiple cells needed for optimum operation, and it does not offer the possibility for air flow control (Sastri, 1998).

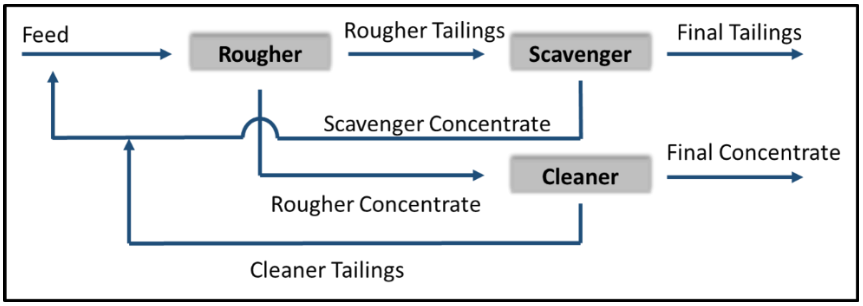


Figure 1.2 Possible configuration of Rougher – Scavenger – Cleaner Flotation Circuit

1.4.1.2 Column Cell

Column flotation depends on the principle of mass separation in a countercurrent flow of air and slurry, which is ideally used in the flotation of fine (<100 microns) particles (Kohmuench et al., 2009). Some of the characteristics that distinguish the column flotation cell from the mechanical cell are its shape, which is cylindrical and taller (up to 16 meters in height) (Kohmuench, Yan and Christodoulou, 2012), its bubble generation system, and its use of wash water (Dobby & Finch, 1990).

Column flotation is the most recent major innovation in flotation equipment. Its first design dates from 1919, when M. Town and S. Flynn developed a countercurrent flow of slurry and air in a cylindrical tank. Inside the tank, previously conditioned pulp was continuously fed into the middle part of the cylinder. Pressurized air, required for bubble generation, was generated from a cloth aerator, or sparger, located at the bottom of the cylinder (Rubinstein, 1995). As a result of problems such as particles' sedimentation at the bottom of the apparatus and clogging of the air sparging system (a cloth aerator or sparger), the use of the column cell was not popular. It was not until the mid-sixties when researchers, P. Boutain and R. Tremblay, began to investigate the mass separation process that occurred on a countercurrent slurry and air in a column. The column flotation developed by these researchers, initially intended for the chemical industry, is known as the "Canadian Column" and today is widely used in the mining industry for mineral processing. The operational principle of the "Canadian Column" is the same as that developed by Town and Flynn: the material/slurry, previously conditioned with reagents, is fed into the column from the middle part of it. Once in the column, the slurry encounters an ascendant stream of air bubbles rising from the bottom of the column and generated by pressurized air from the sparger system.

The first commercial column cell installed at a mineral processing plant was used to clean molybdenum ore in 1981 at Les Mines Gaspe in Quebec, Canada. After its successful application to clean molybdenum, the column flotation apparatus became accepted, and its use widely expanded in the late 1980's through early 1990's for the roughing stage of sulfide and gold ores; the cleaning stage of copper, lead, zinc, and tin; and for ash removal from coal (Rubinstein, 1995).

Throughout the investigation of the column flotation process, it has been found that countercurrent flow provides a better condition for bubble/particle attachment, which is governed by relative velocity, contact time, and inertia forces. The optimum relative velocity for boarding, or attachment, to occur was found by F. Dedek. He discovered that the optimum collision occurs under the following conditions: a relative velocity of bubble and particles in the countercurrent of 10 – 12 cm/s, a bubble size of 1.5 – 2.5 mm, and a slurry superficial flow rate of 2 cm/s (Rubinstein, 1995). The joined condition of the countercurrent flow of slurry and air reduces the bubble rise velocity. These conditions increase retention time and reduce gas requirements, which in turn improve the performance of the cell. With the absence of an impeller, which generates high turbulence, the inertial forces that cause bubble/particle detachment are negligible. In other words, as Rubenstein explains, "*in a countercurrent, the probability of bubble/particle collision is higher because of the large aerated volume of the cell and the long distance the particle and bubble have to travel along the column height*" (Rubinstein, 1995).

The reduced cross-sectional surface area of a column cell benefits froth stability and the formation of a deep froth bed. Having a deep froth bed facilitates the washing of undesirable impurities from the floated product in the bubble swarm by the wash water, which enters from the top of the cell. The primary advantage of having wash water at the top of the cell is the superior separation performance it offers to the column cell compared with the conventional mechanical cell (Kohmuench et al., 2012). Introducing wash water from the top of the cell allows it to permeate through the froth zone, removing dirty and nonselective entrainment of particles trapped between the bubbles. Furthermore, it improves the stability and movement of the froth, allowing a relatively deep (up to 1.5 meters) froth bed to be utilized. The deep froth promotes upgrading and ensures good distribution of the wash water. Figure 1.3 schematically illustrates a column cell with its main components and zones previously mentioned.

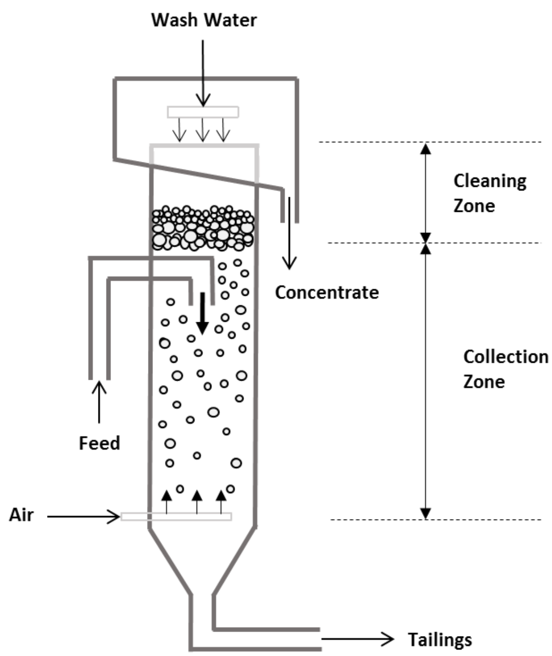


Figure 1.3 Schematic of a column flotation cell and its zones

Despite the fact that the column apparatus produces a product grade superior to conventional mechanical apparatus, its capacity is limited by the amount of bubble surface area available to carry the particles into the froth phase. According to Sastri (1996), the carrying capacity of a column cell is "*the rate of concentrate removal in terms of mass of solids overflowing per unit of time and per unit of column cross sectional area. This is related to the maximum achievable coverage of air bubbles by particles and gives an upper limit to the capacity of flotation columns*" (Sastri, 1996). The carrying capacity of a column cell can be determined by the following equation:

$$C = 4\, Q_g\, D_p\, \rho\, \beta \,/\, D_b$$

where:

β is a particle packing efficiency factor

ρ is the particle density

D_p is the particle diameter in the froth

D_b is the bubble diameter in the froth

Q_g is the gas flow rate

According to the equation above, carrying capacity can be increased if the superficial bubble surface area rate is increased. Increased carrying capacity can be attained by raising the aeration rate or by reducing bubble size. Studies have shown that in the normal range of operation, air rate and column diameter have only a marginal effect on carrying capacity (Sastri, 1996). Therefore, it can be inferred that optimal carrying capacity can be achieved when the compressed gas system used in the column is conducted at the maximum air velocity providing the minimum average bubble size.

1.4.2 Sparging Systems

The aeration or sparging system, also known as the bubble generator device, is the heart of the process in column cells, according to Rubinstein in his book, *Column Flotation*. The service life, operational costs, and economical parameters of flotation columns are tied to the design and operation of the device (Rubinstein, 1995). Proper design and performance of the sparging system is essential for column flotation, as spargers dictate and control bubble size, rise velocity, and air distribution. Hence, spargers dictate both the radial and axial hold-up profiles as well as the liquid phase flow patterns which translate to better flotation column performance (Kulkarni and Joshi, 2011). There are two methods of aeration systems. The first method is the internal air system which is placed near the bottom of the column to directly inject air. The second method is the external air system where gas and the liquid/slurry are introduced into the column via external contacting. This type of sparger is used to aerate the moving slurry, which is pumped from the bottom of the flotation cell and is recirculated as a pulp-air mixture. External spargers present a great advantage in the column flotation process compared to internal spargers since they can be maintained and repaired while the column is in operation. In addition, external spargers are easily operated. These advantages have expedited the development of column flotation.

In 1914, the first sparger devices were made to operate a pneumatic flottyoin column from porous material such as filter cloth and perforated rubber (Rubinstein, 1995). At that time, researchers and operators used a perforated metal frame wrapped in a woolen cloth. The air was then introduced to the slurry through the covered frame. In the early stages of sparger development (early 1900's) only internal spargers were used, which all suffered from (i) plugging due to particles and/or precipitates, (ii) improper gas distribution requiring large numbers of spargers to maintain bubble sizes below 2-3mm, (iii) poor reliability due to tearing and deterioration with use, and (iv) the need to shut down column operation to change them (Finch, 1994). All of these early drawbacks forced operators and developers to improve sparging technologies; however, the more significant improvements only in occurred the last few decades. As sparging technologies improved, the popularity of column flotation significantly grew. Thus, it is important to note that conditions present in the laboratory setting completely differ from conditions at industrial settings. These differences restricted low-pressure internal spargers for use only in the laboratory and for pilot test units (Kulkarni and Joshi, 2011).

Although the overall goal of air sparging is the same for both internal and external spargers; the design, sparging method, and features vary substantially between the sparger types. In the mining industry, three types of spargers dominate the mineral processing field. These are porous spargers, air injectors, and dynamic spargers. A brief explanation on the design and operation of these three types is provided bellow to illustrate their advancements and differences in the mining industry.

1.4.2.1 Static Sparging Systems. Porous Spargers

Perforated plates or pipes, sometimes covered by a porous filter cloth or perforated rubber, were the first type of sparging system used in the early 1900's to operate pneumatic column flotations. With porous materials, bubble generation occurs by the formation of individual bubbles at each orifice. The use of porous materials offers finer bubble sizes if operated at low pressure. Furthermore, since bubbles created by this type of gas distributor are numerous and relatively small, the gas-liquid interfacial area is greater, offering more efficient mass transfer (Kazakis, Mouza, and Paras, 2008). Porous spargers also are less costly and can be reclaimed through washing (Rubinstein, 1995). Perforated and/or porous spargers come in a variety of designs including perforated pipes, frames, rings, grids, and plates/sieves.

While these types of spargers can be used in mineral processing operations, the perforations (or holes) must be large enough to overcome clogging caused by the high concentration of solids in the column's bottom and the long operation times demanded in industrial settings. Unfortunately, in practice, the ability to reduce the hole size to minimize the average bubble size while eliminating fouling, is still an impossibility. Therefore, this inability confines perforated spargers to be implemented for laboratory testing and not in mineral processing applications at an industrial scale. Another disadvantage of perforated spargers that makes them inadequate for mineral processing operations at an industrial scale is the need to shut down flotation operations for repair, and the potential for slurry to permeate into the air system (Rubinstein, 1995).

To compensate for the lack of control in generating optimum bubble sizes, researchers developed various forms of porous spargers; however, persistent fouling also confined them to only laboratory scale work. Figure 1.4 shows a perforated plate and perforated pipe/tube sparger configuration. Here, it can be seen that the perforated plate sparger embraces the full cross sectional area of the column, while the perforated tubes sparger configuration is designed to achieve the necessary air distribution (Kulkarni and Joshi, 2011).

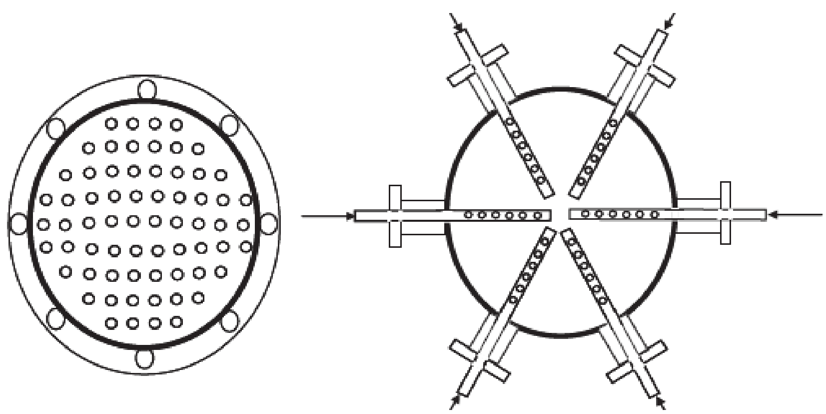


Figure 1.4 Two types of perforated spargers. Left: perforated plate, Right: perforated pipes (Kulkarni and Joshi, 2011)

While various materials have been employed to manufacture porous spargers for industry, such as glass, ceramic, metals, and fabric, the most accepted type for gas dispersion is the sintered porous metal sparger. At the present time, the Mott Corporation, established in 1959, is the lead company in the manufacture of porous spargers through the use of different metals and alloys. The principle of sintered porous metal spargers is to introduce gas into the liquid/pulp through thousands of tiny pores, creating far more numerous smaller bubbles than with drilled pipe spargers. Sintered porous metal spargers result in a larger gas-liquid/slurry contact area thereby reducing the time and volume required to disperse gas into liquid/slurry. The thousands of pores over the surface allow a large volume of gas to be released with a high specific area (Mott Corporation, 2015). Mott's porous spargers are not only known for their uniform gas dispersion, but they are also known for their rigid and durable construction.

Sintered metal spargers are comprised of powdered metal which has been ligated together by subjection to heat below its melting point. This technique produces average pore sizes in the 60 to 100 microns range, thereby allowing them to produce extremely fine bubbles. The most common metals and alloys used in the construction of porous sparger's are aluminum, stainless steel, hastelloy, inconel, nickel, titanium, and alloy 20. The choice depends on the application and special customer requirements such as greater temperature and corrosion resistance (Mott Corporation, 2016). A study conducted at the Aristotle University of Thessaloniki found that sintered metal spargers with a smaller average pore diameter have a more uniform porosity and therefore maintain a more even air distribution. Along with this, a study conducted by the University of Florida found that the average diameter of a bubble emitted from a sintered aluminum or stainless steel sparger ranges from 0.7 to 0.9 millimeters (Kazakis et al., 2008).

Although sintered metal spargers generate very fine average bubble diameters, they still experience plugging problems when exposed to slurry even at a low percentage of solids concentration. For example, according to a study by Rosso and Stenstrom (2006) conducted at 21 wastewater treatment facilities, sintered porous metal spargers used at the facilities require periodic cleaning with water and acid to prevent a rapid decline due to slimes plugging. The study showed that porous spargers require filtered air and water to promote successful continuous flotation, both of which are difficult to attain in mineral processing applications.

Two types of perforated spargers, namely single-phase and two-phase, can be arranged in multiple configurations inside a vessel or tank. A single-phase sintered metal sparger introduces air only through a porous membrane directly into the column, whereas a two-phase sintered metal sparger injects air through porous media around the circumference of a moving stream of water (El-Shall and Svoronos, 2001). These two types of configurations are applied in deinking flotation, wastewater treatment, oil and water separation, hydrogenation, ozonation, pH control, and others. Unfortunately, due to their high maintenance requirements, the use of single- and two-phase spargers is not applicable to mineral flotation processes and is typically confined only to laboratory settings.

1.4.2.2 Dynamic Sparging Systems

1.4.2.2.1 Jetting Sparger System

As previously mentioned, one of the biggest drawbacks to the porous sparging method is plugging when operated in the presence of solids. This prevents them from being used for mineral processing in the mining industry. For this reason, several groups including the U.S. Bureau of Mines (USBM), Cominco, and Canadian Process Technologies (CPT) have developed various forms of high pressure “jetting” spargers

(Kohmuench et al., 2007). A jetting sparger is a device that allows numerous air bubbles to emerge from a small circular orifice known as a nozzle. As Finch (1994) explains, inside a sparger, "*bubbles form as a result of instabilities of the jet surface*," and the amount of bubbles and their sizes are dependent on the length of the jet (Finch, 1994). A sparger device is meant to be operated at high pressure to generate bubbles, further reducing the problem of plugging, which porous spargers present. However, the high-pressure requirement translates into an increased horsepower demand, and, therefore, increased operational cost.

Cominco and the US Bureau of Mines created the first two-phase, high velocity spargers. These spargers mix water and high-pressure air through a small nozzle inside the column before the discharge occurs. The purpose of adding water to the sparger is to create a finer bubble distribution inside the column by shearing the incoming air passing through the sparger (Finch, 1994). The addition of water to the sparger was first proposed to be less than 1% of the volume of gas. Though the jetting spargers proposed by USBM and Cominco showed great improvements in bubble distributions and the possibility to be used for mineral processing, the inability to maintain them without shutting down column operations was still unattainable. Later, a Canadian company called Canadian Processing Technologies, Inc. (CPT) developed a single air phase sparger, called SparJet, and introduced the concept of on-line maintenance. SparJet is a removable air lance that ejects pressurized air from a single nozzle through the side wall of the flotation column. The concept of on-line maintenance is achieved by arranging multiple air lances of varying lengths around the column perimeter. Air is fed into the end of each sparger via tee-valves, which allow the airflow to be adjusted or completely blocked in the event of pressure loss or for required maintenance. The arrangement of multiple spargers around the column not only allows for continuous flotation operation, but it also ensures aeration of the full cross sectional area of the column.

CPT made a number of improvements to previous design of their sparger, which eventually lead to the development of the SlamJet sparger. To facilitate maintenance and prevent slurry from entering the airline, CPT replaced the tee-valve system with a high-tension spring located in the sparger's cage. The spring controls the nozzle aperture as pressurized gas enters the sparger, allowing the position of an internal rod to move towards or away from the nozzle aperture. The spring tension can be adjusted by loosening or tightening a screw located at the end of the sparger, as shown in Figure 1.5 (Kohmuench et al., 2012). With this design, if air pressure were lost, the spring would close the nozzle of the sparger, preventing the backflow of slurry into the air system.

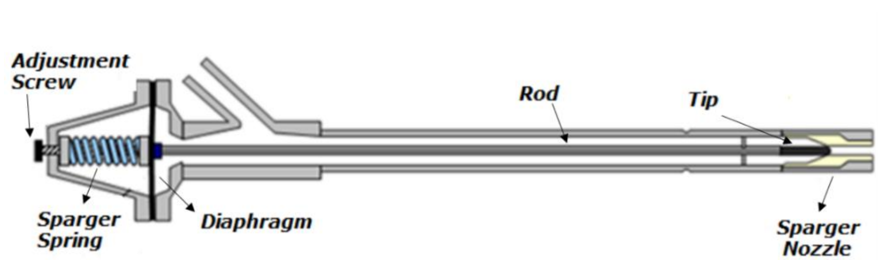


Figure 1.5 SlamJet sparger with its main components

CPT's new design also maximized bubble population by introducing Finch's concept into the operation of the sparger. According to the concept, the total population of bubbles can be acquired by extending the jet length into the column. This can be achieved through an increase in air density by adding water (Finch, 1994). With this in mind, the SlamJet's performance is enhanced with the addition of water below the air supply manifold. High pressure-water and air enter the lance together and are discharged into the column.

In 2007, the Eriez Flotation Division (EFD) acquired CPT. EFD claims that the flotation kinetics in the column is greatly improved due to the high rate of gas dissolution achieved by the SlamJet sparger (Eriez Flotation Division, 2016). Thousands of these spargers have now been placed into commercial service in the minerals processing industries.

1.4.2.2.2 Microcel

Column flotation has been acknowledged as one of the best technologies available to separate fine particles of valuable minerals from their associated unwanted matter. However, the process is less efficient when ultrafine particles in the slurry have to be separated (Yoon, Luttrell, Adel and Mankosa, 1992). It was not until 1988 that professors working at Virginia Tech's Mining and Mineral Engineering department developed a new flotation technology called Microcel™ Column Flotation. The objectives of the Microcel™ system are (i) to create microbubbles, normally in the 50 to 400 microns range, without creating plugging problems, (ii) to generate microbubbles using slurry instead of fresh water in order to minimize fresh water demand, and (iii) to ensure the bubble generator can be maintained and repaired as required without equipment shutdown (U.S. Patent No. US5397001 A).

To accomplish the objectives of the Microcel Column, microbubbles are generated by pumping slurry from the lower part of the column and passing it through parallel, in-line static mixers, which conduct the slurry back to the column at a larger height from the slurry exit port (Kohmuench et al., 2009; U.S. Patent No. US5397001 A). The air required for bubble generation is injected at a high rate into every static mixer at the front end. The slugs of gas formed at the entrance are then broken by the shearing action of the blades, which in turn create microbubbles ranging from 0.1 to 0.4 mm in size (Lakshmanan, Roy and Ramachandran, 2015; Yoon et al., 1992). A schematic of the static mixer is displayed in Figure 1.6.

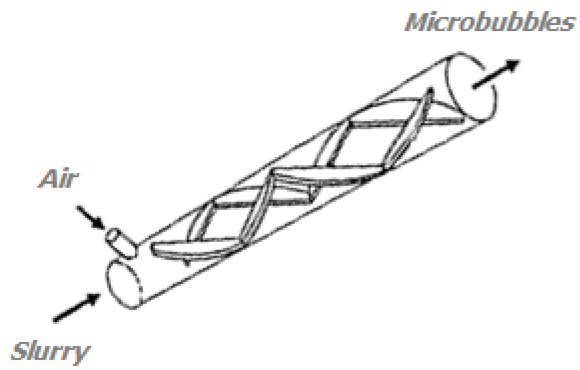


Figure 1.6 Schematic of the Microcel Static Mixer (Yoon et al., 1992)

The principle of Microcel technology is based on the improvement of flotation kinetics by combining pressurized air at a high intensity with small bubbles, which in turn enhances the frequency of bubble-particle collisions and attachment (Kohmuench, et al., 2009; Lakshmanan et al., 2015). Yoon describes the process taking place in the Microcel^{TM} Column Flotation as a three-stage flotation circuit. The use of the static mixer in column flotation applications are as follows: (i) a roughing stage, whereby air rising in the flotation column collides and attaches with hydrophobic particles that are flowing downward into the column flotation; (ii) a cleaning stage, whereby risen bubble-particles of unwanted material are washed in the froth bed to minimize hydraulic entrainment; and (iii) a scavenger stage, whereby the implementation of direct particle contact within a static mixer recycle-circuit gives particles a final opportunity to attach to the air bubbles (U.S. Patent No. US5397001 A, Yoon et al., 1992). A schematic design of the Microcel™ Column Flotation with its three process stages is shown in Figure 1.7.

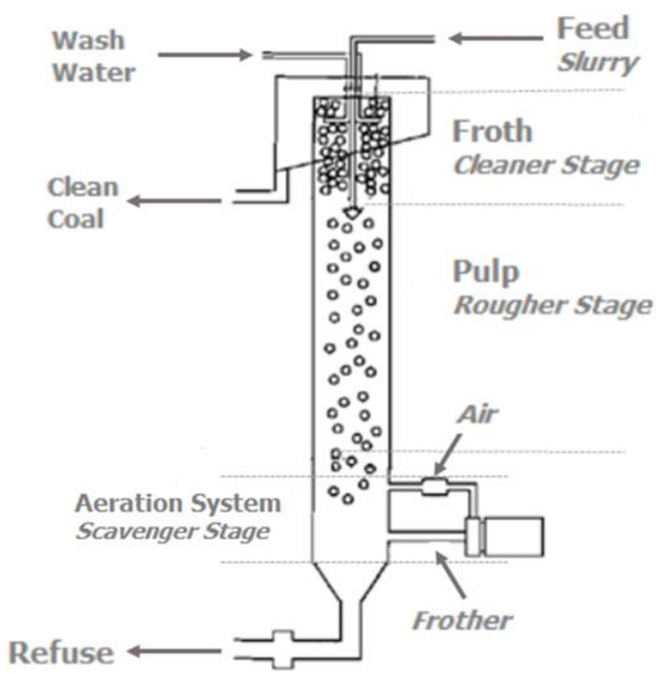


Figure 1.7 Schematic Microcel™ Column Flotation with its three stages (Yoon et al., 1992)

Microcel™ Column Flotation was initially popular for coal cleaning operations, but studies showing metallurgical improvements extended its success for processing other non-coal minerals (Lakshmanan et al., 2015). Based on studies of the Microcel technology's performance, conducted at the Red Dog Mines in North-Western Alaska, it was found that the mean bubble size diameter was reduced from 3.4 to 1.9 mm compared with previous sparger technologies. This reduction in bubble size translates to an improvement in zinc grade by 0.04% and sphalerite by 0.16%. As a result, the final recovery improvement was 2000 tons more of higher grade zinc concentrate per year (Pyecha, Lacouture, Sims, Hope and Stradling, 2006). A similar study was conducted in Peru at the Antamina copper/zinc mine. Microcel technology was employed at Antamina for the cleaning of copper and molybdenum. The process showed a reduction of bubble size from 3.7 to 2.6 mm, representing a 6% increase in copper recovery and a 20% increase in molybdenum (Lakshmanan et al., 2015).

1.4.2.2.3 CavTube

The CavTube is a sparging device that uses hydrodynamic cavitation to generate tiny bubbles, also known as pico-bubbles, in the order of 10^2 microns in size (Concha and Wasmund, 2013). Hydrodynamic cavitation occurs when the liquid pressure is abruptly reduced below its vapor pressure by subjecting it to high flow velocity (Fan, Tao, Honaker, and Luo, 2010). In essence, the CavTube system is a venturi tube wherein the liquid passing through the conical convergent zone increases its velocity due to the dramatic reduction in diameter. This diameter change can be observed in Figure 1.8. The cavitation phenomena results from a pressure change in the liquid while crossing the tube. The liquid has a higher pressure and lower velocity prior to entering the throat than while crossing it. After it passes the throat, the pressure decreases and the velocity increases. This sudden contraction and expansion results in the cavitation, also known as nucleation phenomena (Wasmund and Bain, 2014; Zhou, Xu and Finch, 1993).

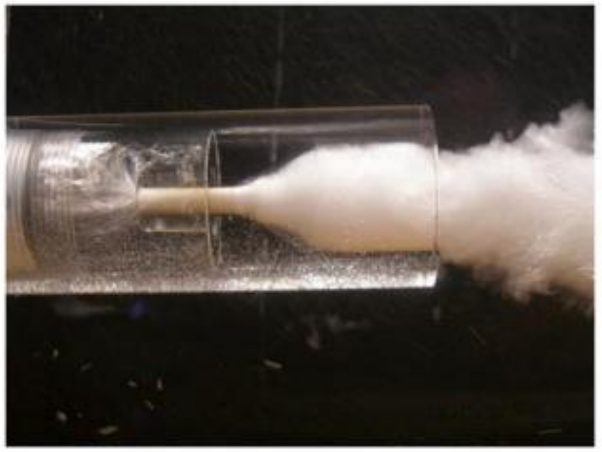


Figure 1.8 CavTube sparging system in a clear plastic model (courtesy of Eriez Flotation Division)

Hydrodynamic cavitation was introduced as a sparging system by inducing the flotation pulp and compressed gas into the venture tube (CavTube) at high velocity. The high velocity combined with the throat geometry generate cavitation in the pulp, which in turn improves flotation due to the attachment of ultrafine particles to the ultrafine bubbles (Zhou et al., 1993; Kohmuench et al., 2012). At the same time, pico-bubbles promote flotation by boosting the attachment of larger bubbles. The pico-bubbles serve as an auxiliary collector of particles (Kohmuench et al., 2009; Concha and Wasmund, 2013). This phenomenon is illustrated by Figure 1.9. The utilization of pico-bubbles in the flotation process decreases the required dosage of collector and increases the probability of bubble/particle attachment. It also decreases the probability of bubble/particle detachment (Kohmuech et al., 2009; Zhou et al., 1993; Wasmund, 2013). These improvements translate into the possibility of floating ultrafine particles, which was impossible with previous technologies.

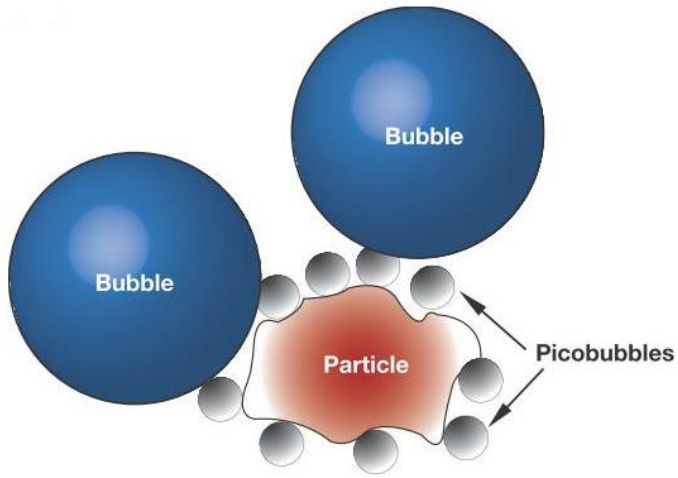


Figure 1.9 Schematic flotation process with pico-bubbles generated by cavitation

2. EVALUATION OF AIR-INJECTION SPARGERS

2.1 Introduction

Column flotation cells have become the most popular machine design for industrial applications that require high purity concentrates. The superior metallurgical performance of column cells can be largely attributed to their unique geometry which readily accommodates the use of froth washing systems. The wash water minimizes the non-selective entrainment of ultrafine gangue material that would otherwise be hydraulically carried in the water reporting to the froth concentrate. The larger height-to-diameter ratio of columns allows a deep froth to be maintained, which is essential to achieve even water distribution. With this unique feature, column cells can provide impressive levels of metallurgical performance closely approaching the ultimate separation curve predicted by flotation release analysis (Kohmuench et al., 2007).

Another very important feature of column cells is the design of the gas sparging system. One popular choice in the minerals processing industry is the Eriez SlamJet® sparger. As shown in Figure 2.1, this type of sparger operates by passing compressed gas through a small discharge nozzle. Fluid turbulence created by the exiting gas disperses and distributes small bubbles into the flotation pulp. The sparger is equipped with an internal moveable rod that is attached to a pressure diaphragm in the back housing of the sparger. The internal rod automatically moves back/forward and opens/closes the nozzle outlet when the compressed gas is switched on/off. This patented design effectively eliminates the accidental backflow of flotation pulp into the injection tube during shutdowns. The sparger can be operated as a gas-only injector or with the introduction of a small amount of high-pressured water (Kohmuench et al., 2009).

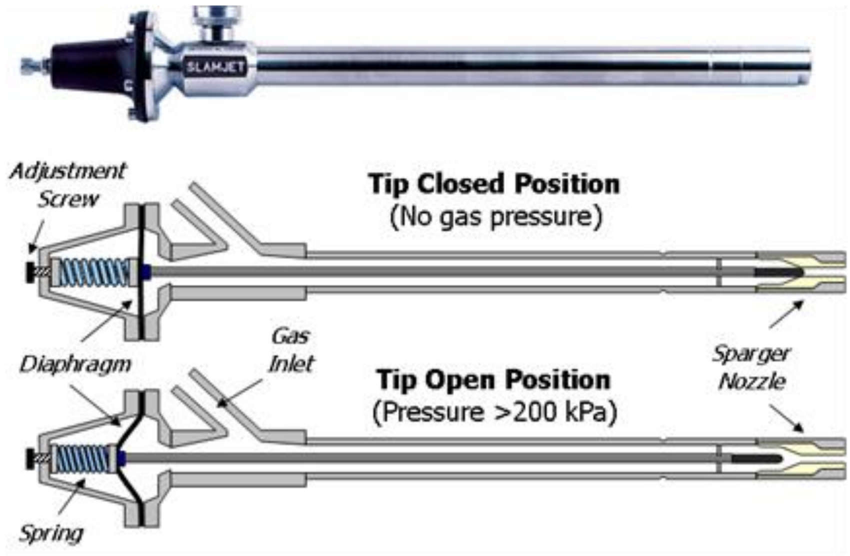


Figure 2. 1 Eriez SlamJet sparger

In order to obtain optimal levels of performance, the sparging system must be properly designed, installed, operated and maintained. An effective sparging system should create small and uniform bubbles throughout the column (Yoon and Luttrell, 1989; Hardie, 1998). In terms of design, this level of performance requires the upfront selection of the proper number of sparger nozzles, the best choice of nozzle diameters, and the best sparger distribution pattern across the column cross-sectional area. After these design decisions have been made, the sparger operating conditions must then be adjusted until optimal levels of performance are achieved for a given application. Typically, operating parameters that can be field adjusted include gas flow rate, water injection rate (if used), inlet pressure, and frother type and dosage. In practice, poorly operated or improperly maintained spargers have the potential to produce undispersed slugs of gas and unwanted burping. This undesirable condition can cause issues for operators such as low recoveries, decreased capacities, and inefficient energy usage.

2.2 Theory

In column flotation, gas dispersion properties play an essential role in mineral recovery. Bubble diameter (d_b), gas flow (Q), and gas holdup ($\mathcal{E}$) are some of the properties that govern column cell performance. However, in order to control and determine these properties, the gas dispersion provided by the sparging system into the column should first be determined. This requires an analysis of internal sparger design and nozzle discharge coefficient.

The design of the gas sparging system is perhaps the single most important factor in determining the effectiveness of gas dispersion in column flotation. For injection-type spargers, the design typically involves a nozzle throat that discharges compressed gas directly into the flotation pulp through a small diameter orifice. Ideally, the operating pressure is set so that the nozzle operates under choked flow conditions. The choked flow condition occurs when high pressure fluid (air/water) is forced to pass through a restricted orifice (nozzle, hole, orifice, etc.) into a lower pressure zone. There, the velocity eventually reaches a point where it is choked which is known as “critical velocity”. At this point, as observed in Figure 2.2, the flow velocity reaches a plateau that is independent of the pressure differential. This velocity is known as sonic velocity and its creation is based on the law of mass conservation.

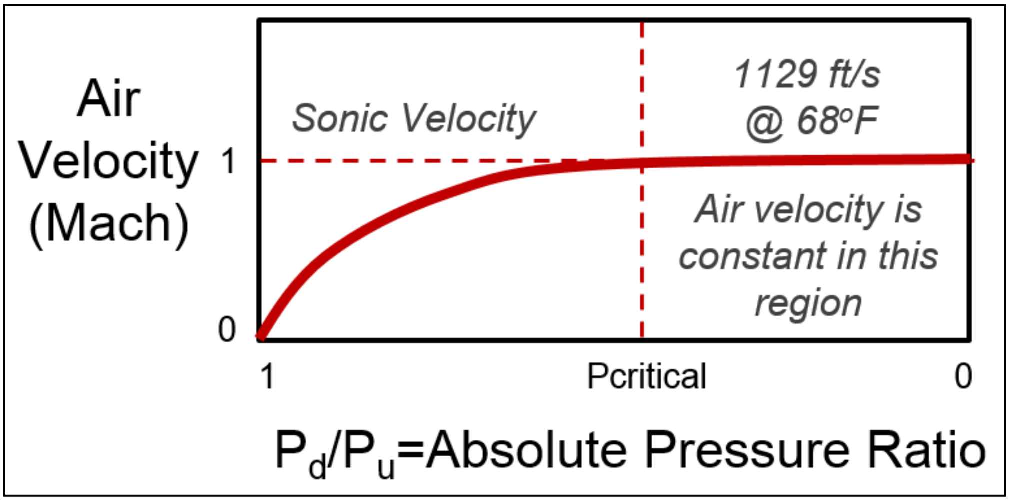


Figure 2. 2 Sonic Velocity Mach = 1

For homogeneous fluids, the physical point at which choking occurs for adiabatic conditions is when the exit plane velocity is at sonic conditions or, in other words, when the velocity reaches Mach number = 1. If the heat capacity ratio (k) for an ideal gas is known, choked flow occurs when the pressure ratio exceeds this velocity. The pressure radio is described by the following expression:

$$\frac{P_d}{P_u} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \qquad [1]$$

where:

P_d = Downstream absolute pressure

P_u = Upstream absolute pressure

k = Heat capacity radio

For dry air (k= 1.4), P_d/P_u=0.528. (0+14.7) psia / (13.17+14.7) psia = 0.528. Thus, choked flow occurs when $P_d < 0.528\ P_u$ or $P_u > 1.89\ P_d$.

Equation [2] can be used to determine the mass of fluid passing through restricted orifices (e. g. nozzle orifices and valves) when the velocity is choked.

$$M = AC\sqrt{k\rho P_u\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}} \qquad [2]$$

where:

C = discharge coefficient

A = nozzle/orifice area

ρ = gas density

From this very well-known equation (Loomis, 1982), it can be inferred that:

(i) for choked flow of gases, mass flow rate is independent of downstream pressure and depends only on temperature and pressure on the upstream side of the restriction;

(ii) the equation mathematically implies that mass flow rate is proportional to hole area and square root of pressure; and

(iii) the mass flow rate is only weakly dependent on gas temperature (via density).

These three phenomena can be observed in Figure 2.3. These two plots show that the gas velocity exiting the nozzle reaches Mach 1 (1129 ft/s) when the absolute pressure ratio exceeds about 0.528. The volumetric air flow rate, however, increases past this point in response to simple compression of the upstream flow and not to an increase in exit velocity.

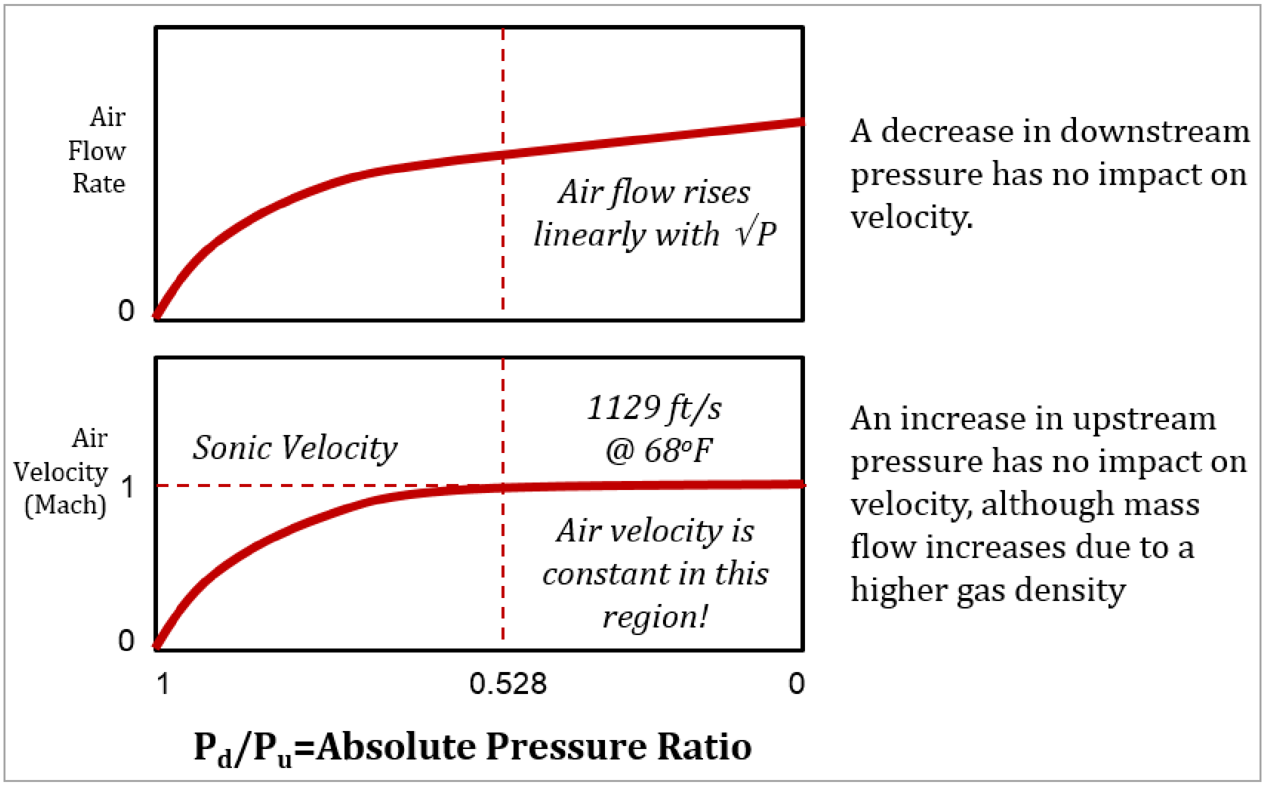


Figure 2. 3 Mass of fluid at restricted orifices

Although jetting spargers are based on the concept of choked flow, industrial limitations like the required system to avoid back flow into the air line, limit the flow of spargers. Due to the spring, rod, and tip combination in spargers' design, a mathematical choked model is not perfectly matched. This phenomenon is better appreciated in Figure 2.4. This plot shows the normalized gas flow (i.e., measured standard gas flow rate divided by the maximum standard gas flow rate observed) as a function of the normalized inlet pressure (i.e., set gas pressure divided by the maximum gas pressure observed). Normalized values were used in this plot to protect the confidentiality of operational data for the sparger manufacturer. Because of the spring backpressure, this particular plot shows that the sparger did not reach choked flow conditions unit a P/Pmax ratio of about 0.7 was reached.

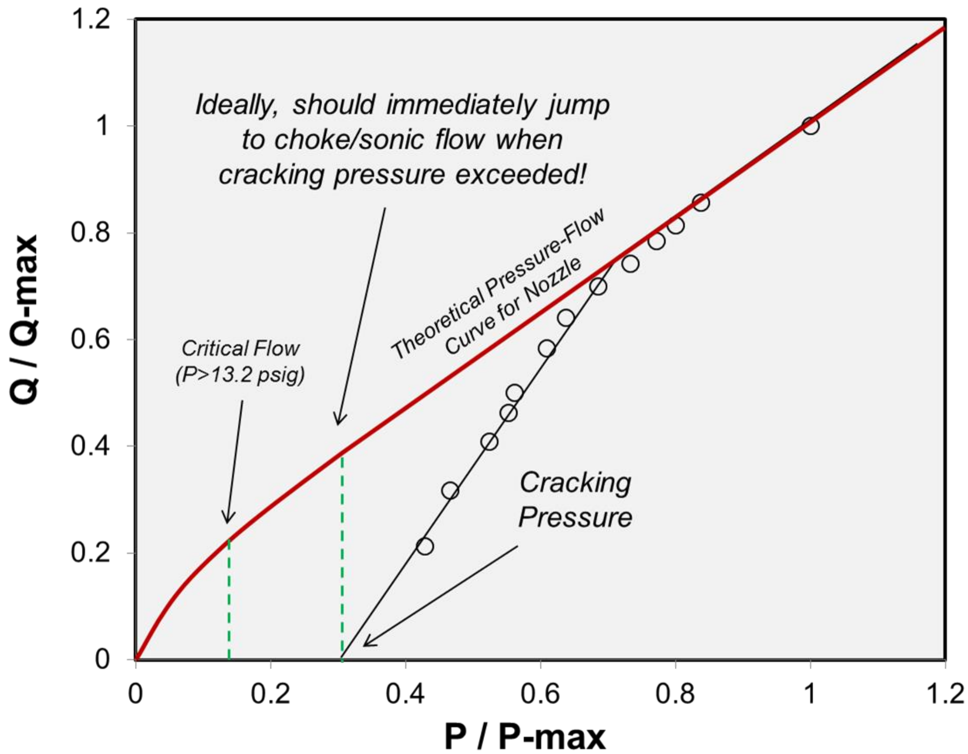


Figure 2. 4 Comparison of theoretical pressure vs flow curve for nozzle and actual curve obtained in jetting systems

In jetting spargers, like the commercially available Eriez SlamJet spargers, a flow restrictor (an integration of spring, rod, and tip) moves back as the cracking pressure is approached. This is due to the compressed gas that creates a counter-pressure to the spring and moves it back, as already illustrated in Figure 2.1. Without the presence of the spring, jetting spargers will match the theoretical pressure-flow relationship, also known as critical flow. Although the flow restrictor is beneficial in the way it avoids back flow of slurry into the air line in plant operations, it is also responsible for unwanted pressure drop in some sparger systems. It can be a detrimental due to higher energy consumption required to reach the theoretical curve. When the flow restrictor is fully open, it is possible to achieve the highest velocity. The best gas dispersion is expected under this condition. Figure 2.5 is a representation of this theory.

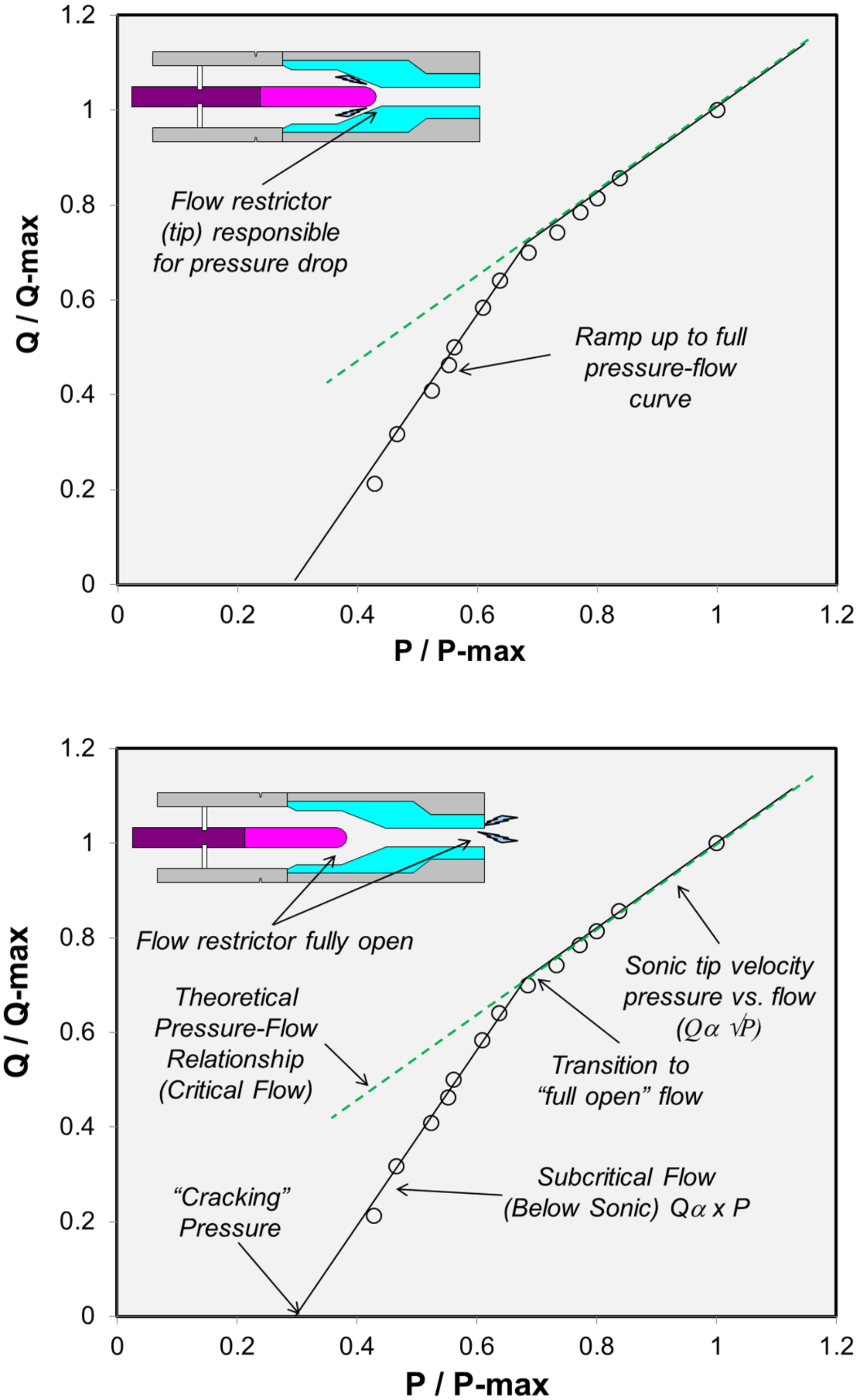


Figure 2. 5 Schematic phenomenon inside a jetting sparger (a) operation prior to being fully open and (b) operation after being fully open

To facilitate calculations and keep consistency in this study, equation [2] can also be written as (Loomis, 1982):

$$Q = 0.5303\,\frac{ACP_u}{\sqrt{T}} \qquad [3]$$

where:

Q = gas flow (volumetric flow of fluid)

A = area of orifice

C = coefficient of flow

P_u = upstream total pressure

T = Upstream total temperature

To make use of equation [3], it is essential to determine the coefficient of flow, which entirely relies on the internal configuration and roundedness of the sparger. These coefficients depend on the nozzle design, but normally are in the 97% to 61% range for simple phase fluid and smooth edge nozzles. When dealing with two phase fluids, such as gas/water, a second coefficient has to be considered in the previous equation. To avoid confusion, the gas coefficient flow can be denoted as C_n, and the water coefficient flow as C_w. Thus, equation [3] can be written as (Loomis, 1982):

$$Q = 0.5303\,\frac{AC_nC_wP_u}{\sqrt{T}} \qquad [4]$$

Because the work in this study is empirical, the gas coefficient flow was determined from experimental data. In light of this, the gas flow obtained from multiple tests representing a set of data were averaged and fitted to a model. Likewise, the water coefficient had to be determined. For this purpose, an empirical model based on pressure gauge, water addition, and a fitting coefficient, was employed. This coefficient is described by equation [5].

$$C_w = K_1\left(1 - \frac{1}{1+W}\right)P + \frac{1}{1+W} \qquad [5]$$

where:

K_1 = fitting coefficient

P = pressure

W = water flow passing through the nozzle

2.3 Experimental

For the evaluation of commercially available SlamJet spargers, a pilot-scale continuous and closed loop air/water test column was designed and constructed at Virginia Tech-Mining Engineering laboratory (Figure 2.6). The configuration of the apparatus for running the tests consisted of two major components: gas flow apparatus and pilot-scale column flotation. Additionally, a data acquisition system was developed and implemented into the circuit for performance monitoring.

Gas-liquid injection rate, frother addition, and inlet pressure are the crucial factors in running sparging systems. This work focused on the study of these factors with the goal of finding the optimum operation of a sparger to assist plant operators in improving recoveries from their column cells. To facilitate this goal, the current study was conducted to quantify changes in gas flow rate, gas holdup, and degas time obtained for different running conditions, two different internal sparger designs, and several different nozzle sizes.

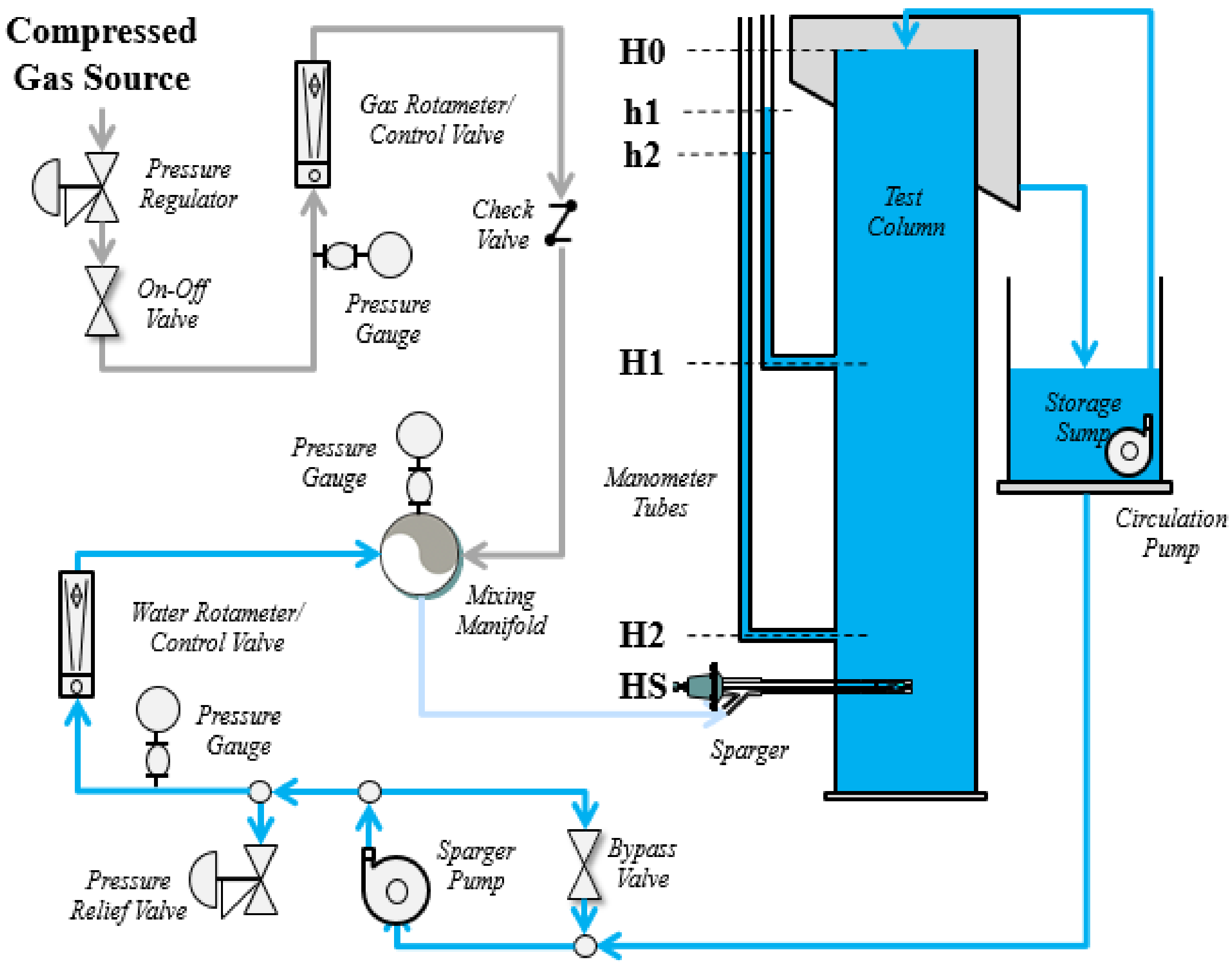


Figure 2. 6 Schematic of the experimental apparatus

The first type of sparger tested was the standard Eriez SlamJet (SLJ) shown previously in Figure 2.1. Tests with this type of sparger were carried out with standard nozzle sizes that are commercially available. The second type of sparger is a modified SlamJet sparger that consists of multiple blades placed along the internal rod with the aim to mix air and water before discharge takes place into the column cell. The new sparger is known as the SlamJet with Turbo Air Jet (SLJ-TAJ). To evaluate this type of sparger, test work was carried out using the SLJ-TAJ sparger equipped with a 4-mm diameter gas discharge nozzle. To account for different running conditions and to evaluate the predictive capabilities of Eq. [3], tests were conducted at low and high inlet pressures, ranging from 40 PSIG to 80 PSIG with 10 PSIG increments; different water flow rates of 0, 0.15, 0.30 and 0.45 GPM; and two different frother concentrations of 0 PPM and10 PPM.

2.3.1 Gas Flow Apparatus

The left side of Figure 2.6 provides a schematic of the experimental gas flow apparatus constructed to evaluate the proposed SlamJet sparger system. During operation, compressed gas (air) was introduced to a pressure regulator set to hold a constant pressure of 620 kPa (90 PSIG). An on-off valve was installed after the pressure regulator to initiate/terminate the gas flow during a test run (Figure 2.7). The compressed gas from the on-off valve was passed to a gas rotameter and 0-134 KPa (0-150 PSI) pressure gauge assembly. The rotameter was equipped with a manual control valve that allowed for precise control of the gas inlet pressure. A check valve was installed after the rotameter to minimize problems associated with the back-flow of pressurized water into the gas monitoring instrumentation. The gas flow from the check valve was passed into a distribution manifold that was connected via a flexible hose to the sparger unit. The distribution manifold was equipped with another 0-134 KPa (0-150 PSI) pressure gauge so that the inlet pressure to the sparger hose could be constantly monitored.

When required, water was added to the distribution manifold after passing through another water rotameter, control valve and pressure gauge assembly. The injection water was pressurized using a high-pressure multi-stage pump. A by-pass loop and pressure relief valve was used to ensure that the high-pressure pump did not exceed safe operating conditions. Water was supplied to the high-pressure pump from a test column filled with water. The closed-loop circuit made it possible to run a wide range of water flow rates without impacting the column water or frother levels.

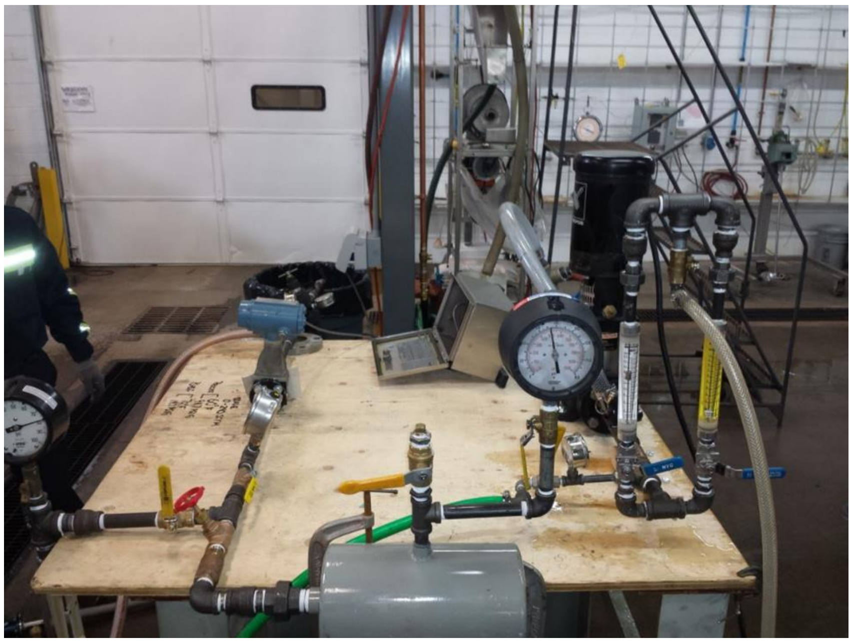


Figure 2. 7 Equipment for air/water supply system

2.3.2 Test Column

The right side of Figure 2.6 provides a schematic of the experimental pilot-scale flotation cell used to evaluate the proposed SlamJet sparger system. The column employed has a height of 3.5 m and an inner diameter of 0.76 m. In order to hold a constant water level in the test column and maintain a constant frother concentration, an auxiliary storage sump equipped with a low-pressure circulation pump was placed next to the test column (Figure 2.8a). This setup, which allowed water to continuously overflow from the test column, made it possible to rapidly recharge water displaced by the gas held up in the system during different test runs.

Two external site tubes for hydrostatic pressure monitoring were installed along the column height for the manual monitoring of gas holdup. The connection ports for the upper and lower manometers tubes were located at distances of 67.5 and 98.5 inches, respectively, from the top of the test column overflow level. In order to monitor gas holdup into the column, readings were made by taking multiple photographs to the manometer tubes for each condition. Then, the readings were averaged to obtain the "mean holdup (%)" values (Figure 2.8b). The average fractional gas holdup ε_1 in the test column (i.e., between elevations H_2 and H_0) was calculated from the level of liquid in the first manometer using the expression:

$$\varepsilon_1 = (H_0 - h_1)/(H_0 - H_2). \quad [6]$$

For comparison, the average fractional gas holdup ε_2 in the upper section of the test column (i.e., between elevations H_1 to H_0) was also calculated using:

$$\varepsilon_2 = (H_0 - h_1)/(H_0 - H_1). \quad [7]$$

Generally, the holdup values determined in the upper section were lower than those in the lower section due to an increase in bubble size resulting from the lower hydrostatic head as bubbles rise to the top of the column.

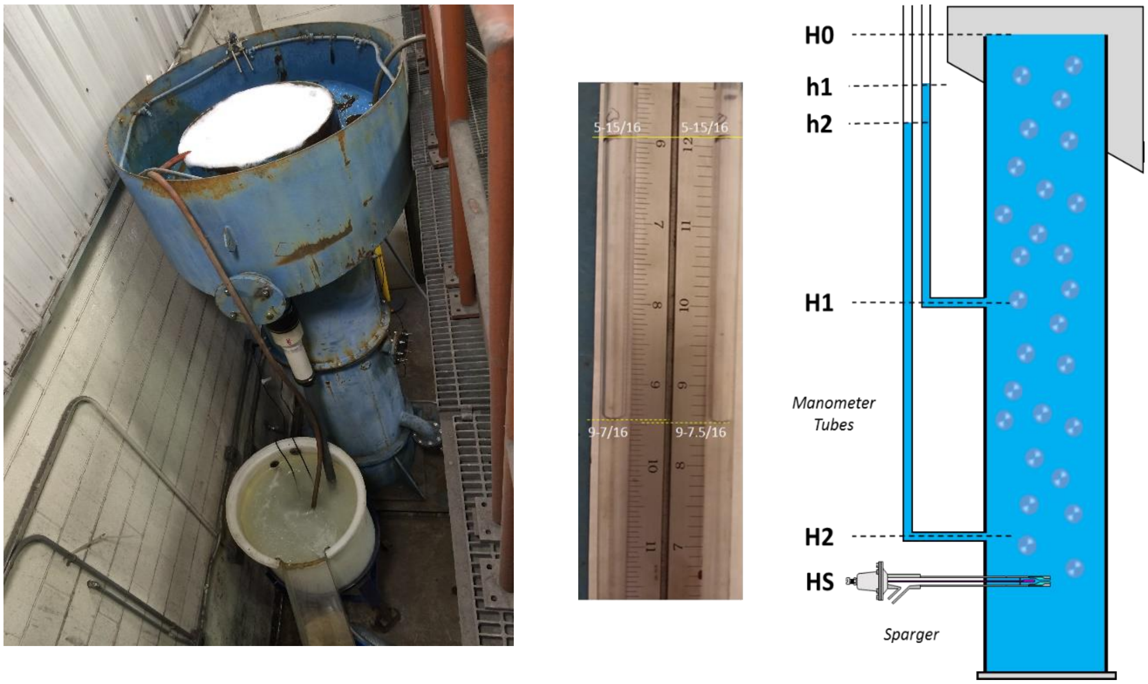
The total fractional gas holdup (Ɛ) can be calculated from:

$$\varepsilon = (h_1 - h_2)/(H_1 - H_2) \quad [8]$$

where:

h_1-h_2 = delta height in manometer levels

H_1-H_2 = delta height in manometer mounts



a) Flotation column and sump tank **b) Data collection using manometer tubes**

Figure 2. 8 Pilot-scale flotation column

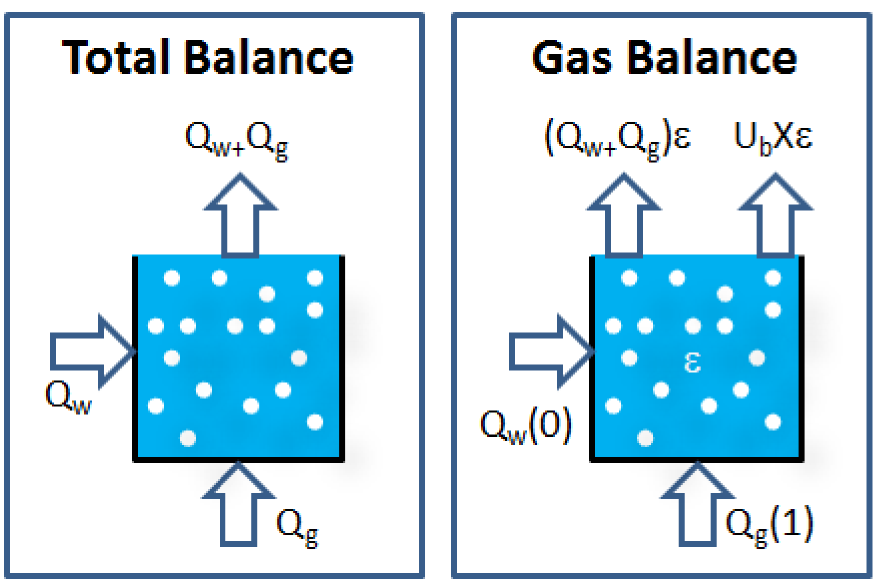


Figure 2. 9 Simplified volumetric balances for total flow (left) and gas flow (right)

For the pilot-scale test column used in the sparging evaluations, the gas holdup can be estimated from a simple volume balance given by equation [9], as illustrated in Figure 2.9.

$$\varepsilon = Q_g/(Q_w + Q_g + U_b X) \qquad [9]$$

where:

Q_g = volumetric gas flow rate

Q_w = volumetric water flow rate

U_b = bubble swarm hindered rise velocity

X = column cross-sectional area

To improve accuracy and more precisely determine the gas holdup in the test column, the manometer tubes were replaced with four high-speed electronic pressure transmitters that were connected to a data acquisition system (LabView). The transmitters were installed at different heights to assess potential differences in bubble size distributions in each section of the test column. A combination of scheme pressure transmitters and data acquisition system allows monitoring of the pressure differences by real time. Likewise, to monitor gas flow in real time, an electronic vortex flowmeter was installed along the airline right after the head gas supplier and connected to the data acquisition system (LabView). The data acquisition system was set up so 10 readings per second can be obtained from the pressure transmitters and vortex flowmeter.

Figure 2.10 shows an example of data obtained from each pressure transmitter in a single test. The gas sparging performance was monitored by means of dynamic pressure transmitter readings taken after the gas was shut off, 60 seconds after running at a known inlet pressure, frother concentration and water injection rate. The pressure difference was taken from the average values of pressure transmitters 2-3 and 3-4 (Figure 2.11).

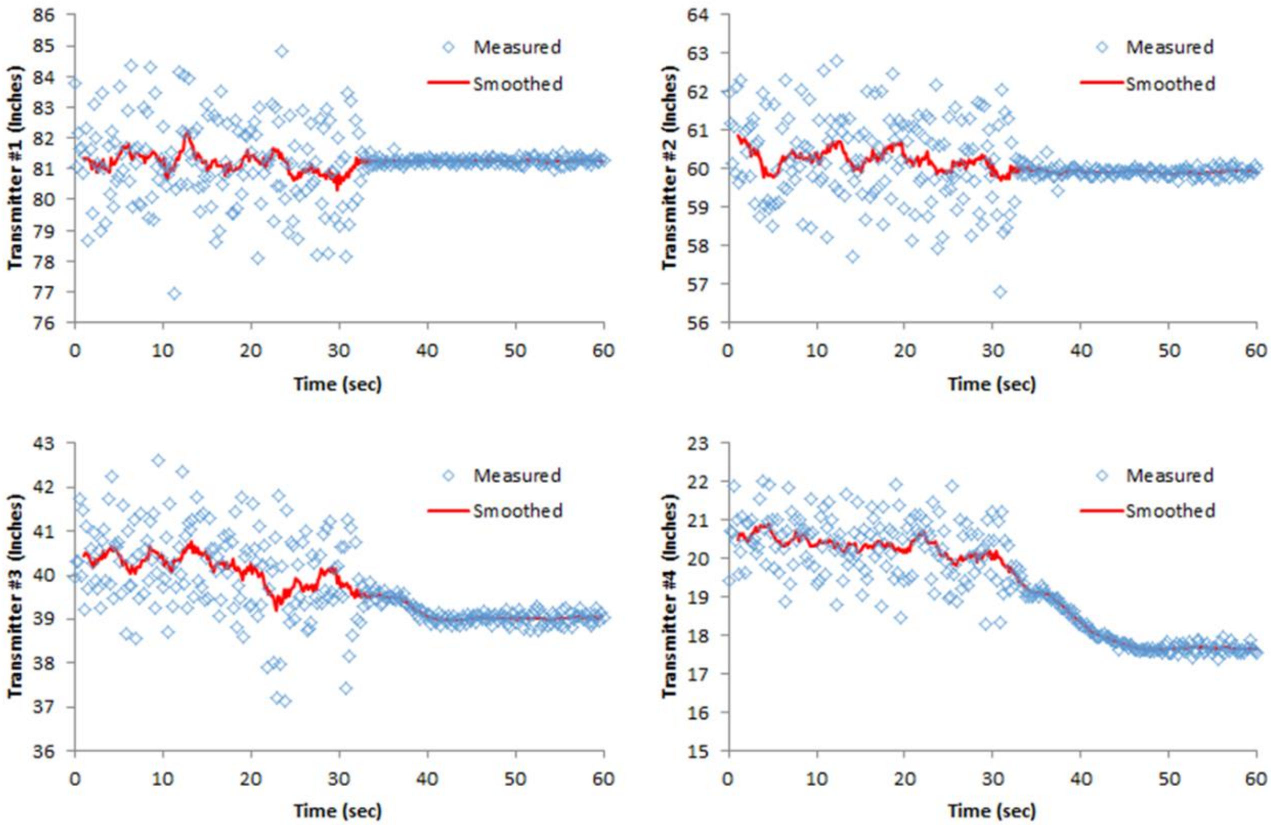


Figure 2. 10 Data obtained from individual pressure transmitters

The massive amount of data obtained from the data acquisition system from a single test made it difficult to evaluate the sparger performance in terms of gas flow and gas holdup. This necessitated a model that would be suitable to analyze, predict, and compare sparger performance over a wide range of conditions. The conditions were chosen as follows:

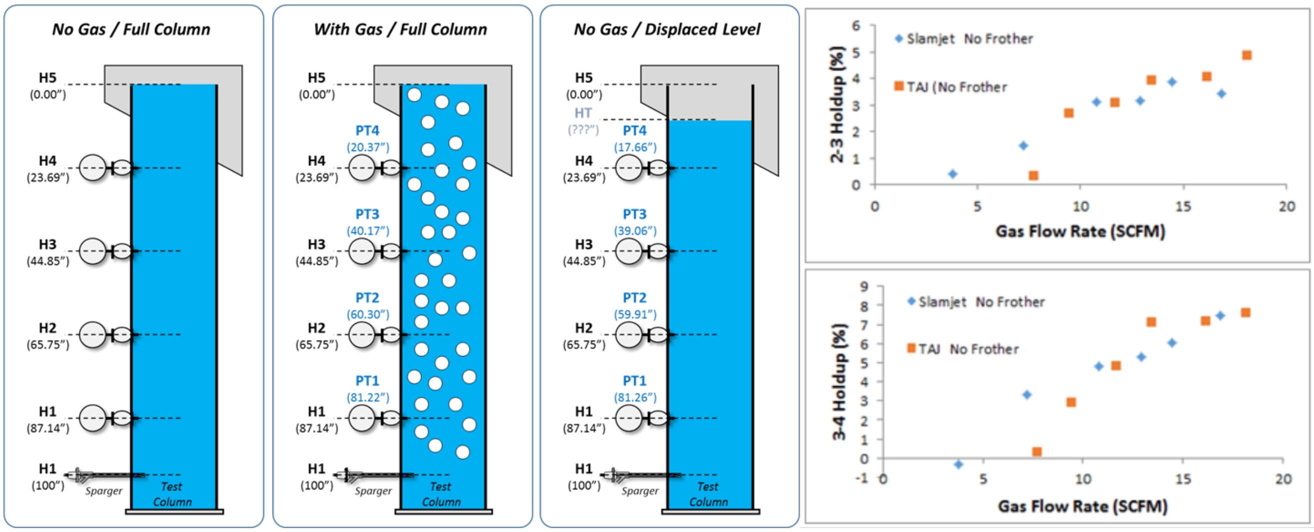
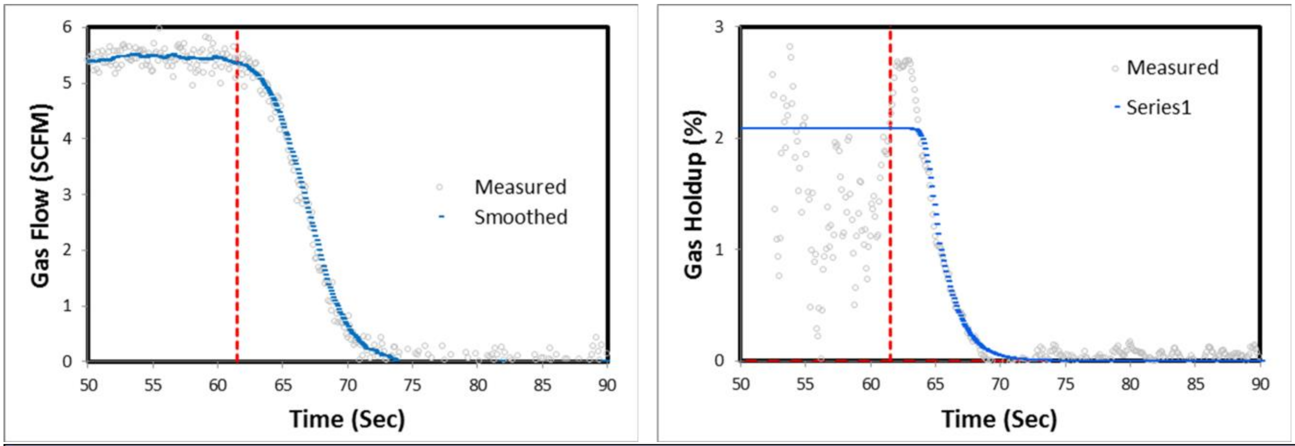


Figure 2. 11 Data collection using pressure transmitters

- Two types of spargers employing the same nozzle diameter: SLJ and SLJ-TAJ,
- 5 different inlet pressures ranging from 0 psig to 100 psig with 10 psig increments,
- 4 different water additions in GPM, and
- 0 PPM and 10 PPM frother dosage conditions.

In total, the amount of data collected employing the data acquisition system was from 80 tests. Here it is easy to see the importance on relying on a balanced model that can facilitate the process of analyzing, comparing, and predicting the percentage of gas holdup and gas flow for each test. Figure 2.12 shows a balance model obtained from a test performed on the SlamJet with Turbo Air Jet (SLJ-TAJ) at a low inlet pressure, intermediate water addition, and 0 PPM frother condition. From this model, it can be observed that the delta holdup into the column was 2.08%, 5.4 SCFM of gas flow during aeration, and 10.98 seconds for a complete column degas once the gas has been shut off. Due to human error, the “Gas Off” time that represents the time when the gas was shut off, had to be manually input for each test.



SLAMJET SPARGER TESTING

Sparger Type:	Slamjet TAJ2	**Frother (PPM):**	0
Description:	Standard Nozzle	**Gas Off (sec):**	61.5

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	0.30	--	--	1.86	--	--	1.99	--
Based on PT On/Off	--	--	0.12	--	--	1.37	--	--	2.08	--
During Aeration ...										
Average	85.39	63.96	21.44	63.96	43.35	20.61	43.35	22.66	20.68	5.44
Maximum	90.72	68.32	22.40	68.32	47.87	20.45	47.87	25.68	22.19	5.96
Minimum	80.49	58.73	21.76	58.73	38.37	20.36	38.37	19.18	19.19	4.98
Range	10.23	9.59	0.64	9.59	9.49	0.10	9.49	6.50	3.00	0.98
Standard Deviation	1.76	1.53	0.23	1.53	1.56	-0.04	1.56	1.13	0.44	0.18
High Outliner (+4 Sigma)	92.44	70.06	22.37	70.06	49.60	20.46	49.60	27.17	22.43	6.14
Low Outlier (-4 Sigma)	78.35	57.85	20.50	57.85	37.09	20.76	37.09	18.16	18.93	4.73
After Degassing ...										
Average	85.05	63.58	21.46	63.58	42.69	20.90	42.69	21.57	21.12	-0.05
Maximum	85.26	63.76	21.50	63.76	42.81	20.95	42.81	21.75	21.06	0.47
Minimum	84.83	63.41	21.42	63.41	42.49	20.92	42.49	21.37	21.12	-0.51
Range	0.43	0.35	0.07	0.35	0.32	0.04	0.32	0.38	-0.06	0.98
Standard Deviation	0.09	0.06	0.03	0.06	0.07	-0.01	0.07	0.07	0.01	0.16
High Outliner (+4 Sigma)	85.39	63.82	21.57	63.82	42.98	20.84	42.98	21.83	21.15	0.58
Low Outlier (-4 Sigma)	84.70	63.35	21.35	63.35	42.39	20.96	42.39	21.30	21.09	-0.69

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	2.08	%	Delta Holdup	2.08	%	Time @	0.99	63.55	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.01	--	Time @	0.75	64.60	sec
Time to Midpoint Holdup (sec):	65.22	sec	Epm	0.70	sec	Time @	0.5	65.22	sec
Power Term in Fitting Model:	73.00	--	2 x Epm	1.41	sec	Time @	0.25	66.40	sec
Power Term in Fitting Model:	49.00	--	Degass Time	10.98	sec	Time @	0.001	74.53	sec
Sum-of-Squares	1022	--							

Figure 2. 12 Balance model for Gas Holdup and Gas Flow from a single test

From the model, a plot of Predicted Gas Holdup (%) vs Measured Gas Holdup (%) can also be obtained, as shown in Figure 2.13. This plot shows how well the model predicts for an individual test or how much scatter is associated with the test data. The more out of line and the farther the points are from the predicted line, the larger the scatter was in the data collection. Figure 2.13 shows that a good fit between predicted and measured could be obtained for most of the experimental tests conducted with the SlamJet sparger system.

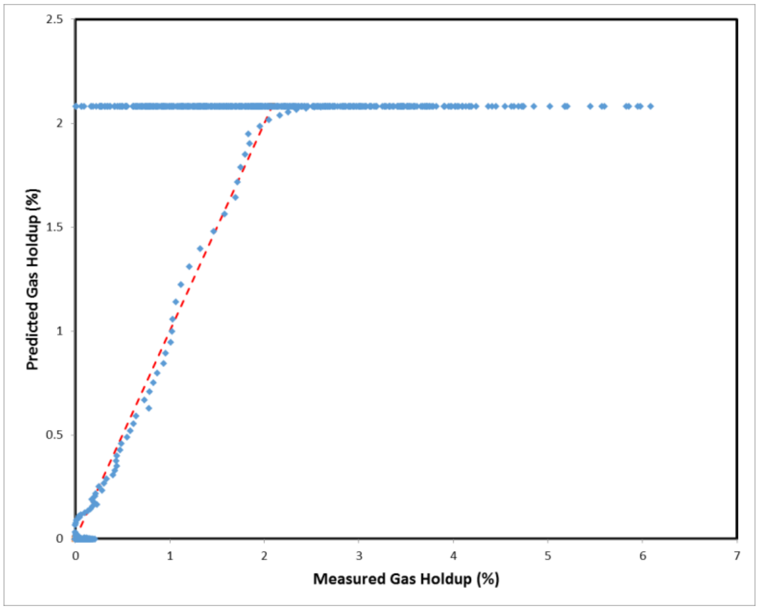


Figure 2. 13 Gas Holdup (%) model-prediction for a single test

Appendix A contains the following information for tests performed with the SlamJet sparger at 0 PPM frother dosage and employing the data acquisition system: (i) testing summary, (ii) "Gas Flow (SCFM) vs Time (sec)" and "Gas Holdup (%) vs Time (sec)" from 50 seconds to the degas culmination time, and (iii) Predicted vs Measured gas holdup profiles.

2.4 Results

2.4.1 Effect of Inlet Pressure

As stated in previous sections, the design of the gas sparging system is perhaps the single most important factor in determining the effectiveness of gas dispersion in column flotation. For jetting-type spargers, such as the patented SlamJet® technology, the design typically involves a nozzle throat that discharges compressed gas directly into the flotation pulp through a small diameter orifice. Ideally, the operating pressure is set so that the nozzle operates under choked flow conditions. As indicated previously in the theory section, Equation [10] describes the flow of gas passing through a restricted opening (e. g. nozzle, orifice, hole, etc.) when air only is employed for the sparger operation and Equation [11] when both air and water are employed for their operation.

$$Q = 0.5303 \frac{ACP_u}{\sqrt{T}} \qquad [10]$$

$$Q = 0.5303 \frac{AC_nC_wP_u}{\sqrt{T}} \qquad [11]$$

Where:

Q = gas flow

A = area of orifice

C = coefficient of flow (air only)

Cn = coefficient of flow for nozzle without water

Cw = coefficient of flow multiplier for nozzle with water

P_u = upstream total pressure

T = Upstream total temperature

Once the flow coefficients are known, Equation [11] can be used to create a model that predicts gas dispersion into the column at specific condition of pressure gauge, nozzle size, and temperature. [Note: Numerical values of the flow coefficients are considered proprietary since sparger manufacturers spend large amounts of time, effort, and funds to accurately determine these values for their particular nozzle designs.] Interestingly, Equation [11] shows that gas flow rate varies linearly with inlet pressure (i.e., increasing the pressure by 10% increases the gas flow by 10%). This inherent characteristic is an attractive feature of injection-type spargers since it allows for simple throttling and control logic. On the other hand, Equation [11] cannot be used to conclude that a 10% increase in orifice area will result in a 10% increase in gas flow rate since C is typically also a function of nozzle design/diameter. Therefore, the selection of an appropriate nozzle size is generally best made in direct consultation with the sparger manufacturer.

To offer guidance in choosing the most appropriate sparger size, sparger manufacturers can also provide plant operators with power demand, in terms of inlet pressure, to achieve a desired gas dispersion into their column flotation operation for the chosen sparger size. In Figure 2.14, normalized graphs of Gas Flow vs. Inlet Pressure are shown for two different sparger sizes (nozzle diameters). The data in these plots have been normalized by dividing the flows and pressures by either the maximum gas flow rate (Qmax) or maximum pressure (Pmax). In general, a larger nozzle size demands more energy, in terms of inlet pressure, than a smaller nozzle. However, it cannot be concluded that a bigger nozzle size provides better performance in terms of gas dispersion. The same gas dispersion can be achieved with different nozzle sizes. Herein lies the importance of selecting the appropriate sparger size for a given gas dispersion application in direct consultation with the sparger manufacturer.

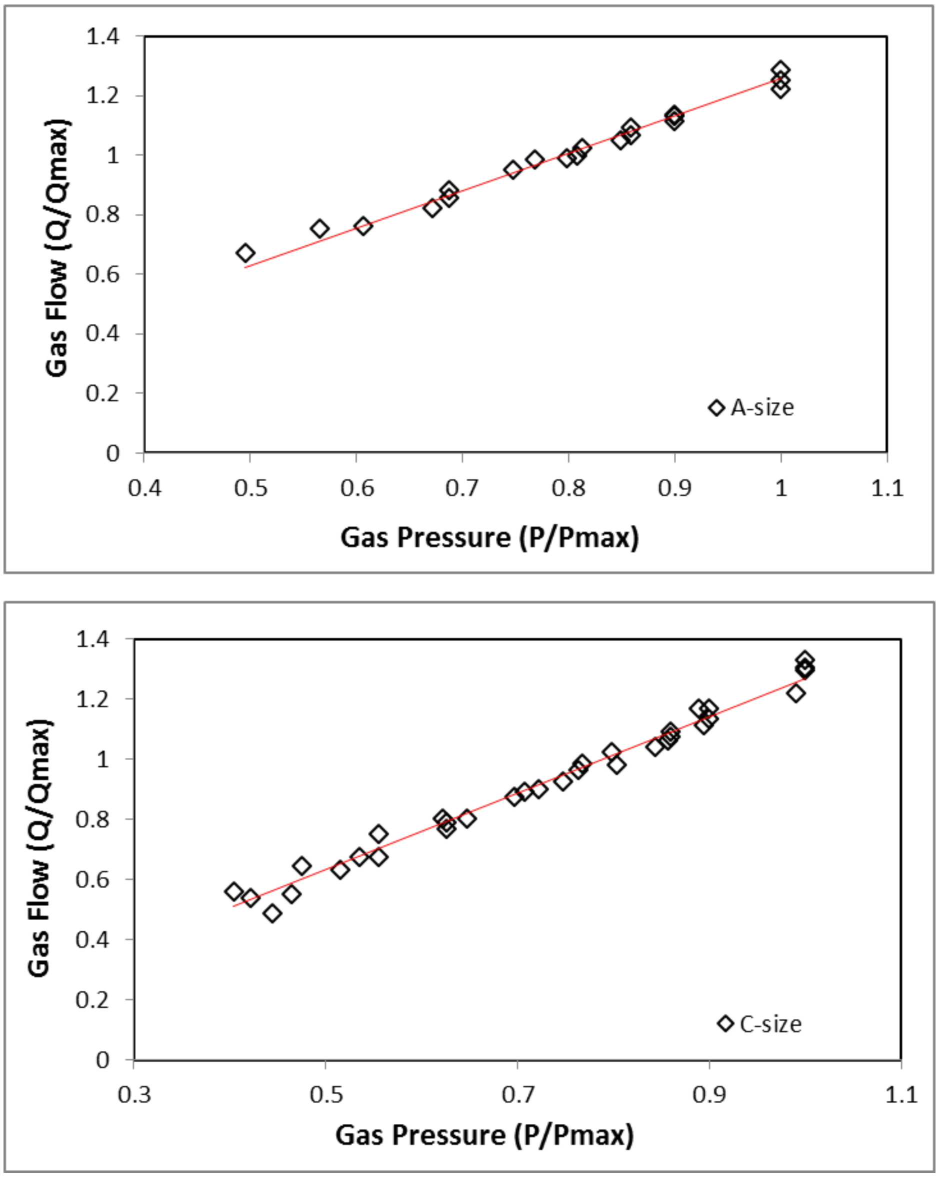


Figure 2. 14 Comparison of Gas Flow vs Gas Pressure for two nozzle size

2.4.2 Effects of Water Injection

The addition of water improves gas dispersion by creating a jetting flow of high-velocity water droplets that efficiently transfer kinetic energy into the flotation pulp as they exit the nozzle. The resultant energy dissipation generates turbulent eddies that help to shear any undispersed pockets of gas into smaller bubbles. The downside of water injection is that it also reduces the gas flow rate. Since the reduction in gas flow with water addition varies for each type and size of nozzle, the manufacturer should generally be consulted prior to attempting this improvement to ensure that the gas compressor and ancillary equipment can handle the new flow and pressure demands.

In order to illustrate the effects of water addition on sparger performance, several series of experiments were conducted using the test column apparatus. In these experiments, a SlamJet sparger equipped with a B-size nozzle was evaluated without water addition (i.e., gas only) and with the addition of three different water injection rates. In each run, the gas holdup (fractional volume of gas to total volume of gas plus liquid contained in the column) was monitored using the externally mounted manometers (Figure 2.8b). The fractional gas holdup (Ɛ) was calculated experimentally by employing Equation [12] and [13], shown in previous section:

$$\varepsilon = (h_1 - h_2) / (H_1 - H_2) \quad [12]$$

$$\varepsilon = Q_g/(Q_w + Q_g + U_b X) \quad [13]$$

Based on theoretical expression given by Equation [13], gas holdup must increase as the gas rate increases and bubble size decreases (i.e., rise velocity of the bubble swarm decreases). Thus, for a given gas flow rate, a higher holdup would be associated with smaller bubbles resulting from improved dispersion (Miskovic and Luttrell, 2012).

The experimental data from the water injection tests are plotted in Figure 2.15. As expected, the gas holdup in the column increased in proportion to the normalized gas rate (Q/Qmax) for all water addition rates evaluated. More importantly, the gas holdup versus gas rate curves shift upward to higher values as the water injection rate increased. When operating at 70% of the maximum gas flow rate tested, the holdup increased from about 15% for the gas-only case to about 17.5% with the addition of a low amount of injection water (which represented about 50% of the maximum water injection rate recommended by the manufacturer. The holdup further increased to near 20% by further increasing the water injection rate to the "normal" level typically recommended by the sparger manufacturer. The holdup increased by nearly 25% as the flow increased from zero (gas only) to the maximum value tested. These data provide strong evidence for the important role of water addition in attaining good gas dispersion for gas injection type spargers.

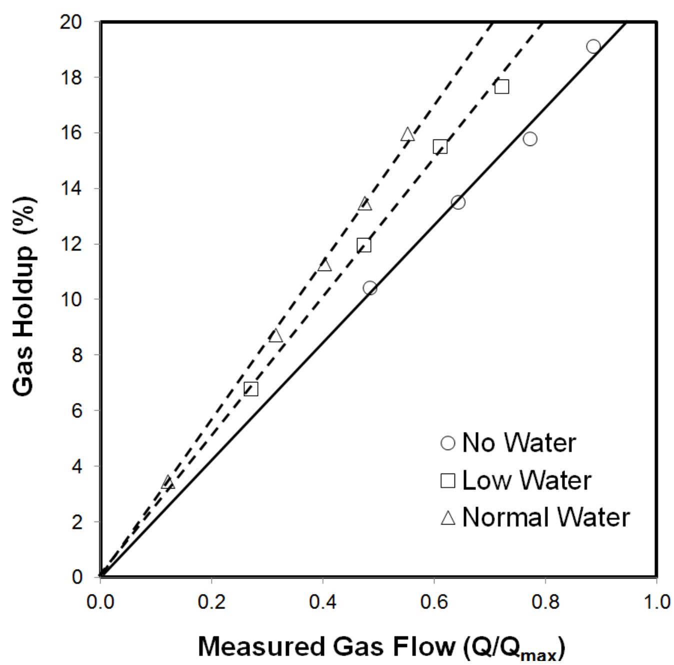


Figure 2. 15 Effect of gas flow rate and water injection rate on gas holdup (10 PPM frother)

2.4.3 Effects of Water-Gas Mixing

In order to work effectively, the pressurized water added to a gas injection sparger must be well mixed into the gas prior to exiting the discharge nozzle. For well-designed systems, this mixing is accomplished using internal networks of gas and water pathways that are incorporated into the structural design of the sparger. The pathways provide turbulence that is sufficient to completely homogenize the gas and water mixture, but not so intense as to create unwanted pressure drops that would otherwise adversely impact the sparger gas rate, dispersion performance and energy demand. The design of the network of mixing pathways, which is proprietary to each manufacturer of commercial spargers, is a key feature that is often not considered by plant operators when purchasing a new gas sparging system or when replacing existing gas spargers from different suppliers.

The importance of the design of the gas-water mixing network is illustrated by the test data shown in Figure 2.16. In this case, experimental tests were carried out using two types of spargers: the standard SlamJet (SLJ) and the SlamJet with Turbo Air Jet (SLJ-TAJ). These series of tests were conducted at 10 PPM of frother using either a "low" amount of injection water (i.e., ~ 50% of the water rate recommended by the manufacturer) or a "normal" level of injection water (i.e., 100% of the water rate recommended by the manufacturer). At each water addition rate, two sets of tests were conducted with and without the network of pathways (TAJ) required to achieve complete mixing of gas and water prior to exiting the discharge nozzle.

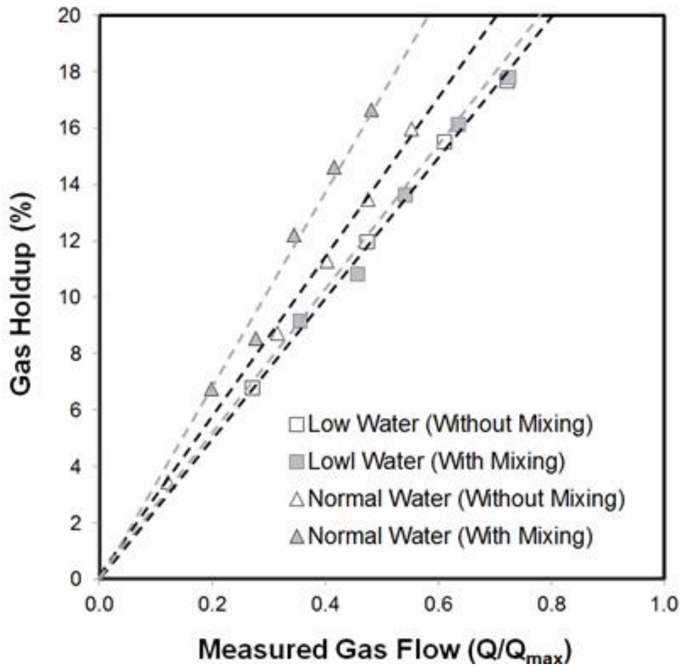


Figure 2. 16 Effect of gas-water mixing pathways on gas holdup (10 PPM frother)

The data plotted in Figure 2.16 indicate that there was only a very light increase in gas holdup when using the mixing pathways for the test runs that used a “low” addition rate of injection water. This suggests that the range of gas velocities spanned in this series of tests were already sufficient to ensure good mixing of water and gas without the need for any source of additional turbulence. However, when pushed to the higher “normal” water injection rates, the sparger equipped with the mixing pathways provided a notably higher gas holdup compared to the otherwise identical counterpart that was not equipped with the mixing pathways. For a gas flow representing about 60% of the full range tested, the gas holdup improved from about 17% to over 20% via the incorporation of the mixing pathways (TAJ) as part of the sparger design. Once again, this data suggests that small changes to the basic design of sparger components can have a dramatic impact on gas dispersion performance.

2.4.4 Effects of Frother Addition Point

One of the most important factors in determining the overall performance of a gas sparging system is the type and dosage of frother employed. Frothers are surfactants that lower the surface tension of the flotation pulp so as to permit the generation of small gas bubbles and promote the formation of a stable froth phase. Chemicals used commercially as frothing agents include various types of aliphatic alcohols, natural (pine) oils and cresylic acids (Laskowski, J. 1989). For columns, stronger frothing agents such as polyglycolethers may also be used to accommodate the large froth depths required for froth washing. When used, these stronger frothers are typically used as mixtures with other types of frothing agents to minimize the buildup of persistent downstream froth in launders, sumps and piping networks.

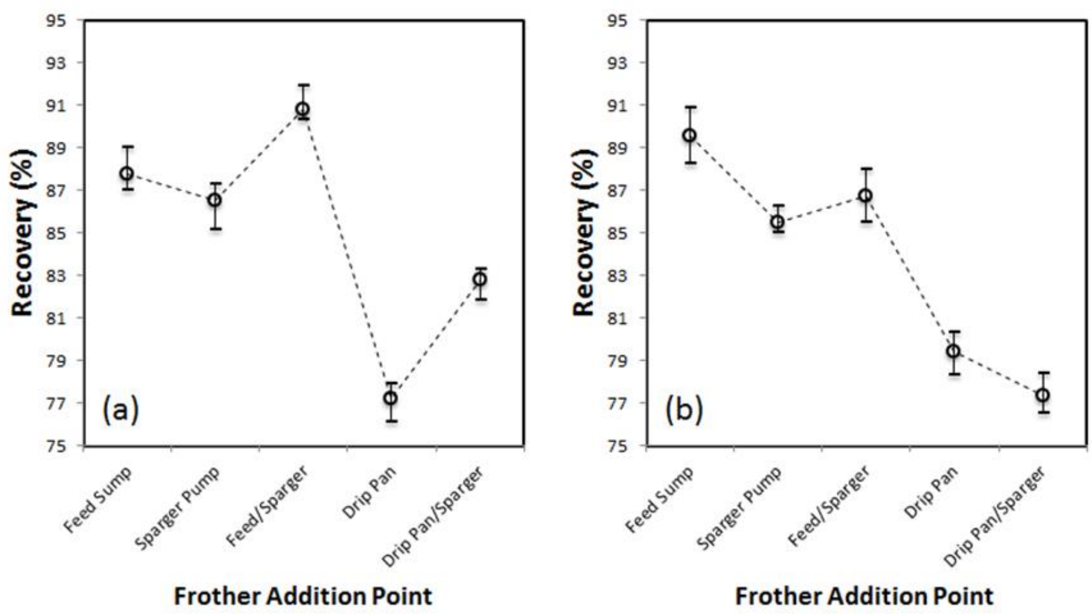


Figure 2. 17 Effect of frother addition point on flotation recovery for plant sites (a) and (b)

One often overlooked factor in frother use is the location of the injection point. For example, Figure 2.17 shows the effect of injecting frother into different locations around a column cell. In each case, the total dosage of frothing agent added by the reagent pumps was held constant. Five different frother addition methods were examined: (i) all frother added to the feed sump, (ii) all frother added to the sparger water injection pump, (iii) frother split equally between the feed sump and sparger water injection pump, (iv) all frother added to the wash water drip pan and (v) frother split equally between the wash water drip pan and the sparger water injection pump.

The evaluation of frother injection point was conducted at two different plant sites. For the first site, the in-plant test data (Figure 2.17a) shows that the best overall recovery of floatable solids was obtained when the frother was equally split between the feed sump and water injection pump. This provided nearly a 3-4 percentage point increase in recovery compared to adding all the frother into either the feed sump or sparger pump alone. However, for the second plant site, the test data plotted in Figure 2.17b) indicated that the best addition point was the feed sump. This addition point provided a recovery that was 3-4 percentage points higher than when added to the sparger pump and 2-3 percentage points higher when split between the feed sump and sparger water pump. Another important observation from both these plots is that any addition of frother to the wash water resulted in a substantial decline in recovery. This result was not unexpected since most of the wash water reports to the froth product launder, thereby reducing the amount of residual frother available to enter the flotation pulp for small bubble creation/stabilization. These data suggest that plant operators should carefully evaluate frother dosage levels and frother injection points to identify optimal operating conditions during routine performance audits of gas sparger installations.

2.4.5 Pressure vs. Time Monitoring

In order to determine improvements in gas dispersion offered by a new sparger type called SlamJet with Turbo Air Jet (SLJ-TAJ) and the effect of frother dosage in mineral processing applications, experimental tests were carried out in a pilot-scale flotation cell at different frother conditions with two types of spargers offered by Eriez Flotation Division: SlamJet and SlamJet with Turbo Air Jet. Both spargers were equipped with the same nozzle size of 4 mm for a fair comparison. As previously explained, the TAJ sparger type is a modified SlamJet sparger that consists of multiple blades designed and placed along the internal rod with the aim to mix air and water just before the discharge takes place in the column cell.

The series of tests were conducted at 0 and 6 PPM of frother, at the same inlet pressure, and using a "normal" level of injection water (i.e., 100% of the water rate recommended by the manufacturer). At each frother dosage, two sets of tests were conducted with and without the network of pathways (TAJ) required to achieve complete mixing of gas and water prior to exiting the discharge nozzle. The tests were monitored employing the pressure transmitter and data acquisition system (LabView) in a continuous mode, but with different two time period: (i) the spargers run for a fixed time (e.g., 180 sec) to allow air-holdup to come to steady state value and (ii) gas and water flow rates completely cut off while the monitoring system actively records gas holdup as a function of time (e. g., 120 sec) while gas releases from the column.

It is known that small bubbles have a lower rise velocity than large bubbles; therefore, the longer the gas takes to be released from the column cell, the better the gas distribution into the column due to the creation of smaller bubbles. The shape of such a “degas” curve is shown in Figure 2.18. The data provided in this plot is indicative of bubble size distributions present in the column that were generated by two different sparger types at two different froth levels. From the profiles, it can be observed that the sparger with the network pathways (Turbo Air Jet) improved gas dispersion when operated under low froth condition (6 PPM) compared to the standard SlamJet. This improvement can be observed from the longer period of time this curve takes to completely release the gas and reach a stable condition of 0% gas holdup. From the profiles it also can be observed that tests carried out with both spargers, standard SlamJet and SlamJet with TAJ, at 0 PPM do not show any difference in terms of gas dispersion. In conclusion, the TAJ modification appears to improve sparger gas dispersion only when frother is added to stabilize the formed bubbles, but not under test conditions with surfactant-free solutions.

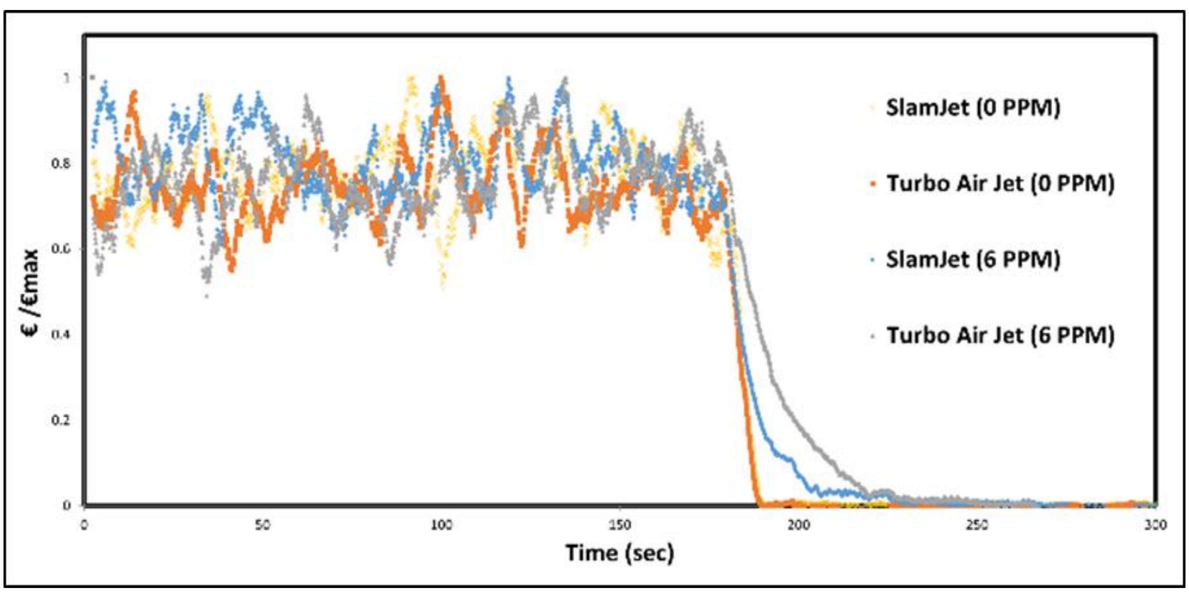


Figure 2. 18 Effect of frother dosage for test performed with SLJ and SLJ-TAJ

2.5 Discussion

2.5.1 Performance Modeling

To facilitate the selection of the sparger device, "Pressure vs Gas Flow" curves were developed for all the available industrial-size SlamJet spargers manufactured by the Eriez Flotation Division. These curves allow the plant operator to do a better selection of the aeration system that can bring an optimal column flotation performance without increasing energy consumption. It is important to know that this selection must be made with a manufacturer representative since they have an ample understanding of sparger performance, operation, and energy demand.

Figure 2.19 displays normalized graphs of Gas Flow vs Inlet Pressure for all full-scale commercial operations of SlamJet spargers offered by the Eriez Flotation Division for this study. The experimental data in these plots have been normalized by dividing the flows and pressures by the maximum gas flow rate (Qmax) and maximum inlet pressure (Pmax). As mentioned in a previous section, in terms of inlet pressure, a larger sparger nozzle demands more energy consumption than a smaller sparger. However, a larger sparger does not always deliver better gas dispersion to the column cell. Here it is important to consult sparger manufacturers for a better selection of sparger that is specifically designed for a given application. Furthermore, in order to compare all spargers offered by Eriez Flotation Division, a plot of the experimentally measured and mathematically predicted gas flow rates for the SlamJet spargers evaluated in this study is provided in Figure 2.20. As already indicated, these data were collected using several different sparger sizes that are used in full-scale commercial operations within the minerals processing applications. Figure 2.20 shows that extremely good correlations were obtained between the predicted and measured gas flow rates. The data provide a correlation coefficient of R^2 = 0.998 for the entire experimental data set. The ability of sparger manufacturers to accurately estimate gas flow rates based on sparger design and operating data is a valuable asset for plant operators.

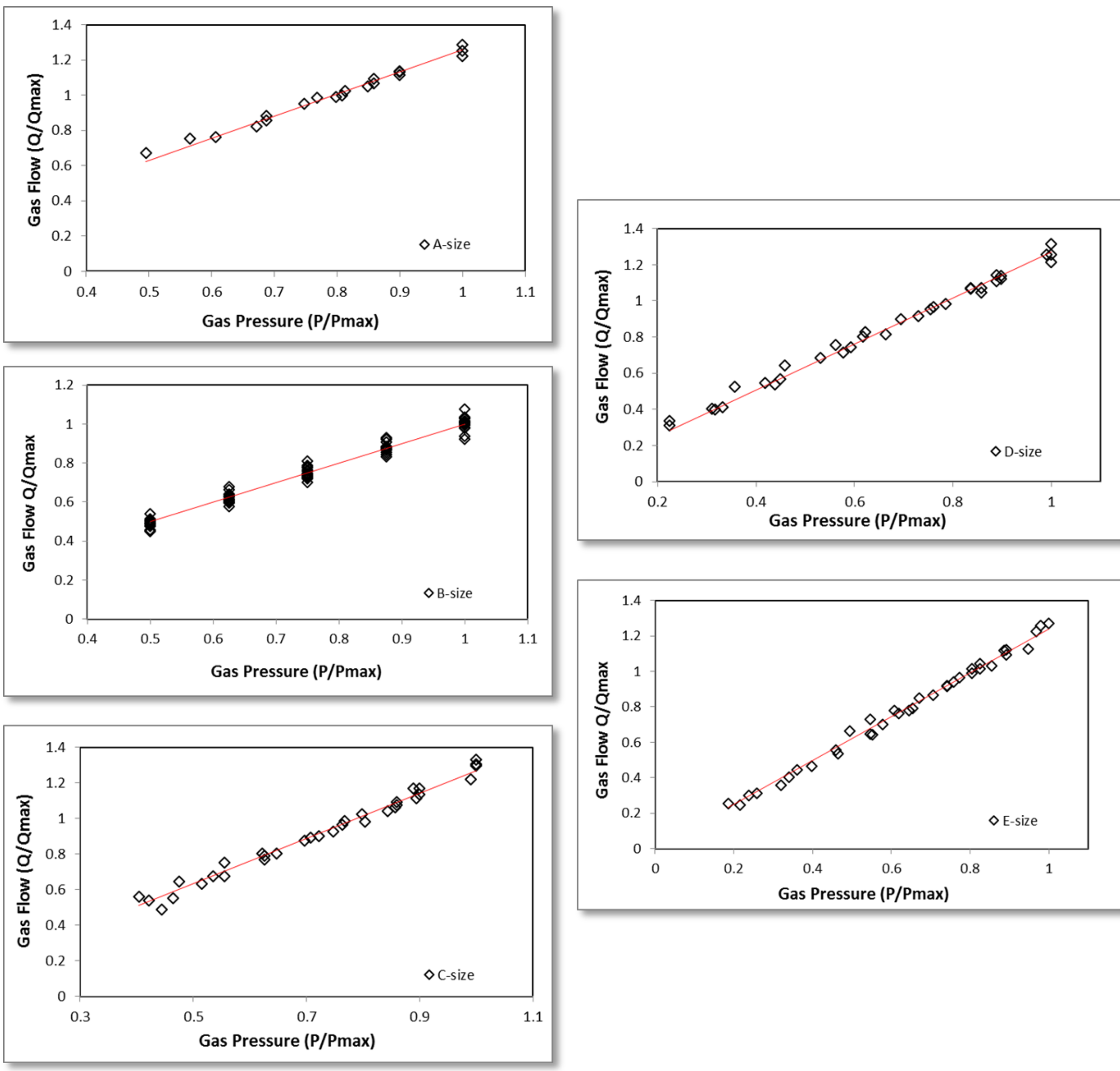


Figure 2. 19 Gas Flow vs Gas Pressure for all industrial-size spargers offered by Eriez Manufacturing

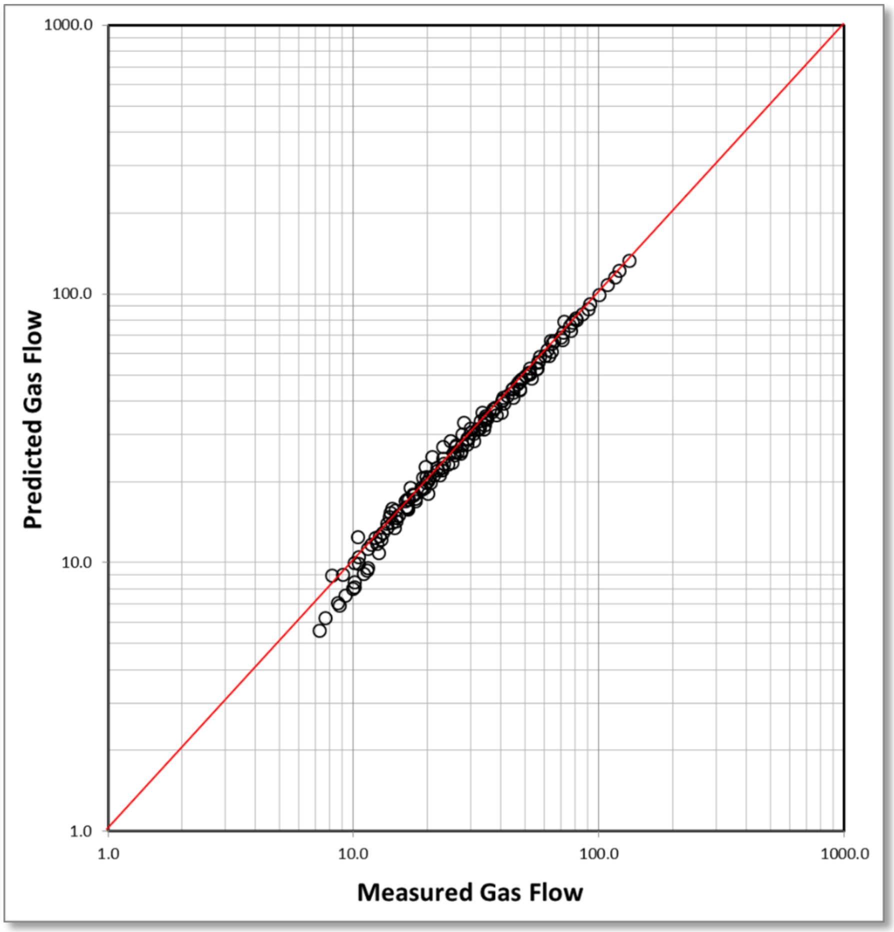


Figure 2. 20 Correlation of "Measured Gas Flow vs Predicted Gas Flow" for all nozzle sizes

2.5.2 Sparger Maintenance

2.5.2.1 Pressure Calibration

SlamJet® spargers are equipped with an adjustable screw that allows the pressure at which the internal rod pulls back away from the nozzle to be set. This pressure, which is commonly referred to as the "cracking pressure," is normally set at the factory to 200 kPa (30 PSI) prior to delivery to customers. Unfortunately, the cracking pressure may need to be readjusted in the field to accommodate changes caused by routine maintenance or normal wear-and-tear. When this occurs, it is possible that the cracking pressure will be incorrectly set, resulting in spargers that operate along different flow-pressure curves. This improper calibration of cracking pressures results in less than optimal operating conditions since less gas flow is obtained for the given compressor load. More importantly, the difference in gas flow rate from each sparger has the potential to induce unwanted axial mixing of the flotation pulp. The occurrence of such back-mixing has long been known to be detrimental to the metallurgical performance of column-type flotation cells (Dobby and Finch, 1985). Proper balancing of sparger flows and cracking pressures is necessary to ensure that this condition never occurs.

2.5.2.2 Non – OEM Components

As with any engineered device, the performance of a gas sparger depends on the integration of many individual components. For example, field experience has shown that the replacement of wear-resistant ceramic nozzles with locally fabricated metallic nozzles offers much shorter life spans and poorer long-term performance in terms of gas dispersion due to nozzle erosion/corrosion. Such changes often have large costly impacts on metallurgical performance while only saving pennies in replacement costs. While operators often understand the importance of utilizing high-quality OEM (original equipment manufacturer) parts for critical parts such as gas nozzles, they occasionally fail to recognize that the replacement of other types of parts assumed to be non-critical can also have a dramatic impact on sparger performance. For example, Figure 2.21 shows a flow-pressure curve for a commercial sparger in which the gas connector port was replaced with a similar connector. The data in this plot have been normalized by dividing the flows and pressures by either the maximum gas flow rate

(Qmax) or maximum pressure (Pmax). At the highest pressure, the non-OEM replacement part reduced the gas flow rate by nearly 20%.

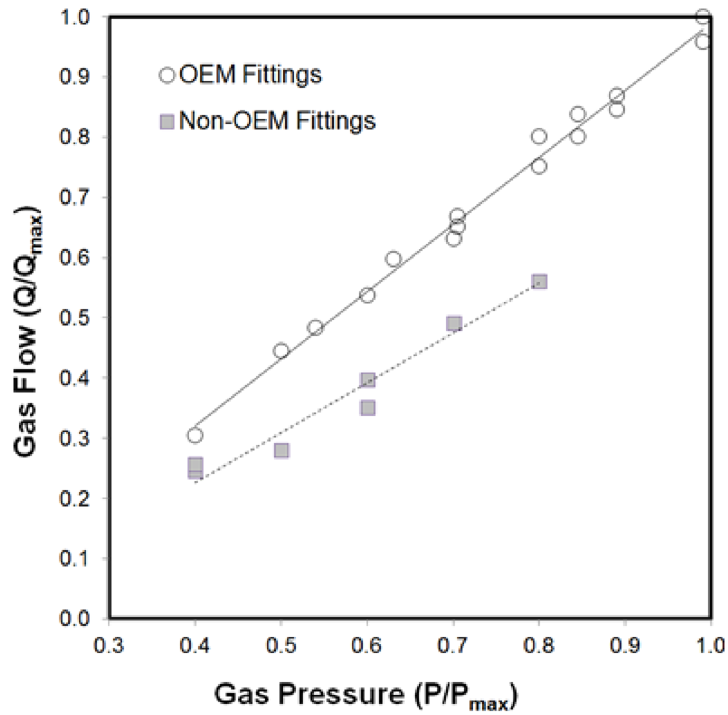


Figure 2. 21 Impact of installing a non-OEM gas inlet port on gas flow-pressure performance

A close inspection of the sparger equipment showed that the reduction was created by a non-OEM connector that, unknown to the owner of the sparger, had a smaller internal orifice (see Figure 2.22). The smaller orifice inadvertently restricted the gas flow, which in industrial practice would lower the gas flux through the column and reduce recovery. To compensate, the operator would be forced to run at a higher gas pressure to attain the same gas flow rate. This condition would result in a higher compressor load and power cost to attain the same net recovery of floatable materials. In this case, fractions of pennies would be saved at a tremendous cost to metallurgical performance. Therefore, plant operators are highly encouraged to conduct a detailed study of all components – even those thought to be relatively minor and non-critical – when performing audits of their gas sparging systems.

Figure 2. 22 Photograph of an incorrectly sized gas connector having too small

2.6 Conclusions

The effectiveness of a gas sparging system is highly dependent on a wide range of design and operating parameters. In industrial practice, these parameters can be optimized to ensure that peak metallurgical performance is achieved in column flotation circuits. The optimization often requires plant operators to schedule performance audits of the gas sparging system. By working with the sparger manufacturers, plant operators can compare expected and actual levels of performance to determine whether they have selected the proper sparger design, nozzle size, internal parts, distribution pattern, proper balancing of gas/water flows, elimination of unnecessary pressure drops, staged injection of frothing agents, and operating conditions for their particular application. This information can be used to fine tune the functionality of the sparging system in response to ever changing plant feed conditions. Sites where such audits have been performed have noted marked improvements in performance including enhanced flotation kinetics, better system stability and reduced power demand. It is recommended that plant operators conduct this type of audit on an annual basis to ensure that optimal levels of performance are maintained in their column circuits.

As with any flotation system, a failure to identify and correct any unfavorable conditions can result in lower recoveries, poorer metallurgical upgrading, decreased capacities, increased circulating loads, higher reagent consumption and inefficient energy usage. Fortunately, most sparger manufacturers are willing to assist in the performance audits and to make recommendations as to how these issues can be avoided and eliminated. Most improvements require comparatively little cost compared to the losses in revenue that may result from poor performance.

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Appendix A - Balance Model

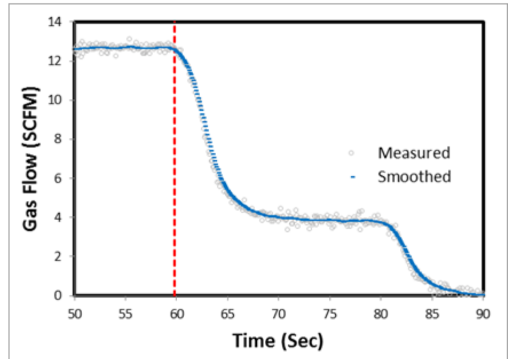
SLAMJET SPARGER TESTING

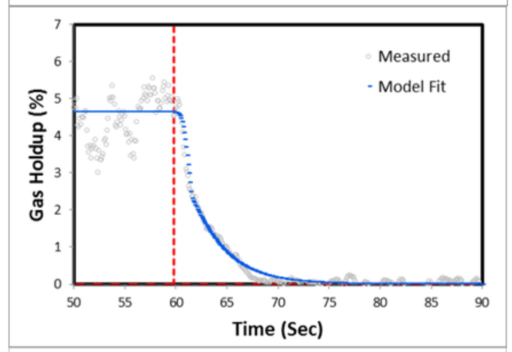
Sparger Type: Slamjet
Description: Standard Nozzle
Frother (PPM): 0
Gas Off (sec): 59.8

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	1.23	--	--	2.65	--	--	4.37	--
Based on PT On/Off	--	--	0.98	--	--	2.02	--	--	4.63	--
During Aeration ...										
Average	83.81	62.57	21.24	62.57	42.13	20.44	42.13	21.95	20.18	12.60
Maximum	87.39	66.60	20.79	66.60	44.60	22.00	44.60	23.93	20.67	13.16
Minimum	79.40	59.09	20.31	59.09	39.31	19.78	39.31	20.31	19.00	11.86
Range	7.99	7.51	0.48	7.51	5.28	2.22	5.28	3.62	1.66	1.30
Standard Deviation	0.97	0.84	0.13	0.84	0.67	0.17	0.67	0.55	0.12	0.21
High Outliner (+4 Sigma)	87.68	65.92	21.76	65.92	44.80	21.12	44.80	24.16	20.64	13.43
Low Outlier (-4 Sigma)	79.93	59.22	20.71	59.22	39.45	19.77	39.45	19.74	19.72	11.76
After Degassing ...										
Average	83.87	62.42	21.45	62.42	41.56	20.87	41.56	20.40	21.16	0.00
Maximum	84.06	62.60	21.46	62.60	41.72	20.88	41.72	20.57	21.15	0.55
Minimum	83.68	62.27	21.41	62.27	41.39	20.88	41.39	20.23	21.16	-0.45
Range	0.38	0.33	0.05	0.33	0.33	0.00	0.33	0.34	-0.01	1.00
Standard Deviation	0.06	0.06	0.00	0.06	0.08	-0.02	0.08	0.07	0.01	0.16
High Outliner (+4 Sigma)	84.12	62.66	21.46	62.66	41.87	20.80	41.87	20.66	21.21	0.64
Low Outlier (-4 Sigma)	83.62	62.18	21.44	62.18	41.25	20.94	41.25	20.14	21.11	-0.64

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	4.63	%	Delta Holdup	4.63	%	Time @	0.99	60.17	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.01	--	Time @	0.75	60.99	sec
Time to Midpoint Holdup (sec):	61.47	sec	Epm	0.55	sec	Time @	0.5	61.47	sec
Power Term in Fitting Model:	88.57	--	2 x Epm	1.09	sec	Time @	0.25	63.93	sec
Power Term in Fitting Model:	22.44	--	Degass Time	22.10	sec	Time @	0.001	82.27	sec
Sum-of-Squares	685	--							





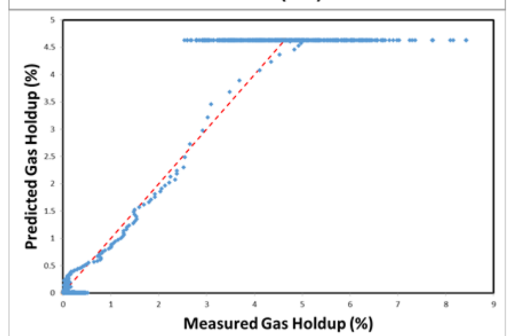


Figure A. 1 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet
Description: Standard Nozzle

Frother (PPM): 0
Gas Off (sec): 60.9

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	-0.10	--	--	2.74	--	--	3.26	--
Based on PT On/Off	--	--	-0.36	--	--	2.33	--	--	3.31	--
During Aeration ...										
Average	84.15	62.63	21.52	62.63	42.21	20.42	42.21	21.79	20.41	9.94
Maximum	89.40	69.13	20.27	69.13	45.44	23.69	45.44	24.49	20.95	10.42
Minimum	79.52	58.33	21.19	58.33	38.60	19.74	38.60	19.08	19.52	9.48
Range	9.88	10.80	-0.92	10.80	6.84	3.96	6.84	5.41	1.43	0.94
Standard Deviation	1.53	1.32	0.22	1.32	1.15	0.16	1.15	0.86	0.29	0.17
High Outliner (+4 Sigma)	90.29	67.91	22.39	67.91	46.82	21.08	46.82	25.23	21.59	10.62
Low Outlier (-4 Sigma)	78.01	57.36	20.66	57.36	37.59	19.77	37.59	18.35	19.24	9.27
After Degassing ...										
Average	83.84	62.40	21.44	62.40	41.48	20.91	41.48	20.37	21.11	0.08
Maximum	84.05	62.56	21.49	62.56	41.68	20.88	41.68	20.57	21.11	0.56
Minimum	83.63	62.24	21.39	62.24	41.25	20.99	41.25	20.20	21.04	-0.39
Range	0.42	0.32	0.10	0.32	0.43	-0.12	0.43	0.36	0.07	0.95
Standard Deviation	0.07	0.06	0.01	0.06	0.08	-0.02	0.08	0.07	0.01	0.16
High Outliner (+4 Sigma)	84.13	62.63	21.50	62.63	41.80	20.82	41.80	20.64	21.16	0.74
Low Outlier (-4 Sigma)	83.55	62.17	21.39	62.17	41.17	21.00	41.17	20.10	21.06	-0.58

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	3.31	%	Delta Holdup	3.31	%	Time @	0.99	61.36	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.02	--	Time @	0.75	63.02	sec
Time to Midpoint Holdup (sec):	64.00	sec	Epm	1.12	sec	Time @	0.5	64.00	sec
Power Term in Fitting Model:	45.00	--	2 x Epm	2.24	sec	Time @	0.25	65.73	sec
Power Term in Fitting Model:	33.00	--	Degass Time	16.67	sec	Time @	0.001	78.03	sec
Sum-of-Squares	1108	--							

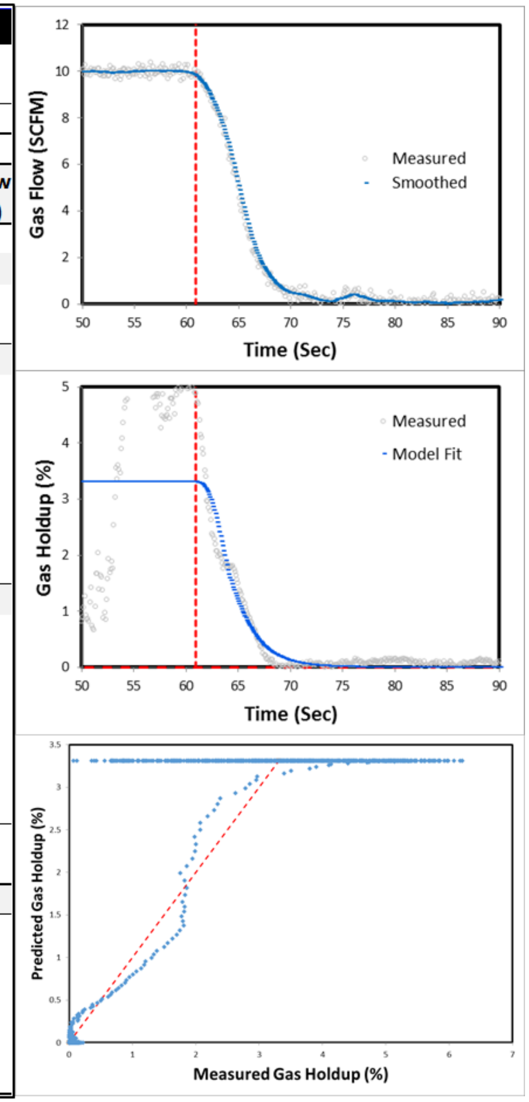


Figure A. 2 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type:	Slamjet	**Frother (PPM):**	0
Description:	Standard Nozzle	**Gas Off (sec):**	61.4

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	0.51	--	--	2.31	--	--	2.94	--
Based on PT On/Off	--	--	0.52	--	--	1.22	--	--	3.30	--
During Aeration ...										
Average	85.12	63.73	21.39	63.73	43.21	20.51	43.21	22.73	20.48	7.07
Maximum	89.79	68.22	21.57	68.22	46.82	21.40	46.82	26.25	20.57	7.59
Minimum	79.09	58.64	20.45	58.64	39.41	19.23	39.41	17.18	22.23	6.64
Range	10.71	9.59	1.12	9.59	7.41	2.17	7.41	9.07	-1.66	0.95
Standard Deviation	1.81	1.54	0.27	1.54	1.35	0.20	1.35	1.06	0.28	0.17
High Outliner (+4 Sigma)	92.37	69.90	22.47	69.90	48.60	21.30	48.60	26.99	21.61	7.74
Low Outlier (-4 Sigma)	77.86	57.55	20.31	57.55	37.83	19.73	37.83	18.48	19.35	6.39
After Degassing ...										
Average	85.02	63.52	21.50	63.52	42.75	20.77	42.75	21.57	21.18	0.38
Maximum	85.26	63.73	21.54	63.73	42.95	20.78	42.95	21.80	21.15	2.29
Minimum	84.79	63.31	21.49	63.31	42.54	20.76	42.54	21.37	21.17	-0.42
Range	0.47	0.42	0.05	0.42	0.40	0.02	0.40	0.43	-0.03	2.71
Standard Deviation	0.09	0.07	0.01	0.07	0.07	0.00	0.07	0.08	0.00	0.42
High Outliner (+4 Sigma)	85.37	63.82	21.55	63.82	43.05	20.77	43.05	21.88	21.17	2.05
Low Outlier (-4 Sigma)	84.68	63.22	21.45	63.22	42.46	20.77	42.46	21.27	21.19	-1.29

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	3.30	%	Delta Holdup	3.30	%	Time @	0.99	59.49	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.02	--	Time @	0.75	61.69	sec
Time to Midpoint Holdup (sec):	63.00	sec	Epm	1.51	sec	Time @	0.5	63.00	sec
Power Term in Fitting Model:	33.00	--	2 x Epm	3.01	sec	Time @	0.25	64.60	sec
Power Term in Fitting Model:	35.00	--	Degass Time	16.46	sec	Time @	0.001	75.95	sec
Sum-of-Squares	1876	--							

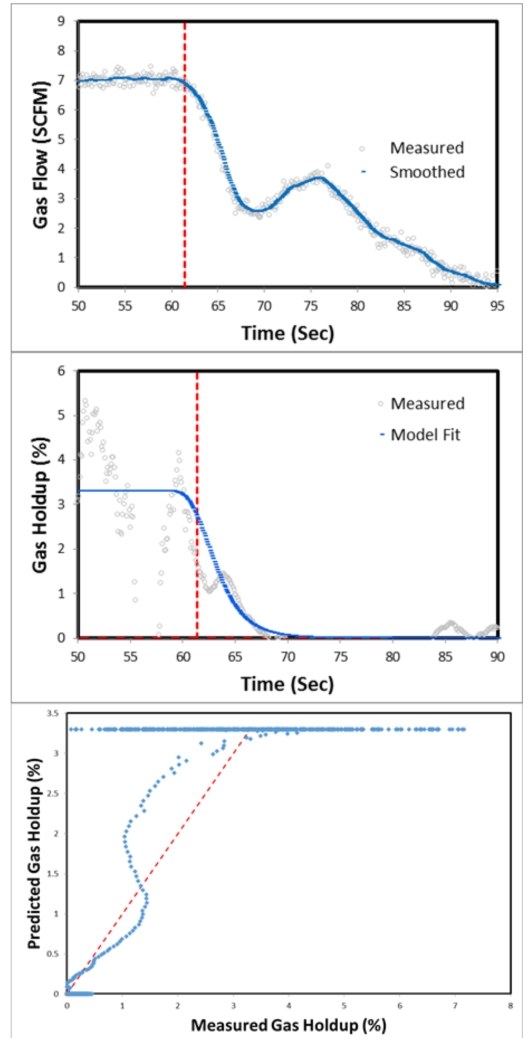


Figure A. 3 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet
Description: Standard Nozzle

Frother (PPM): 0
Gas Off (sec): 62

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	0.45	--	--	1.40	--	--	2.51	--
Based on PT On/Off	--	--	0.16	--	--	0.90	--	--	2.57	--
During Aeration ...										
Average	85.31	63.91	21.40	63.91	43.20	20.71	43.20	22.63	20.57	6.37
Maximum	91.48	69.54	21.94	69.54	48.09	21.45	48.09	26.60	21.49	6.87
Minimum	79.89	58.41	21.48	58.41	38.34	20.06	38.34	18.93	19.41	5.78
Range	11.59	11.13	0.45	11.13	9.75	1.38	9.75	7.67	2.08	1.09
Standard Deviation	2.10	1.87	0.23	1.87	1.70	0.17	1.70	1.22	0.48	0.17
High Outliner (+4 Sigma)	93.72	71.39	22.33	71.39	50.00	21.39	50.00	27.53	22.47	7.05
Low Outlier (-4 Sigma)	76.90	56.42	20.48	56.42	36.40	20.02	36.40	17.74	18.67	5.70
After Degassing ...										
Average	84.98	63.54	21.44	63.54	42.65	20.89	42.65	21.54	21.11	0.00
Maximum	85.23	63.70	21.53	63.70	42.85	20.86	42.85	21.79	21.05	0.51
Minimum	84.77	63.35	21.42	63.35	42.42	20.93	42.42	21.34	21.08	-0.61
Range	0.46	0.35	0.11	0.35	0.43	-0.07	0.43	0.45	-0.03	1.12
Standard Deviation	0.09	0.07	0.02	0.07	0.08	-0.02	0.08	0.08	0.01	0.17
High Outliner (+4 Sigma)	85.34	63.81	21.52	63.81	42.99	20.82	42.99	21.84	21.15	0.69
Low Outlier (-4 Sigma)	84.63	63.27	21.35	63.27	42.31	20.96	42.31	21.24	21.08	-0.69

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	2.57	%	Delta Holdup	2.57	%	Time @	0.99	57.76	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.04	--	Time @	0.75	61.34	sec
Time to Midpoint Holdup (sec):	63.50	sec	Epm	2.51	sec	Time @	0.5	63.50	sec
Power Term in Fitting Model:	20.00	--	2 x Epm	5.02	sec	Time @	0.25	65.12	sec
Power Term in Fitting Model:	35.00	--	Degass Time	18.78	sec	Time @	0.001	76.55	sec
Sum-of-Squares	717	--							

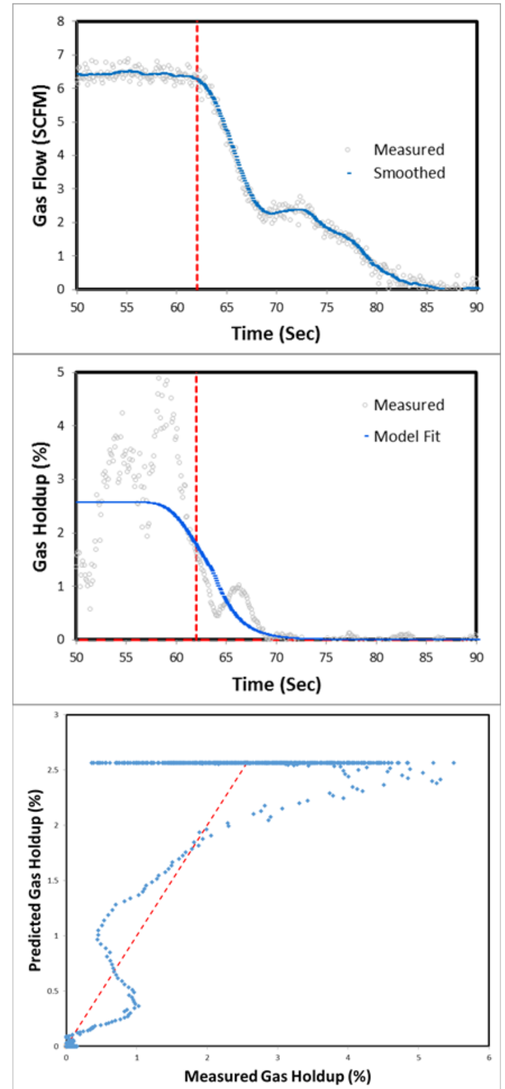


Figure A. 4 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet
Description: Standard Nozzle

Frother (PPM): 0
Gas Off (sec): 60.6

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	1.48	--	--	4.10	--	--	5.50	--
Based on PT On/Off	--	--	1.06	--	--	3.59	--	--	5.81	--
During Aeration ...										
Average	82.70	61.52	21.18	61.52	41.38	20.14	41.38	21.44	19.94	16.30
Maximum	86.37	64.54	21.83	64.54	43.45	21.09	43.45	22.70	20.75	16.96
Minimum	76.35	59.58	16.78	59.58	38.65	20.93	38.65	20.11	18.54	15.66
Range	10.01	4.96	5.05	4.96	4.80	0.16	4.80	2.59	2.21	1.30
Standard Deviation	0.81	0.61	0.21	0.61	0.48	0.13	0.48	0.39	0.09	0.22
High Outliner (+4 Sigma)	85.96	63.95	22.02	63.95	43.29	20.66	43.29	22.99	20.30	17.17
Low Outlier (-4 Sigma)	79.44	59.10	20.35	59.10	39.48	19.62	39.48	19.90	19.58	15.43
After Degassing ...										
Average	82.60	61.19	21.41	61.19	40.30	20.89	40.30	19.13	21.17	-0.03
Maximum	82.82	61.39	21.43	61.39	40.44	20.95	40.44	19.29	21.16	0.45
Minimum	82.44	61.02	21.42	61.02	40.18	20.84	40.18	19.01	21.17	-0.51
Range	0.38	0.38	0.01	0.38	0.27	0.11	0.27	0.28	-0.01	0.96
Standard Deviation	0.08	0.07	0.01	0.07	0.06	0.02	0.06	0.06	0.00	0.16
High Outliner (+4 Sigma)	82.92	61.49	21.43	61.49	40.54	20.95	40.54	19.37	21.17	0.59
Low Outlier (-4 Sigma)	82.28	60.90	21.38	60.90	40.07	20.83	40.07	18.90	21.17	-0.65

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	5.81	%	Delta Holdup	5.81	%	Time @	0.99	58.06	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.04	--	Time @	0.75	62.06	sec
Time to Midpoint Holdup (sec):	64.50	sec	Epm	2.83	sec	Time @	0.5	64.50	sec
Power Term in Fitting Model:	18.00	--	2 x Epm	5.67	sec	Time @	0.25	65.77	sec
Power Term in Fitting Model:	45.00	--	Degass Time	16.53	sec	Time @	0.001	74.59	sec
Sum-of-Squares	658	--							

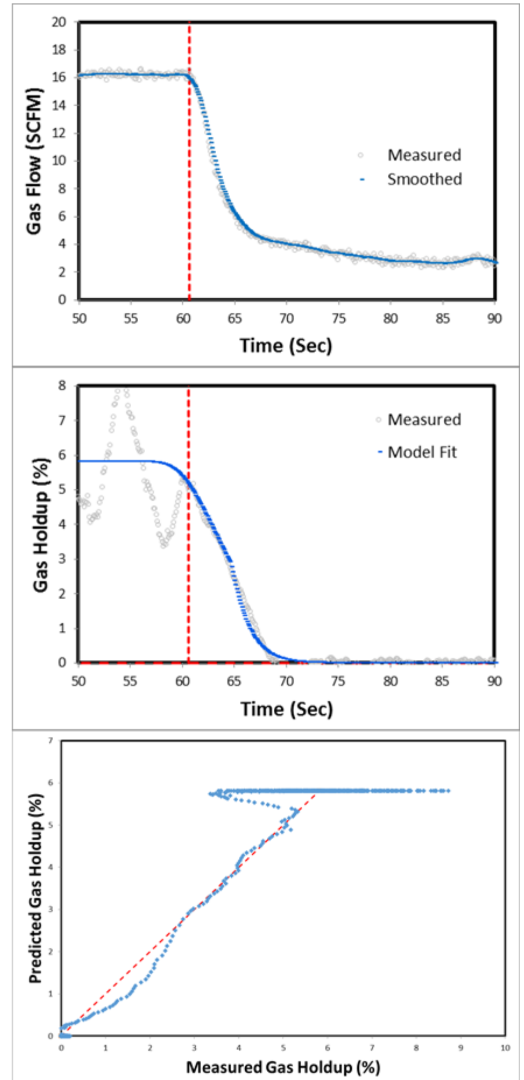


Figure A. 5 Model Summary for SLJ

SLAMJET SPARGER TESTING

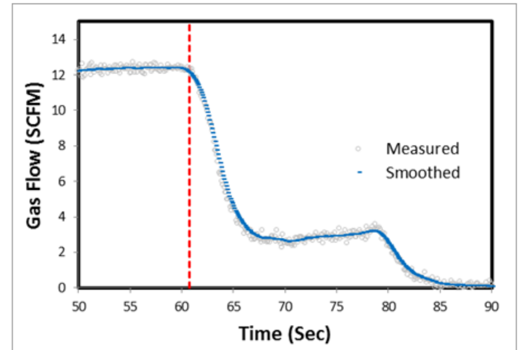
Sparger Type: Slamjet
Description: Standard Nozzle

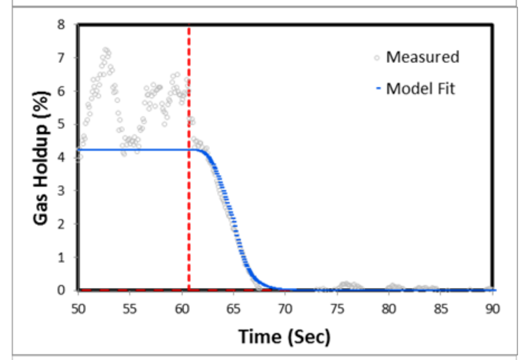
Frother (PPM): 0
Gas Off (sec): 60.7

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	0.91	--	--	3.03	--	--	4.06	--
Based on PT On/Off	--	--	0.62	--	--	2.54	--	--	4.23	--
During Aeration ...										
Average	83.52	62.22	21.30	62.22	41.85	20.36	41.85	21.61	20.24	12.41
Maximum	89.83	66.12	23.72	66.12	45.34	20.77	45.34	24.03	21.31	12.96
Minimum	78.06	57.96	20.10	57.96	38.63	19.32	38.63	18.67	19.97	11.79
Range	11.77	8.16	3.61	8.16	6.71	1.45	6.71	5.36	1.35	1.17
Standard Deviation	1.53	1.16	0.37	1.16	1.06	0.10	1.06	0.82	0.24	0.18
High Outliner (+4 Sigma)	89.64	66.86	22.77	66.86	46.10	20.77	46.10	24.88	21.22	13.15
Low Outlier (-4 Sigma)	77.41	57.57	19.84	57.57	37.61	19.96	37.61	18.34	19.27	11.68
After Degassing ...										
Average	82.92	61.48	21.44	61.48	40.59	20.90	40.59	19.45	21.14	0.04
Maximum	83.14	61.67	21.47	61.67	40.76	20.91	40.76	19.65	21.12	0.62
Minimum	82.71	61.28	21.42	61.28	40.38	20.90	40.38	19.27	21.11	-0.50
Range	0.44	0.39	0.04	0.39	0.38	0.01	0.38	0.37	0.01	1.12
Standard Deviation	0.07	0.08	-0.01	0.08	0.08	0.00	0.08	0.05	0.03	0.17
High Outliner (+4 Sigma)	83.20	61.82	21.38	61.82	40.91	20.91	40.91	19.65	21.26	0.72
Low Outlier (-4 Sigma)	82.64	61.14	21.49	61.14	40.27	20.88	40.27	19.25	21.02	-0.63

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	4.23	%	Delta Holdup	4.23	%	Time @	0.99	61.72	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.02	--	Time @	0.75	63.70	sec
Time to Midpoint Holdup (sec):	64.87	sec	Epm	1.34	sec	Time @	0.5	64.87	sec
Power Term in Fitting Model:	38.06	--	2 x Epm	2.69	sec	Time @	0.25	65.74	sec
Power Term in Fitting Model:	65.53	--	Degass Time	9.96	sec	Time @	0.001	71.67	sec
Sum-of-Squares	1227	--							





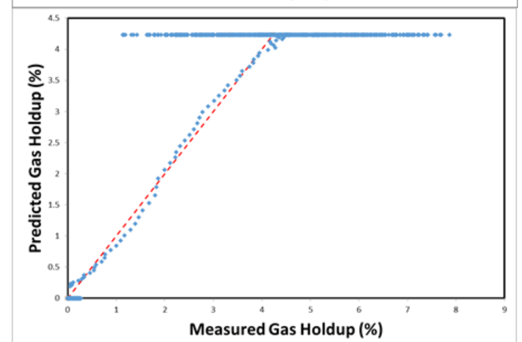


Figure A. 6 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet
Description: Standard Nozzle

Frother (PPM): 0
Gas Off (sec): 60.8

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	0.87	--	--	2.77	--	--	3.51	--
Based on PT On/Off	--	--	0.85	--	--	1.76	--	--	3.88	--
During Aeration ...										
Average	84.60	63.29	21.31	63.29	42.87	20.42	42.87	22.51	20.36	8.65
Maximum	90.11	67.96	22.15	67.96	46.83	21.13	46.83	25.72	21.12	9.20
Minimum	78.87	58.64	20.23	58.64	37.91	20.73	37.91	20.00	17.90	8.21
Range	11.24	9.32	1.92	9.32	8.93	0.40	8.93	5.71	3.21	0.99
Standard Deviation	1.77	1.55	0.23	1.55	1.34	0.21	1.34	0.98	0.36	0.16
High Outliner (+4 Sigma)	91.69	69.47	22.22	69.47	48.23	21.24	48.23	26.44	21.79	9.29
Low Outlier (-4 Sigma)	77.51	57.10	20.41	57.10	37.51	19.59	37.51	18.58	18.93	8.00
After Degassing ...										
Average	84.56	63.06	21.50	63.06	42.28	20.78	42.28	21.10	21.18	-0.05
Maximum	84.80	63.21	21.59	63.21	42.44	20.77	42.44	21.30	21.14	0.54
Minimum	84.33	62.89	21.45	62.89	42.15	20.74	42.15	20.96	21.19	-0.52
Range	0.46	0.32	0.15	0.32	0.29	0.03	0.29	0.34	-0.05	1.06
Standard Deviation	0.09	0.08	0.01	0.08	0.05	0.02	0.05	0.07	-0.01	0.16
High Outliner (+4 Sigma)	84.90	63.36	21.54	63.36	42.50	20.87	42.50	21.36	21.14	0.59
Low Outlier (-4 Sigma)	84.22	62.76	21.46	62.76	42.06	20.70	42.06	20.83	21.23	-0.68

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	3.88	%	Delta Holdup	3.88	%	Time @	0.99	61.86	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.01	--	Time @	0.75	62.72	sec
Time to Midpoint Holdup (sec):	63.23	sec	Epm	0.57	sec	Time @	0.5	63.23	sec
Power Term in Fitting Model:	86.69	--	2 x Epm	1.15	sec	Time @	0.25	64.93	sec
Power Term in Fitting Model:	33.00	--	Degass Time	15.23	sec	Time @	0.001	77.09	sec
Sum-of-Squares	1280	--							

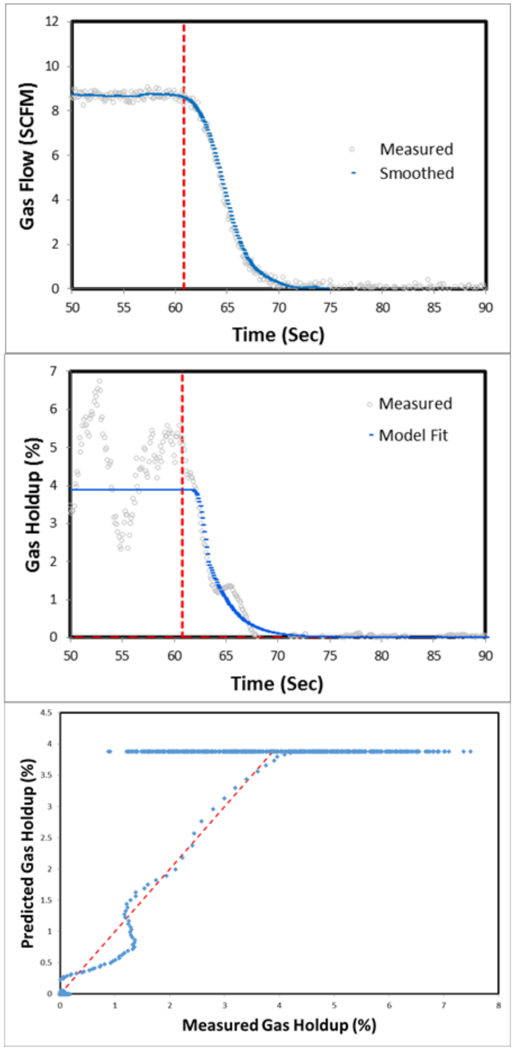


Figure A. 7 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type:	Slamjet	**Frother (PPM):**	0
Description:	Standard Nozzle	**Gas Off (sec):**	61.2

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	0.04	--	--	1.62	--	--	3.16	--
Based on PT On/Off	--	--	-0.20	--	--	1.09	--	--	3.04	--
During Aeration ...										
Average	84.63	63.14	21.49	63.14	42.48	20.66	42.48	22.04	20.43	8.11
Maximum	91.20	68.47	22.73	68.47	47.35	21.12	47.35	25.10	22.25	8.68
Minimum	78.87	57.92	20.96	57.92	37.70	20.22	37.70	18.00	19.70	7.58
Range	12.32	10.55	1.77	10.55	9.65	0.91	9.65	7.10	2.55	1.10
Standard Deviation	2.21	1.85	0.36	1.85	1.76	0.09	1.76	1.21	0.55	0.18
High Outliner (+4 Sigma)	93.48	70.54	22.94	70.54	49.52	21.01	49.52	26.90	22.63	8.82
Low Outlier (-4 Sigma)	75.77	55.73	20.04	55.73	35.43	20.31	35.43	17.19	18.24	7.39
After Degassing ...										
Average	84.35	62.90	21.45	62.90	42.01	20.89	42.01	20.94	21.07	-0.02
Maximum	84.56	63.14	21.42	63.14	42.23	20.91	42.23	21.08	21.15	0.52
Minimum	84.06	62.64	21.42	62.64	41.74	20.91	41.74	20.75	20.99	-0.47
Range	0.49	0.49	0.00	0.49	0.50	0.00	0.50	0.33	0.17	0.99
Standard Deviation	0.07	0.08	-0.01	0.08	0.08	0.00	0.08	0.07	0.01	0.17
High Outliner (+4 Sigma)	84.62	63.21	21.41	63.21	42.34	20.87	42.34	21.22	21.12	0.64
Low Outlier (-4 Sigma)	84.07	62.58	21.48	62.58	41.68	20.90	41.68	20.65	21.03	-0.68

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	3.04	%	Delta Holdup	3.04	%	Time @	0.99	61.14	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.02	--	Time @	0.75	63.14	sec
Time to Midpoint Holdup (sec):	64.33	sec	Epm	1.36	sec	Time @	0.5	64.33	sec
Power Term in Fitting Model:	37.24	--	2 x Epm	2.72	sec	Time @	0.25	66.12	sec
Power Term in Fitting Model:	32.03	--	Degass Time	17.76	sec	Time @	0.001	78.90	sec
Sum-of-Squares	1584	--							

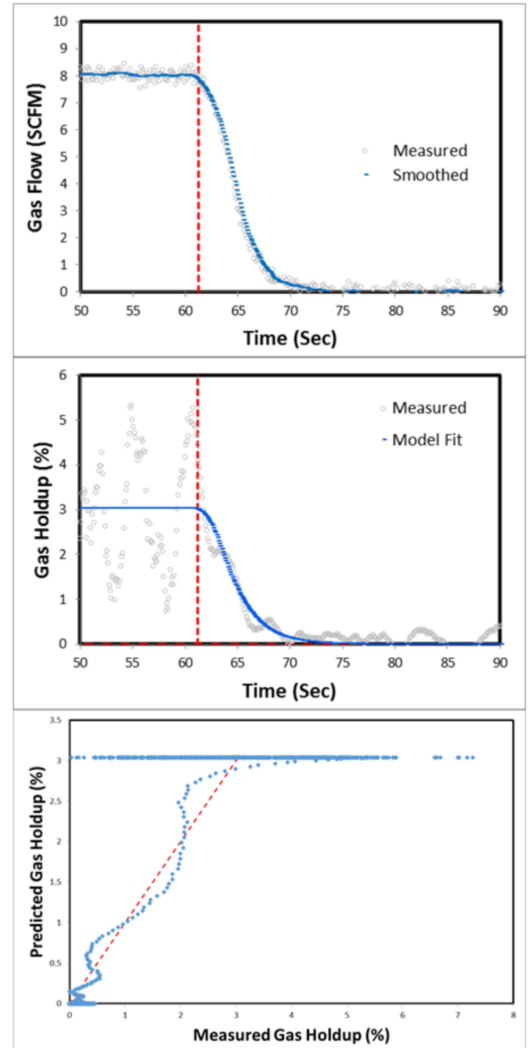


Figure A. 8 Model Summary for SLJ

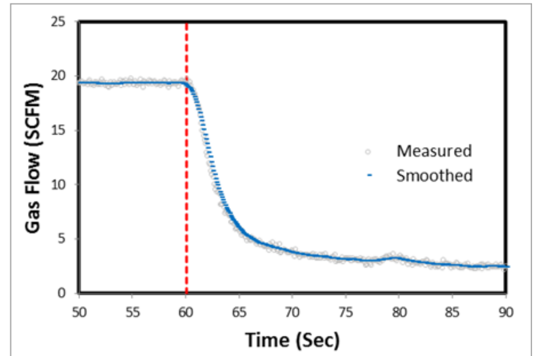
SLAMJET SPARGER TESTING

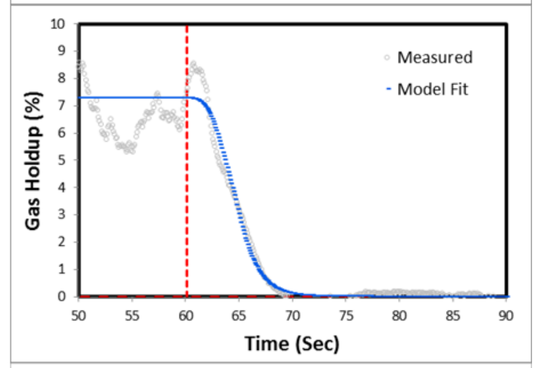
Sparger Type: Slamjet **Frother (PPM):** 0
Description: Standard Nozzle **Gas Off (sec):** 60.1

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	2.36	--	--	5.05	--	--	6.94	--
Based on PT On/Off	--	--	1.97	--	--	4.55	--	--	7.28	--
During Aeration ...										
Average	81.75	60.75	20.99	60.75	40.81	19.94	40.81	21.18	19.64	19.32
Maximum	85.88	62.75	23.13	62.75	42.53	20.22	42.53	22.77	19.77	19.88
Minimum	78.62	58.67	19.95	58.67	38.89	19.78	38.89	19.75	19.14	18.74
Range	7.26	4.08	3.18	4.08	3.64	0.44	3.64	3.02	0.63	1.14
Standard Deviation	0.77	0.65	0.13	0.65	0.53	0.11	0.53	0.43	0.10	0.18
High Outliner (+4 Sigma)	84.83	63.34	21.49	63.34	42.94	20.39	42.94	22.89	20.05	20.04
Low Outlier (-4 Sigma)	78.66	58.17	20.49	58.17	38.69	19.48	38.69	19.46	19.22	18.59
After Degassing ...										
Average	81.54	60.13	21.41	60.13	39.24	20.89	39.24	18.06	21.18	0.03
Maximum	81.73	60.28	21.45	60.28	39.37	20.92	39.37	18.26	21.11	1.43
Minimum	81.30	59.95	21.35	59.95	39.10	20.85	39.10	17.93	21.17	-0.44
Range	0.43	0.33	0.09	0.33	0.27	0.06	0.27	0.33	-0.06	1.87
Standard Deviation	0.07	0.06	0.01	0.06	0.06	0.00	0.06	0.06	-0.01	0.25
High Outliner (+4 Sigma)	81.83	60.38	21.45	60.38	39.47	20.91	39.47	18.32	21.15	1.01
Low Outlier (-4 Sigma)	81.25	59.88	21.38	59.88	39.01	20.87	39.01	17.81	21.20	-0.96

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	7.28	%	Delta Holdup	7.28	%	Time @	0.99	61.13	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.02	--	Time @	0.75	63.28	sec
Time to Midpoint Holdup (sec):	64.55	sec	Epm	1.46	sec	Time @	0.5	64.55	sec
Power Term in Fitting Model:	34.78	--	2 x Epm	2.93	sec	Time @	0.25	65.77	sec
Power Term in Fitting Model:	47.00	--	Degass Time	13.06	sec	Time @	0.001	74.19	sec
Sum-of-Squares	504	--							





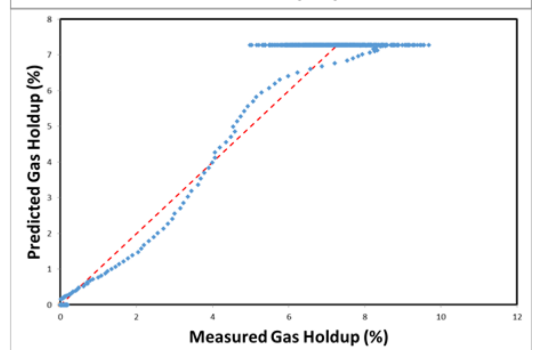


Figure A. 9 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet
Description: Standard Nozzle

Frother (PPM): 0
Gas Off (sec): 60.6

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	1.26	--	--	3.28	--	--	4.86	--
Based on PT On/Off	--	--	0.84	--	--	2.96	--	--	4.95	--
During Aeration ...										
Average	82.82	61.59	21.23	61.59	41.28	20.31	41.28	21.21	20.07	14.40
Maximum	88.47	68.06	20.41	68.06	44.88	23.18	44.88	23.58	21.30	15.24
Minimum	78.48	54.49	23.99	54.49	37.58	16.91	37.58	18.31	19.28	13.63
Range	10.00	13.57	-3.57	13.57	7.30	6.28	7.30	5.28	2.02	1.62
Standard Deviation	1.55	1.44	0.11	1.44	1.13	0.31	1.13	0.84	0.29	0.27
High Outliner (+4 Sigma)	89.02	67.35	21.67	67.35	45.80	21.54	45.80	24.57	21.23	15.46
Low Outlier (-4 Sigma)	76.62	55.84	20.79	55.84	36.76	19.08	36.76	17.84	18.92	13.34
After Degassing ...										
Average	82.20	60.79	21.41	60.79	39.86	20.93	39.86	18.74	21.12	0.01
Maximum	82.43	60.97	21.46	60.97	40.10	20.87	40.10	18.94	21.16	0.54
Minimum	82.03	60.59	21.44	60.59	39.73	20.86	39.73	18.57	21.16	-0.50
Range	0.39	0.38	0.01	0.38	0.37	0.02	0.37	0.37	0.00	1.04
Standard Deviation	0.08	0.08	0.00	0.08	0.07	0.01	0.07	0.05	0.02	0.16
High Outliner (+4 Sigma)	82.53	61.12	21.41	61.12	40.16	20.96	40.16	18.95	21.21	0.63
Low Outlier (-4 Sigma)	81.87	60.47	21.41	60.47	39.56	20.90	39.56	18.53	21.03	-0.61

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	4.95	%	Delta Holdup	4.95	%	Time @	0.99	60.50	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.02	--	Time @	0.75	62.63	sec
Time to Midpoint Holdup (sec):	63.89	sec	Epm	1.45	sec	Time @	0.5	63.89	sec
Power Term in Fitting Model:	34.81	--	2 x Epm	2.89	sec	Time @	0.25	65.47	sec
Power Term in Fitting Model:	36.00	--	Degass Time	16.11	sec	Time @	0.001	76.62	sec
Sum-of-Squares	1268	--							

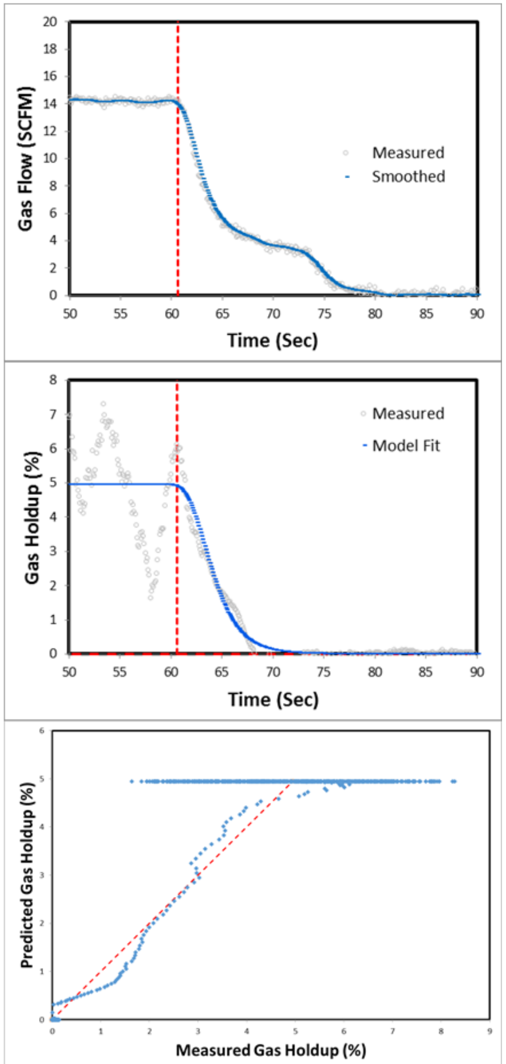


Figure A. 10 Model Summary for SLJ

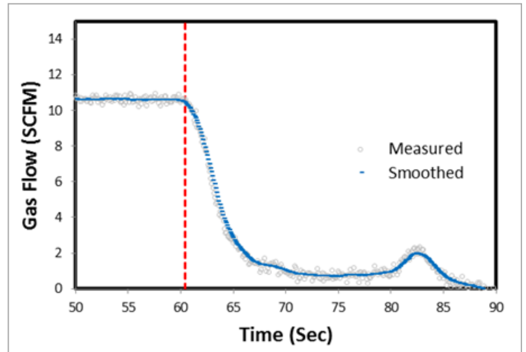
SLAMJET SPARGER TESTING

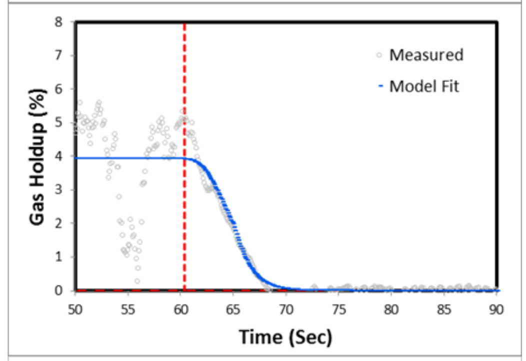
Sparger Type:	Slamjet	**Frother (PPM):**	0
Description:	Standard Nozzle	**Gas Off (sec):**	60.4

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	0.54	--	--	3.17	--	--	3.53	--
Based on PT On/Off	--	--	0.44	--	--	2.18	--	--	3.92	--
During Aeration ...										
Average	84.08	62.69	21.38	62.69	42.36	20.33	42.36	22.00	20.36	10.60
Maximum	89.89	66.97	22.92	66.97	46.84	20.14	46.84	25.49	21.34	11.17
Minimum	78.18	57.55	20.62	57.55	38.29	19.27	38.29	18.89	19.40	10.03
Range	11.71	9.42	2.30	9.42	8.55	0.87	8.55	6.61	1.94	1.14
Standard Deviation	1.75	1.50	0.25	1.50	1.30	0.19	1.30	1.08	0.23	0.19
High Outliner (+4 Sigma)	91.07	68.67	22.39	68.67	47.56	21.11	47.56	26.30	21.26	11.37
Low Outlier (-4 Sigma)	77.09	56.71	20.38	56.71	37.15	19.56	37.15	17.70	19.45	9.83
After Degassing ...										
Average	83.85	62.37	21.48	62.37	41.59	20.79	41.59	20.40	21.19	-0.05
Maximum	84.04	62.53	21.51	62.53	41.77	20.76	41.77	20.58	21.19	0.47
Minimum	83.64	62.20	21.44	62.20	41.44	20.77	41.44	20.25	21.18	-0.48
Range	0.40	0.33	0.07	0.33	0.34	-0.01	0.34	0.33	0.01	0.95
Standard Deviation	0.06	0.06	0.00	0.06	0.08	-0.01	0.08	0.07	0.01	0.16
High Outliner (+4 Sigma)	84.11	62.63	21.48	62.63	41.89	20.74	41.89	20.66	21.23	0.60
Low Outlier (-4 Sigma)	83.60	62.12	21.48	62.12	41.29	20.84	41.29	20.14	21.15	-0.71

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	3.92	%	Delta Holdup	3.92	%	Time @	0.99	60.93	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.03	--	Time @	0.75	63.43	sec
Time to Midpoint Holdup (sec):	64.92	sec	Epm	1.72	sec	Time @	0.5	64.92	sec
Power Term in Fitting Model:	29.85	--	2 x Epm	3.43	sec	Time @	0.25	66.05	sec
Power Term in Fitting Model:	51.06	--	Degass Time	12.86	sec	Time @	0.001	73.79	sec
Sum-of-Squares	1606	--							





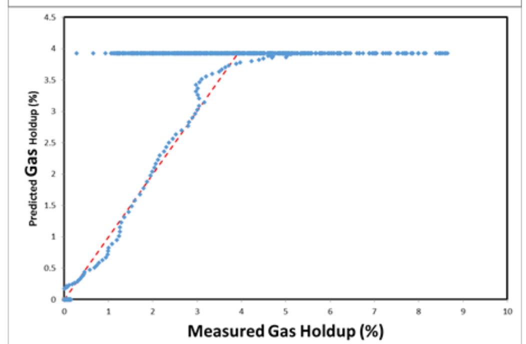


Figure A. 11 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet
Description: Standard Nozzle

Frother (PPM): 0
Gas Off (sec): 60.8

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	1.07	--	--	2.87	--	--	3.78	--
Based on PT On/Off	--	--	0.84	--	--	2.51	--	--	3.55	--
During Aeration ...										
Average	84.10	62.83	21.27	62.83	42.43	20.40	42.43	22.13	20.30	9.43
Maximum	90.05	69.29	20.75	69.29	50.19	19.10	50.19	25.37	24.83	10.08
Minimum	75.88	56.13	19.76	56.13	36.03	20.10	36.03	18.24	17.78	8.91
Range	14.16	13.16	1.00	13.16	14.17	-1.00	14.17	7.12	7.05	1.16
Standard Deviation	2.36	2.04	0.33	2.04	1.76	0.28	1.76	1.29	0.47	0.18
High Outliner (+4 Sigma)	93.55	70.97	22.59	70.97	49.46	21.50	49.46	27.29	22.17	10.16
Low Outlier (-4 Sigma)	74.64	54.68	19.95	54.68	35.39	19.29	35.39	16.96	18.43	8.71
After Degassing ...										
Average	83.70	62.25	21.45	62.25	41.33	20.92	41.33	20.28	21.05	-0.02
Maximum	83.93	62.43	21.50	62.43	41.53	20.90	41.53	20.47	21.06	0.50
Minimum	83.48	62.06	21.43	62.06	41.20	20.86	41.20	20.14	21.06	-0.49
Range	0.44	0.37	0.07	0.37	0.33	0.04	0.33	0.33	-0.01	0.99
Standard Deviation	0.08	0.08	0.00	0.08	0.07	0.01	0.07	0.06	0.02	0.17
High Outliner (+4 Sigma)	84.04	62.58	21.46	62.58	41.63	20.95	41.63	20.50	21.12	0.65
Low Outlier (-4 Sigma)	83.37	61.93	21.44	61.93	41.04	20.89	41.04	20.06	20.98	-0.70

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	3.55	%	Delta Holdup	3.55	%	Time @	0.99	58.40	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.03	--	Time @	0.75	61.28	sec
Time to Midpoint Holdup (sec):	63.00	sec	Epm	1.99	sec	Time @	0.5	63.00	sec
Power Term in Fitting Model:	25.00	--	2 x Epm	3.98	sec	Time @	0.25	65.01	sec
Power Term in Fitting Model:	28.00	--	Degass Time	21.17	sec	Time @	0.001	79.58	sec
Sum-of-Squares	1667	--							

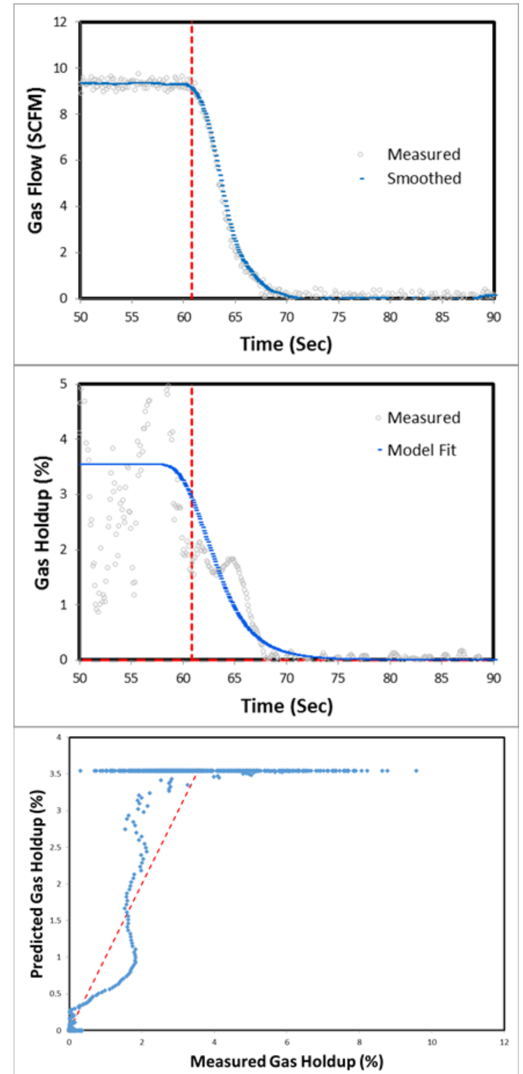


Figure A. 12 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet
Description: Standard Nozzle

Frother (PPM): 0
Gas Off (sec): 60.1

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	3.09	--	--	6.59	--	--	7.52	--
Based on PT On/Off	--	--	2.79	--	--	6.02	--	--	7.76	--
During Aeration ...										
Average	80.73	59.89	20.84	59.89	40.28	19.62	40.28	20.76	19.51	22.23
Maximum	86.26	62.90	23.36	62.90	41.91	20.99	41.91	21.89	20.02	22.75
Minimum	77.60	56.77	20.82	56.77	38.23	18.54	38.23	17.24	20.99	21.76
Range	8.66	6.13	2.54	6.13	3.68	2.44	3.68	4.66	-0.97	0.99
Standard Deviation	0.81	0.74	0.08	0.74	0.54	0.20	0.54	0.49	0.06	0.19
High Outliner (+4 Sigma)	83.99	62.84	21.14	62.84	42.44	20.40	42.44	22.70	19.74	22.99
Low Outlier (-4 Sigma)	77.47	56.94	20.53	56.94	38.11	18.84	38.11	18.82	19.29	21.47
After Degassing ...										
Average	80.63	59.19	21.43	59.19	38.32	20.87	38.32	17.17	21.16	0.48
Maximum	80.79	59.41	21.37	59.41	38.55	20.87	38.55	17.33	21.21	2.75
Minimum	80.37	59.05	21.32	59.05	38.15	20.90	38.15	16.98	21.17	-0.48
Range	0.41	0.37	0.05	0.37	0.40	-0.03	0.40	0.35	0.04	3.23
Standard Deviation	0.08	0.09	-0.01	0.09	0.08	0.01	0.08	0.05	0.03	0.71
High Outliner (+4 Sigma)	80.95	59.54	21.40	59.54	38.63	20.91	38.63	17.36	21.27	3.30
Low Outlier (-4 Sigma)	80.31	58.84	21.47	58.84	38.01	20.83	38.01	16.97	21.04	-2.35

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	7.76	%	Delta Holdup	7.76	%	Time @	0.99	59.44	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.04	--	Time @	0.75	63.38	sec
Time to Midpoint Holdup (sec):	65.76	sec	Epm	2.78	sec	Time @	0.5	65.76	sec
Power Term in Fitting Model:	18.74	--	2 x Epm	5.55	sec	Time @	0.25	66.72	sec
Power Term in Fitting Model:	60.65	--	Degass Time	13.81	sec	Time @	0.001	73.25	sec
Sum-of-Squares	629	--							

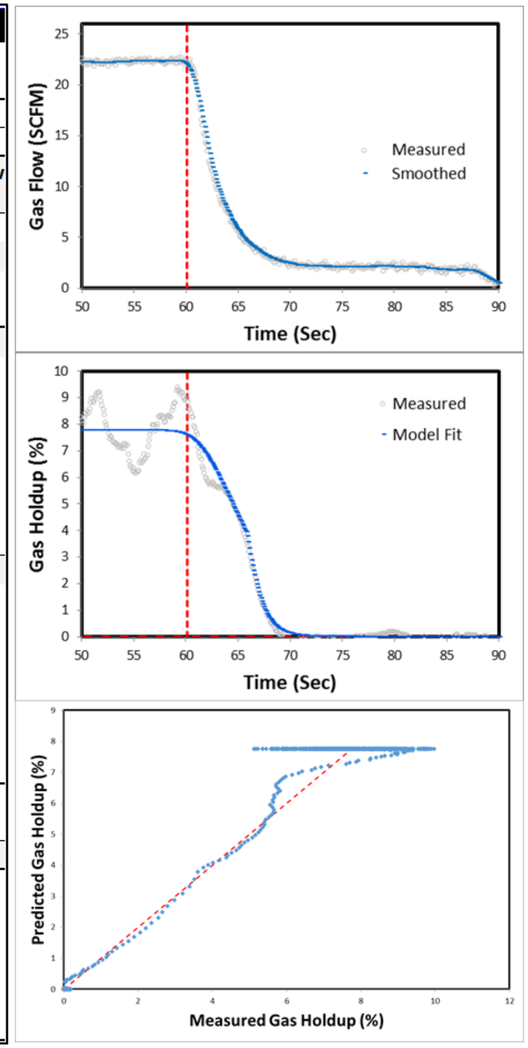


Figure A. 13 Model Summary for SLJ

SLAMJET SPARGER TESTING

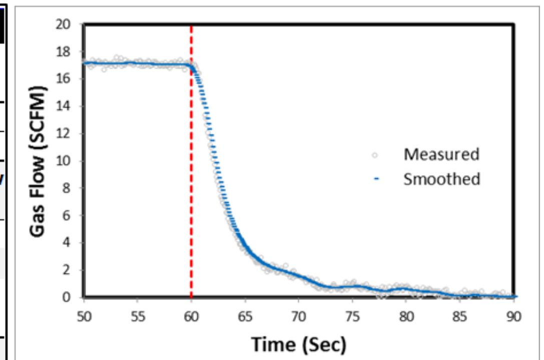
Sparger Type: Slamjet
Description: Standard Nozzle

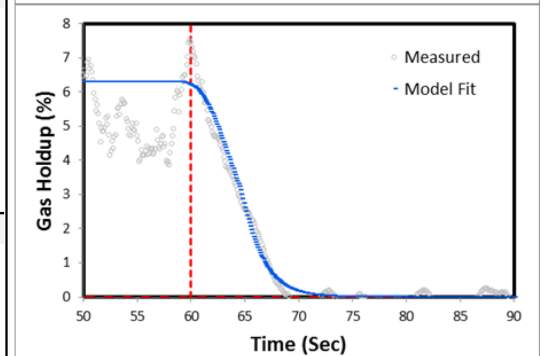
Frother (PPM): 0
Gas Off (sec): 60

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	1.95	--	--	4.13	--	--	6.14	--
Based on PT On/Off	--	--	1.53	--	--	3.74	--	--	6.30	--
During Aeration ...										
Average	82.30	61.22	21.08	61.22	41.09	20.13	41.09	21.28	19.80	17.12
Maximum	94.42	67.25	27.17	67.25	44.03	23.23	44.03	23.56	20.47	17.71
Minimum	76.57	50.15	26.42	50.15	37.00	13.15	37.00	18.82	18.18	16.42
Range	17.85	17.10	0.74	17.10	7.03	10.08	7.03	4.74	2.29	1.29
Standard Deviation	1.72	1.35	0.37	1.35	0.97	0.38	0.97	0.70	0.26	0.22
High Outliner (+4 Sigma)	89.18	66.61	22.58	66.61	44.95	21.65	44.95	24.10	20.86	18.00
Low Outlier (-4 Sigma)	75.43	55.84	19.59	55.84	37.23	18.61	37.23	18.47	18.75	16.24
After Degassing ...										
Average	81.78	60.37	21.41	60.37	39.45	20.92	39.45	18.31	21.14	0.00
Maximum	81.98	60.59	21.39	60.59	39.77	20.82	39.77	18.46	21.30	0.55
Minimum	81.48	60.18	21.30	60.18	39.25	20.93	39.25	18.13	21.13	-0.52
Range	0.50	0.41	0.09	0.41	0.52	-0.11	0.52	0.34	0.18	1.07
Standard Deviation	0.08	0.08	0.00	0.08	0.08	0.01	0.08	0.05	0.03	0.16
High Outliner (+4 Sigma)	82.11	60.70	21.42	60.70	39.76	20.94	39.76	18.52	21.24	0.64
Low Outlier (-4 Sigma)	81.44	60.04	21.40	60.04	39.15	20.89	39.15	18.11	21.04	-0.64

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	6.30	%	Delta Holdup	6.30	%	Time @	0.99	59.68	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.03	--	Time @	0.75	62.68	sec
Time to Midpoint Holdup (sec):	64.48	sec	Epm	2.08	sec	Time @	0.5	64.48	sec
Power Term in Fitting Model:	24.49	--	2 x Epm	4.16	sec	Time @	0.25	65.91	sec
Power Term in Fitting Model:	40.00	--	Degass Time	16.25	sec	Time @	0.001	75.94	sec
Sum-of-Squares	923	--							





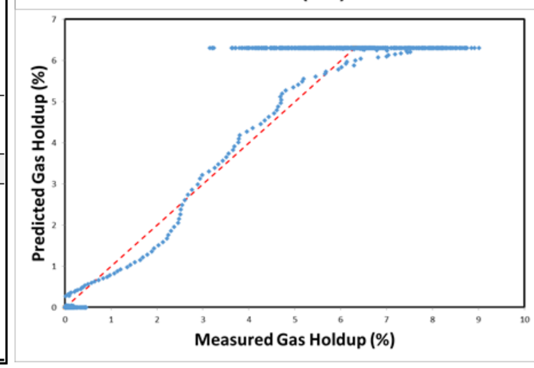


Figure A. 14 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet
Description: Standard Nozzle

Frother (PPM): 0
Gas Off (sec): 60.4

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	1.79	--	--	4.04	--	--	4.48	--
Based on PT On/Off	--	--	1.50	--	--	3.13	--	--	4.89	--
During Aeration ...										
Average	83.27	62.16	21.12	62.16	42.01	20.15	42.01	21.85	20.15	12.66
Maximum	89.27	65.78	23.49	65.78	45.17	20.61	45.17	24.86	20.32	13.41
Minimum	77.10	57.60	19.50	57.60	37.82	19.78	37.82	18.06	19.77	11.99
Range	12.17	8.19	3.99	8.19	7.35	0.84	7.35	6.80	0.55	1.43
Standard Deviation	1.80	1.33	0.47	1.33	1.15	0.18	1.15	0.99	0.16	0.23
High Outliner (+4 Sigma)	90.46	67.48	22.98	67.48	46.61	20.87	46.61	25.82	20.79	13.58
Low Outlier (-4 Sigma)	76.09	56.84	19.25	56.84	37.41	19.43	37.41	17.89	19.52	11.73
After Degassing ...										
Average	83.03	61.60	21.44	61.60	40.79	20.80	40.79	19.60	21.19	-0.05
Maximum	83.25	61.75	21.50	61.75	40.99	20.76	40.99	19.80	21.19	0.47
Minimum	82.88	61.38	21.49	61.38	40.68	20.71	40.68	19.41	21.27	-0.56
Range	0.37	0.37	0.01	0.37	0.31	0.05	0.31	0.40	-0.08	1.03
Standard Deviation	0.08	0.07	0.00	0.07	0.06	0.01	0.06	0.08	-0.01	0.17
High Outliner (+4 Sigma)	83.35	61.89	21.45	61.89	41.05	20.84	41.05	19.91	21.14	0.63
Low Outlier (-4 Sigma)	82.72	61.30	21.43	61.30	40.54	20.76	40.54	19.30	21.24	-0.72

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	4.89	%	Delta Holdup	4.89	%	Time @	0.99	61.61	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.02	--	Time @	0.75	63.48	sec
Time to Midpoint Holdup (sec):	64.58	sec	Epm	1.26	sec	Time @	0.5	64.58	sec
Power Term in Fitting Model:	40.27	--	2 x Epm	2.53	sec	Time @	0.25	66.99	sec
Power Term in Fitting Model:	24.00	--	Degass Time	23.20	sec	Time @	0.001	84.81	sec
Sum-of-Squares	892	--							

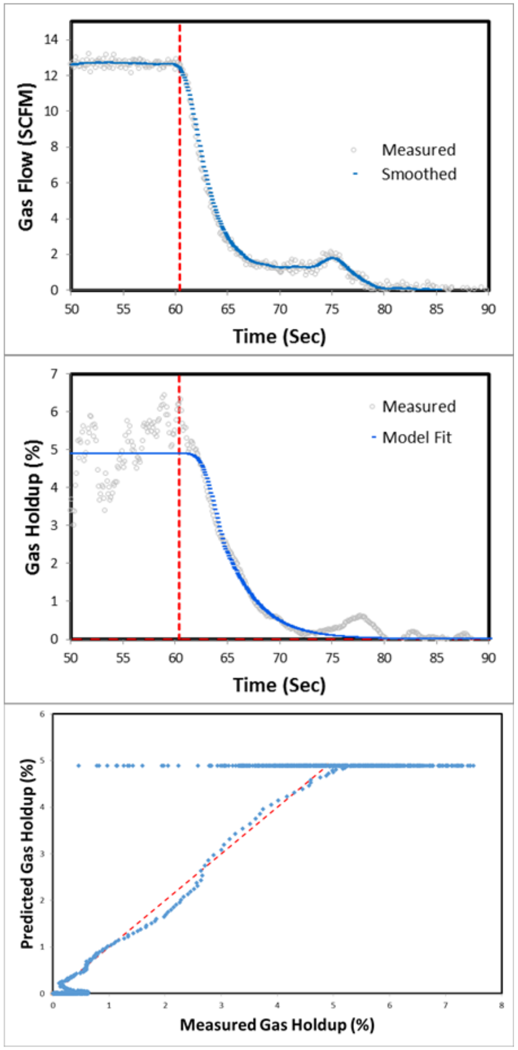


Figure A. 15 Model Summary for SLJ

SLAMJET SPARGER TESTING										
Sparger Type:	Slamjet								**Frother (PPM):**	0
Description:	Standard Nozzle								**Gas Off (sec):**	60.3
	PT #1 (Inch)	**PT #2 (Inch)**	**PT #1-2 (Inch)**	**PT #2 (Inch)**	**PT #3 (Inch)**	**PT #2-3 (Inch)**	**PT #3 (Inch)**	**PT #4 (Inch)**	**PT #3-4 (Inch)**	**Gas Flow (SCFM)**
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	3.16	--	--	3.35	--	--	4.36	--
Based on PT On/Off	--	--	3.00	--	--	2.87	--	--	4.23	--
During Aeration ...										
Average	83.35	62.53	20.82	62.53	42.23	20.30	42.23	22.05	20.18	11.64
Maximum	89.46	70.69	18.77	70.69	46.89	23.80	46.89	25.44	21.46	12.19
Minimum	62.45	55.34	7.11	55.34	37.46	17.88	37.46	18.51	18.96	11.15
Range	27.01	15.35	11.66	15.35	9.43	5.92	9.43	6.93	2.50	1.04
Standard Deviation	2.56	2.04	0.53	2.04	1.65	0.39	1.65	1.29	0.36	0.18
High Outliner (+4 Sigma)	93.60	70.67	22.93	70.67	48.82	21.85	48.82	27.20	21.61	12.34
Low Outlier (-4 Sigma)	73.10	54.38	18.71	54.38	35.65	18.74	35.65	16.90	18.74	10.94
After Degassing ...										
Average	83.32	61.86	21.46	61.86	40.96	20.90	40.96	19.89	21.07	-0.02
Maximum	83.48	62.08	21.41	62.08	41.21	20.86	41.21	20.06	21.15	0.60
Minimum	83.13	61.64	21.49	61.64	40.75	20.89	40.75	19.70	21.05	-0.55
Range	0.35	0.43	-0.09	0.43	0.46	-0.03	0.46	0.36	0.10	1.15
Standard Deviation	0.08	0.08	0.00	0.08	0.08	0.00	0.08	0.06	0.02	0.18
High Outliner (+4 Sigma)	83.64	62.19	21.45	62.19	41.29	20.90	41.29	20.13	21.16	0.69
Low Outlier (-4 Sigma)	83.01	61.53	21.48	61.53	40.64	20.89	40.64	19.66	20.98	-0.72

PT #3-4 Gas Holdup Fitting Parameters									
Average Gas Holdup (Gas On):	4.23	%	Delta Holdup	4.23	%	Time @	0.99	60.51	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.02	--	Time @	0.75	62.14	sec
Time to Midpoint Holdup (sec):	63.10	sec	Epm	1.10	sec	Time @	0.5	63.10	sec
Power Term in Fitting Model:	45.14	--	2 x Epm	2.20	sec	Time @	0.25	65.11	sec
Power Term in Fitting Model:	28.00	--	Degass Time	19.20	sec	Time @	0.001	79.70	sec
Sum-of-Squares	1473	--							

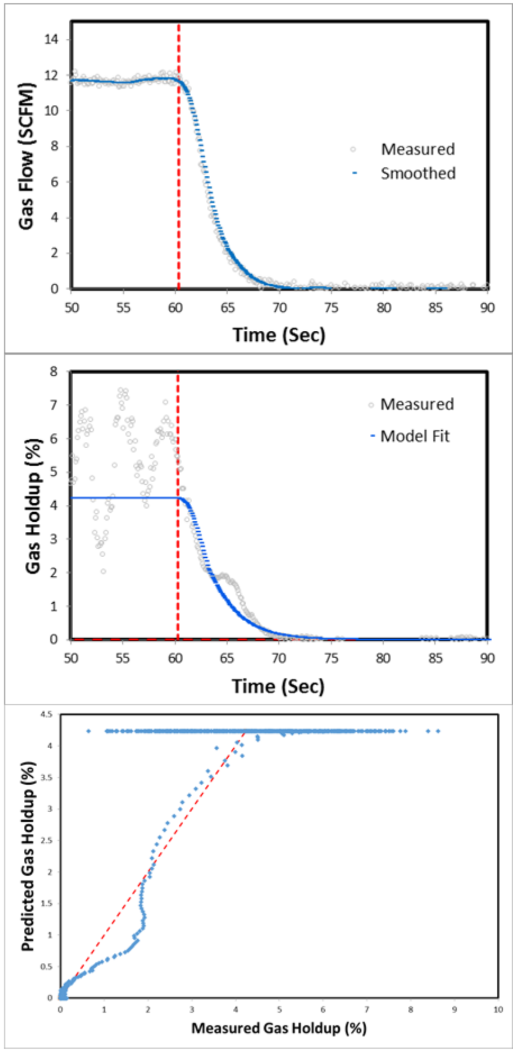


Figure A. 16 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet **Frother (PPM):** 0
Description: Standard Nozzle **Gas Off (sec):** 59.7

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	3.05	--	--	7.61	--	--	8.50	--
Based on PT On/Off	--	--	2.64	--	--	6.97	--	--	8.78	--
During Aeration ...										
Average	80.13	59.28	20.84	59.28	39.88	19.40	39.88	20.58	19.31	25.01
Maximum	88.51	61.63	26.87	61.63	41.73	19.91	41.73	22.00	19.73	25.53
Minimum	75.10	54.65	20.45	54.65	37.23	17.42	37.23	19.12	18.11	24.53
Range	13.41	6.99	6.43	6.99	4.50	2.48	4.50	2.89	1.62	1.00
Standard Deviation	1.06	0.76	0.30	0.76	0.61	0.15	0.61	0.47	0.13	0.17
High Outliner (+4 Sigma)	84.37	62.32	22.06	62.32	42.30	20.01	42.30	22.46	19.84	25.67
Low Outlier (-4 Sigma)	75.88	56.25	19.63	56.25	37.46	18.79	37.46	18.69	18.77	24.34
After Degassing ...										
Average	79.82	58.41	21.41	58.41	37.55	20.85	37.55	16.39	21.17	0.73
Maximum	80.01	58.63	21.38	58.63	37.78	20.85	37.78	16.53	21.25	2.17
Minimum	79.63	58.25	21.38	58.25	37.30	20.96	37.30	16.20	21.09	-0.70
Range	0.38	0.38	0.00	0.38	0.49	-0.10	0.49	0.33	0.16	2.87
Standard Deviation	0.07	0.08	-0.01	0.08	0.09	-0.01	0.09	0.05	0.04	0.62
High Outliner (+4 Sigma)	80.09	58.72	21.37	58.72	37.91	20.81	37.91	16.60	21.31	3.20
Low Outlier (-4 Sigma)	79.55	58.10	21.45	58.10	37.20	20.90	37.20	16.18	21.02	-1.74

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	8.78	%	Delta Holdup	8.78	%	Time @	0.99	60.33	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.03	--	Time @	0.75	63.28	sec
Time to Midpoint Holdup (sec):	65.06	sec	Epm	2.05	sec	Time @	0.5	65.06	sec
Power Term in Fitting Model:	25.09	--	2 x Epm	4.10	sec	Time @	0.25	65.96	sec
Power Term in Fitting Model:	64.00	--	Degass Time	11.73	sec	Time @	0.001	72.06	sec
Sum-of-Squares	812	--							

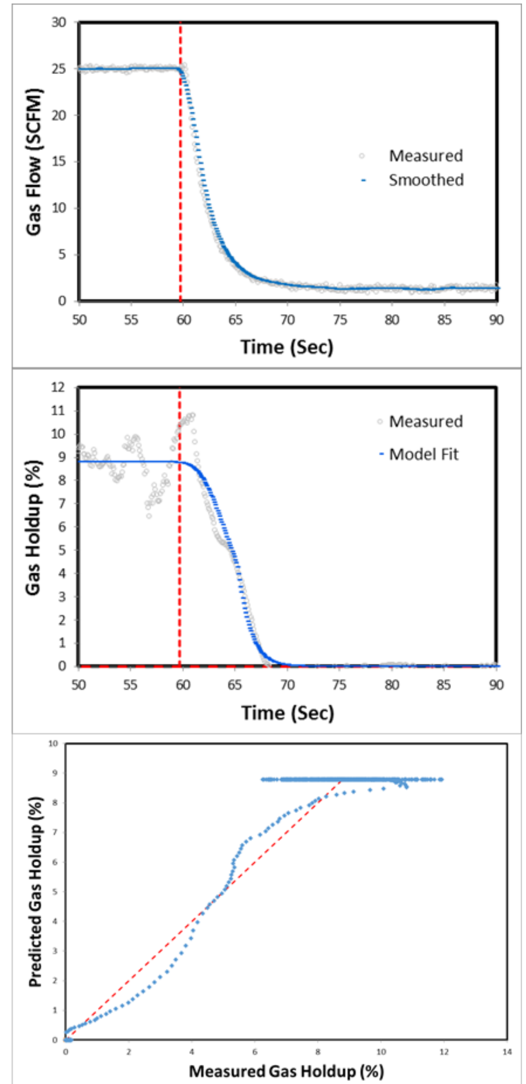


Figure A. 17 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet
Description: Standard Nozzle

Frother (PPM): 0
Gas Off (sec): 59.8

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	2.98	--	--	4.76	--	--	6.79	--
Based on PT On/Off	--	--	2.58	--	--	4.38	--	--	6.94	--
During Aeration ...										
Average	81.50	60.65	20.86	60.65	40.64	20.00	40.64	20.98	19.67	19.86
Maximum	87.91	67.13	20.78	67.13	43.80	23.33	43.80	23.12	20.68	20.39
Minimum	71.66	57.67	13.99	57.67	38.16	19.51	38.16	18.66	19.49	19.36
Range	16.25	9.46	6.79	9.46	5.64	3.82	5.64	4.46	1.19	1.03
Standard Deviation	1.43	1.05	0.39	1.05	0.90	0.15	0.90	0.68	0.23	0.17
High Outliner (+4 Sigma)	87.24	64.84	22.40	64.84	44.26	20.59	44.26	23.69	20.57	20.56
Low Outlier (-4 Sigma)	75.77	56.45	19.31	56.45	37.03	19.42	37.03	18.27	18.77	19.16
After Degassing ...										
Average	81.18	59.77	21.41	59.77	38.85	20.92	38.85	17.72	21.13	-0.01
Maximum	81.38	59.94	21.43	59.94	39.03	20.92	39.03	17.91	21.12	0.48
Minimum	81.00	59.60	21.40	59.60	38.71	20.89	38.71	17.52	21.19	-0.54
Range	0.38	0.34	0.03	0.34	0.32	0.02	0.32	0.39	-0.07	1.02
Standard Deviation	0.07	0.06	0.01	0.06	0.07	-0.01	0.07	0.07	0.01	0.16
High Outliner (+4 Sigma)	81.45	60.02	21.44	60.02	39.13	20.88	39.13	17.98	21.16	0.64
Low Outlier (-4 Sigma)	80.90	59.51	21.39	59.51	38.56	20.95	38.56	17.45	21.11	-0.66

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	6.94	%	Delta Holdup	6.94	%	Time @	0.99	59.68	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.03	--	Time @	0.75	62.68	sec
Time to Midpoint Holdup (sec):	64.48	sec	Epm	2.08	sec	Time @	0.5	64.48	sec
Power Term in Fitting Model:	24.49	--	2 x Epm	4.16	sec	Time @	0.25	65.91	sec
Power Term in Fitting Model:	40.00	--	Degass Time	16.25	sec	Time @	0.001	75.94	sec
Sum-of-Squares	829	--							

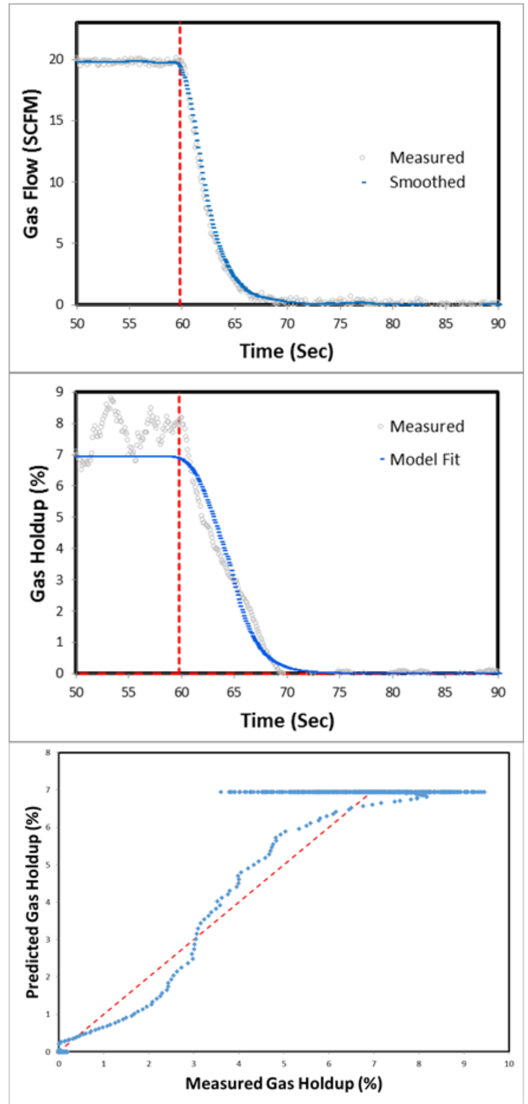


Figure A. 18 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet
Description: Standard Nozzle

Frother (PPM): 0
Gas Off (sec): 60.3

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	3.37	--	--	4.17	--	--	5.83	--
Based on PT On/Off	--	--	3.18	--	--	3.16	--	--	6.23	--
During Aeration ...										
Average	82.61	61.84	20.77	61.84	41.71	20.12	41.71	21.84	19.87	14.50
Maximum	88.40	65.97	22.44	65.97	44.92	21.05	44.92	25.00	19.92	15.34
Minimum	77.50	56.23	21.27	56.23	37.96	18.27	37.96	18.72	19.24	13.75
Range	10.91	9.74	1.17	9.74	6.96	2.78	6.96	6.28	0.68	1.60
Standard Deviation	1.62	1.40	0.23	1.40	1.18	0.22	1.18	0.97	0.21	0.32
High Outliner (+4 Sigma)	89.10	67.43	21.68	67.43	46.43	21.00	46.43	25.70	20.72	15.79
Low Outlier (-4 Sigma)	76.12	56.25	19.87	56.25	37.00	19.25	37.00	17.98	19.02	13.21
After Degassing ...										
Average	82.46	61.01	21.46	61.01	40.23	20.78	40.23	19.03	21.19	-0.03
Maximum	82.64	61.20	21.44	61.20	40.34	20.86	40.34	19.18	21.17	0.54
Minimum	82.27	60.86	21.41	60.86	40.07	20.78	40.07	18.86	21.21	-0.53
Range	0.37	0.34	0.03	0.34	0.27	0.08	0.27	0.31	-0.05	1.07
Standard Deviation	0.06	0.07	-0.01	0.07	0.06	0.01	0.06	0.06	0.00	0.18
High Outliner (+4 Sigma)	82.72	61.30	21.42	61.30	40.47	20.83	40.47	19.26	21.21	0.68
Low Outlier (-4 Sigma)	82.21	60.71	21.50	60.71	39.98	20.73	39.98	18.81	21.17	-0.73

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	6.23	%	Delta Holdup	6.23	%	Time @	0.99	58.60	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.05	--	Time @	0.75	62.88	sec
Time to Midpoint Holdup (sec):	65.50	sec	Epm	3.05	sec	Time @	0.5	65.50	sec
Power Term in Fitting Model:	17.00	--	2 x Epm	6.10	sec	Time @	0.25	66.63	sec
Power Term in Fitting Model:	51.43	--	Degass Time	15.79	sec	Time @	0.001	74.38	sec
Sum-of-Squares	874	--							

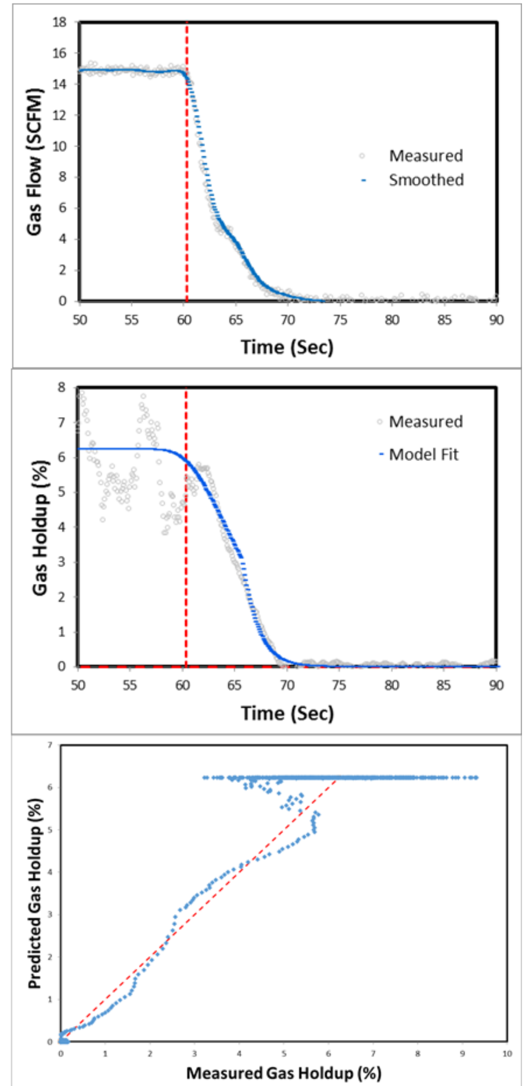


Figure A. 19 Model Summary for SLJ

SLAMJET SPARGER TESTING

Sparger Type: Slamjet
Description: Standard Nozzle

Frother (PPM): 0
Gas Off (sec): 60.1

	PT #1 (Inch)	PT #2 (Inch)	PT #1-2 (Inch)	PT #2 (Inch)	PT #3 (Inch)	PT #2-3 (Inch)	PT #3 (Inch)	PT #4 (Inch)	PT #3-4 (Inch)	Gas Flow (SCFM)
PT Height (Inches from top)	88.10	66.60	21.50	66.60	45.60	21.00	45.60	24.50	21.10	--
Local Gas Holdup (%)										
Based on PT Height	--	--	0.81	--	--	3.06	--	--	4.43	--
Based on PT On/Off	--	--	0.58	--	--	2.63	--	--	4.29	--
During Aeration ...										
Average	83.46	62.14	21.33	62.14	41.78	20.36	41.78	21.62	20.16	11.68
Maximum	88.74	67.45	21.29	67.45	46.57	20.89	46.57	25.66	20.90	12.21
Minimum	75.37	55.96	19.41	55.96	37.02	18.94	37.02	17.95	19.07	11.04
Range	13.38	11.49	1.88	11.49	9.54	1.95	9.54	7.72	1.83	1.17
Standard Deviation	2.25	1.77	0.48	1.77	1.63	0.14	1.63	1.25	0.38	0.17
High Outliner (+4 Sigma)	92.48	69.22	23.25	69.22	48.30	20.93	48.30	26.60	21.70	12.37
Low Outlier (-4 Sigma)	74.45	55.05	19.40	55.05	35.26	19.79	35.26	16.63	18.63	10.99
After Degassing ...										
Average	83.29	61.84	21.45	61.84	40.94	20.91	40.94	19.87	21.07	-0.03
Maximum	83.47	62.03	21.44	62.03	41.12	20.92	41.12	20.02	21.10	0.42
Minimum	83.08	61.65	21.43	61.65	40.78	20.87	40.78	19.69	21.08	-0.58
Range	0.39	0.38	0.00	0.38	0.34	0.05	0.34	0.33	0.01	1.00
Standard Deviation	0.08	0.08	-0.01	0.08	0.08	0.01	0.08	0.05	0.02	0.17
High Outliner (+4 Sigma)	83.61	62.18	21.43	62.18	41.24	20.94	41.24	20.07	21.17	0.63
Low Outlier (-4 Sigma)	82.98	61.50	21.48	61.50	40.63	20.88	40.63	19.66	20.97	-0.69

PT #3-4 Gas Holdup Fitting Parameters

Average Gas Holdup (Gas On):	4.29	%	Delta Holdup	4.29	%	Time @	0.99	62.72	sec
Average Gas Holdup (Baseline):	0.00	%	Imperfection	0.01	--	Time @	0.75	63.97	sec
Time to Midpoint Holdup (sec):	64.70	sec	Epm	0.83	sec	Time @	0.5	64.70	sec
Power Term in Fitting Model:	61.11	--	2 x Epm	1.67	sec	Time @	0.25	66.34	sec
Power Term in Fitting Model:	35.00	--	Degass Time	15.27	sec	Time @	0.001	77.99	sec
Sum-of-Squares	1639	--							

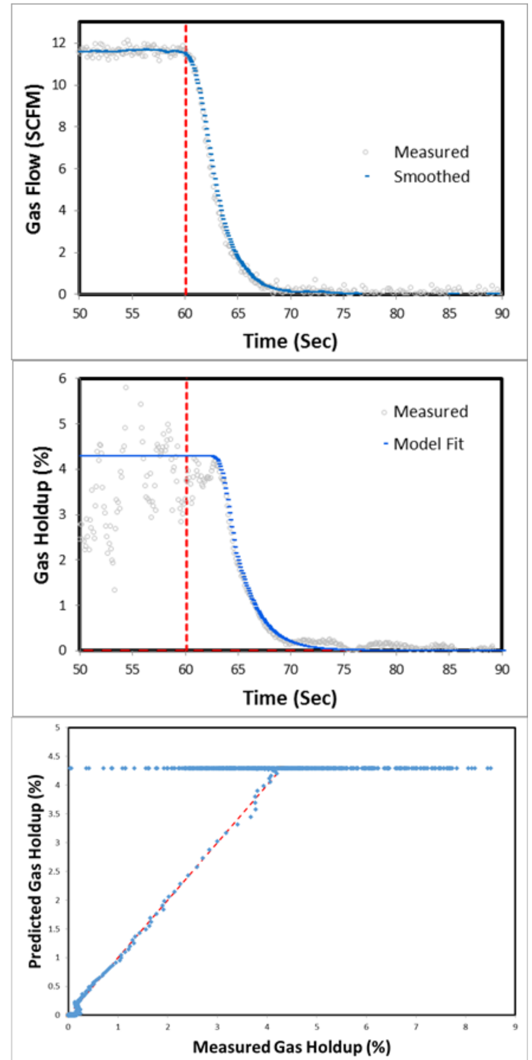


Figure A. 20 Model Summary for SLJ