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Investigating Airlift Pump Performance under Three-Phase Flow Conditions

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Abstract – Airlift pumps are widely utilized in many industries for the transport of three-phase flows. The solid particle behavior in the pump riser is dependent on the pump design parameters, such as the pump riser length and diameter, as well as the physical properties of the carrying liquid, and the characteristics of the solid particles. In this study, the momentum behavior of solid particles in the pump riser was experimentally investigated for an airlift pump handling solid particles consisting of 5mm glass spheres. This airlift pump had a 60-degree halo-like slot injector and was tested at a constant submergence ratio of 0.7. High-speed images were used to identify the solid particle trajectories in the air-water-solid three-phase mixture in the pump risers. The results show that the transport of solid particles is strongly dependent on the liquid distribution in the three-phase mixture, which can be referred to as the liquid flow pattern. The solid particles are transported mainly by the liquid slugs; however, the particles in the lower portion of the liquid slug slow down due to gravitational forces. As well, the total mass lifted by the pump under two-phase flow conditions is found to be significantly lower when the pump is used to transport three-phase flows.

***Keywords*:** Airlift pump; Three-phase flow; Performance; Effectiveness; Air-water-solid

1. Introduction

Airlift pumps serve a wide range of industrial applications, including flow recirculation and aeration purposes in aquaculture and sewage treatment, as well as the lifting of heavy, viscous liquids like hydrocarbons in oil and gas extraction, and the safe transport of explosive and toxic fluids in chemical processing plants. These pumps consist of a vertical pipe (i.e., a riser pipe) submerged into a tank containing liquid. The pipe is connected to a gas injector at the lower part of the pipe riser. Gas injection creates a gas-liquid mixture within the riser, with the two-phase mixture having a lower specific gravity. This buoyancy-driven mechanism propels the liquid phase upward, achieving the pumping action. Airlift pumps are advantageous due to the absence of internal moving mechanical components. This results in lower maintenance costs, enhanced reliability, and reduced energy consumption compared to conventional rotary pumps [1-2].

Airlift pumping systems are unique in that they use the buoyancy effect in the gas phase to transport liquids. This sets them apart from traditional single-phase fluid flow systems. In airlift systems, the fluid flow rate is not solely determined by the energy injected through the gas but rather by complex relationships including the interaction of multiple fluid phases, system geometry, and operational parameters [3]. This interaction dictates the performance and efficiency of the system. Unlike single-phase systems, which control flow rates directly through energy input, airlift pumping is complex as various elements, such as bubble characteristics and geometrical considerations, collectively influence the deliverability and effectiveness [4].

The introduction of solid particles into airlift pumping systems, particularly within mining applications, transforms the behavior of multiphase flows and introduces a host of additional controlling factors. Beyond the interfacial forces governing gas-liquid interactions in two-phase flows, the presence of solid particles in the liquid phase causes significant changes in the fundamental physical properties, including density, viscoelasticity, and surface tension [5-7]. The specific attributes of these solid particles, such as size, surface roughness, shape, density, distribution, and solubility, play an essential role in shaping the rheological characteristics of the mixture. As a result, the fluid dynamics lose the simplicity of Newtonian behavior and instead exhibit the complexity of a non-Newtonian fluid. This makes the overall performance of the system more complex [8].

It is worth noting, however, that these correlations are only valid within specific operating conditions and tend to yield substantial prediction errors when projected beyond their originally established ranges. Developing universal relationships for solid particle hydraulic conveyance has remained a challenge, mainly due to the intricate nature of the flow behaviors.

Furthermore, existing correlations designed to predict the process parameters concentrate on the macroscopic aspects and lack insights into the trajectory of the liquid-solid flow within the riser [9-10]. Achieving a more thorough understanding of hydraulic transport to ensure dependable applications demands a more detailed approach.

To fill the above-mentioned gaps, this study discusses the solid particle trajectory behavior under a wide range of inlet gas flow rates. Furthermore, this study compares the liquid discharge rate between two-phase and three-phase flow, and the possible reasons behind their differences. This study has been conducted experimentally; all experiments have been carried out at a submergence ratio of 0.7 (i.e., Sr=70%) using a 60-degree halo air injector. The solid particles used in this study are 5mm glass particles with a density of 2835 kg/m^3.

2. Methodology

2.1. Experimental apparatus

Figure 1 shows a schematic diagram of the experimental configuration using an airlift pump. To maintain a consistent liquid level in the secondary supply tank and calculate the submergence ratio of the airlift pumping system, liquid from the reservoir tank was continuously pumped into the secondary tank. The submergence ratio, a critical parameter, was set to 70% and calculated by dividing the static head (H_S) by the overall pipe length (L). To begin the process of lifting the liquid/solid mixture up the riser, air was introduced into the mixture using an airlift pump. Precise control of the air flow rate, which ranged from 6 to 41 liters per minute (LPM), was achieved using a mass flow controller (MFC). The experimental setup included a collection tank and a solids strainer located beyond the separator, which directed solids and fluids towards a measuring tank marked in 2-liter intervals. This measuring tank served two purposes: quantifying the volume of the collected liquid and providing a base for the solids strainer to collect the solid particles. The volumetric liquid flow rate (measured in LPM) was determined by timing the flow of the water into the measurement tank using a stopwatch. Additionally, the weight of the solid particles was measured on a digital scientific scale to determine the solid weight production associated with each gas inlet air flow rate. Figure 2 provides a schematic depiction of the air injector.

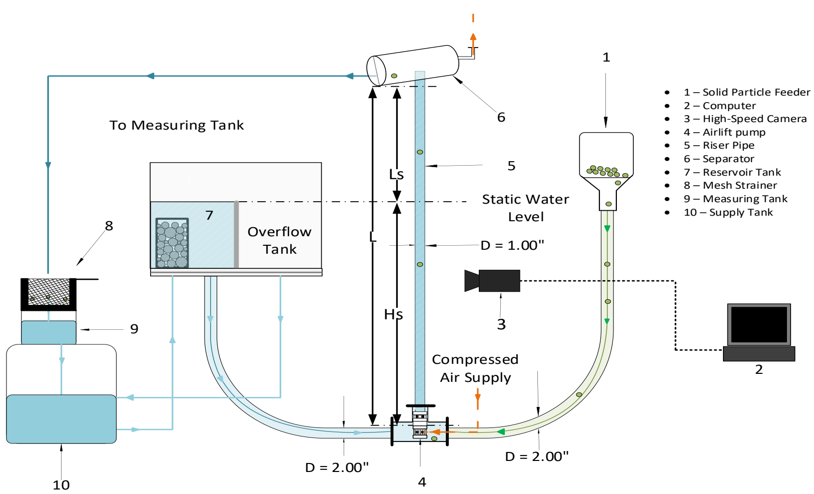

Fig. 1: Schematic diagram of the test loop.

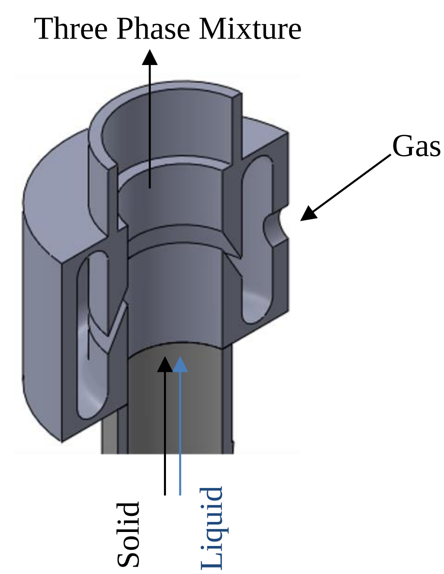

Fig. 2: Schematic view of the air injector.

High speed images, taken at a location Z/D = 35 downstream of the injector, were analyzed for eight different gas injection rates ranging from 6 LPM to 41 LPM. The movement of the solid particles was obtained by comparing a set of images that tracked the displacement of these particles between eight frames. This was scaled using the known diameter of the riser, as well as the time elapsed between the frames. Finally, the solid particles were followed throughout the passing of one liquid slug within the recorded frame.

2. Results and discussions

2.1. Pumping performance and effectiveness

Figs. 3a and 4b show the flow rates and effectiveness of the lifted liquid and solid mass for the lifting solids, respectively. Note that the pumping effectiveness presented in Figure 3b has been calculated using the Kassab et al. method [4] as follows:

$$E = \frac{\dot{M}_{Solid}}{\dot{M}_{Air}} \tag{1}$$

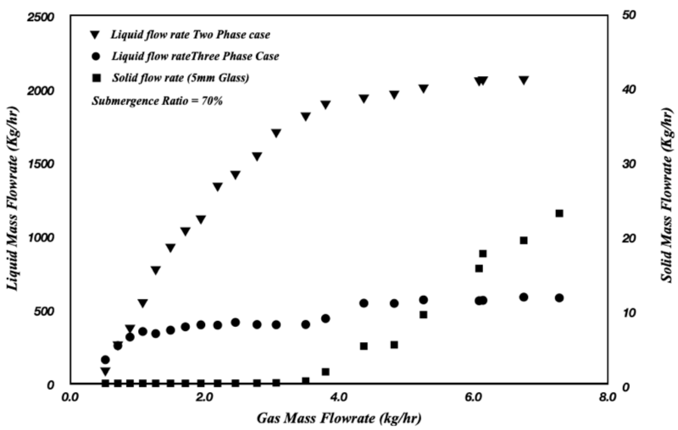

Fig. 3a: Liquid mass flow rate in two-phase and three-phase flows, as well as 5mm glass solid particle mass production.

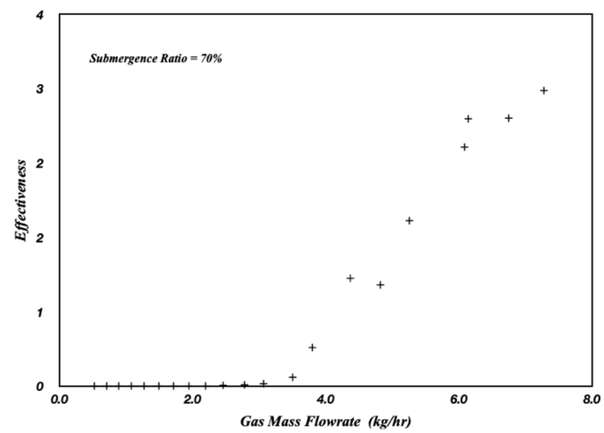

Fig. 3b: The effectiveness of solid particle production.

Unlike the two-phase flow, the three-phase flow behavior is expected to accommodate the following trends:

- At the initial and low gas injection flux, J_G, the actual liquid velocity, u_L, in the riser is much lower than the solid particle terminal velocity, u_{ST}. Hence, no solid particles will enter the riser section, and the initial liquid production should match that of the two-phase conditions at a specific gas flux under the different submergence ratios. This is presented in Fig. 3a.
- During the early period in the three-phase flow, the gas volumetric flux required for early liquid start-up should match the volumetric gas flux in the two-phase flow, as described earlier. However, due to the configuration of the set-up, in which the inlet section for the solid particles intersects with the liquid feed line, the potential for solid particle compaction due to gravity is introduced. This compaction phenomenon can result in a reduction in the flow rate of the liquid phase within the three-phase system. This can then impact the overall discharge rate of the liquid.
- The following trend occurs when the actual liquid rate matches the terminal velocity of the solid particles as the solids begin their upward trajectory beyond the injection point and into the riser. However, within the unique flow dynamics of the airlift system, the gas fraction plays an important role in establishing a dynamic mixture flow. As the gas phase exerts minimal to virtually no drag force on the solid particles, some of these solids lack the necessary momentum to sustain their ascent and instead descend. This phenomenon leads to the accumulation of solids inside the riser pipe, triggering a choking effect that diminishes both the liquid and solid flow rates. This is illustrated in Figure 4.

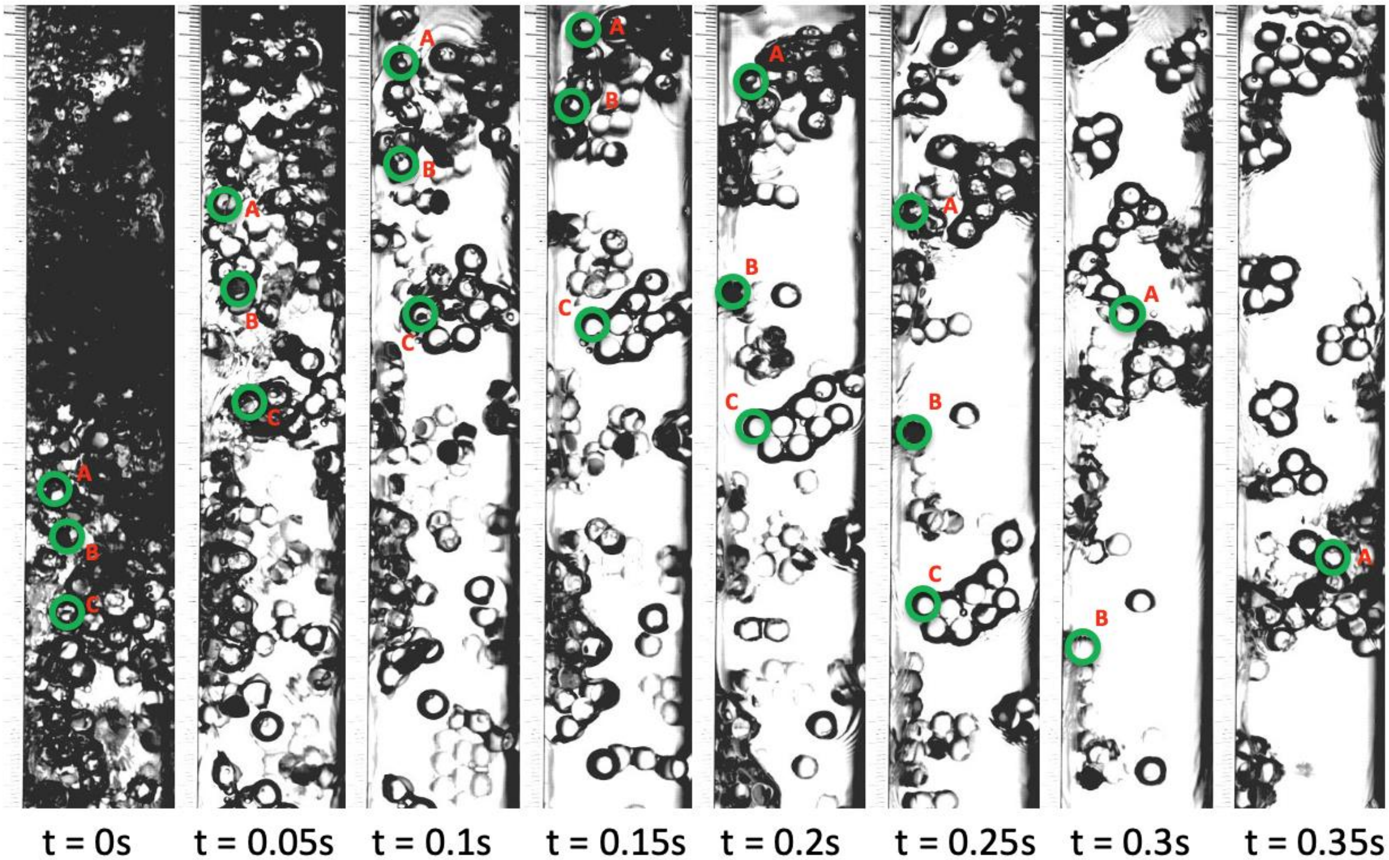

Fig. 4: Flow visualization of the tracking of three 5mm glass particles with an inlet gas flow rate of 41 LPM.

At the end of this cycle, the ascending solid particles carried by the liquid phase will strike the descending solids within the gas phase and increase the total momentum of the solid system. As a result, all solids are discharged from the riser, which can be seen in Figure 3a where the solid particle terminal velocity has been reached; however, no physical solid production is visible before an $\dot{m}_G$ of 3.0. Applying the momentum equation (Equation 2), it is assumed that the upward movement of a solid against a stagnant solid will end the transition period when the actual liquid rate reaches twice that of the solid particle terminal velocity:

$$[m_1 v_1]_{terminal\ velocity} + [m_2 v_2]_{stationary} = 2\ m_{total} v_{final} \quad (2)$$

As the group of solid particles and the wall effect reduce the solid terminal velocity, one can conclude that a range of 1.5 to 2 times the terminal velocity is required to lift all solids out of the riser and reach the steady-state condition. When the input mass flow rate matches the output mass flow rate, the steady state condition is established. During this cycle, the liquid and solid performance follows the trend of a standard airlift system.

Modelling the construction for three-phase flow using the force balance equation, in which there is no change in the momentum of the system over time, is applicable only under steady state flow conditions. Under these conditions the gross mass in is equal to the gross mass out. However, under transient flow conditions, solid particles are stored in the system since the drag force is insufficient to lift these particles out of the riser. As well, the inverted velocity vector of the descending particles will slow down the rising solid particles and collide with the large gas bubbles. This will cause these bubbles to burst into smaller bubbles, reduce their speed, or invert the gas velocity vector downward. The coexistence of the three phases complicates the computational modelling as one must understand the phenomena associated with bubble-fluid, bubble-solid, solid-fluid, solid-solid, and finally, bubble-bubble interaction, thus modifying the multiphase flow physics.

Moreover, it is important to mention the drastic decrease in the liquid discharge rates, as seen in Figure 3a. This is a result of the increased slurry density, which highly influences the performance of the airlift pump, as seen in the experiment by Rosettani et al. [11]. As mentioned before, the liquid in a three-phase flow is the carrying medium. With the introduction of the solid particles, the liquid density is then altered to a higher density known as the slurry density, which can be calculated using Equation 3:

$$\rho_{slurry} = (\beta_S \rho_S) + [(1 - \beta_S)\rho_L] \tag{3}$$

in which β_S represents the solid volumetric fraction, which can be obtained from Equation 4 as follows:

$$\beta_S = \frac{Q_S}{Q_S + Q_L} \tag{4}$$

By increasing the slurry density, which is the increased solid volumetric fraction in the liquid, the buoyancy force increases relative to the gas. This increases the gas slippage velocity, which deforms the gaseous Taylor bubble into a churn-like shape that bears through the liquid slug above. This phenomenon will cause increased shear forces on the slurry from the inner wall of the riser. This reduces its ascending velocity, and results in the downwards motion of the solids and the liquid, as mentioned earlier and presented in Figure 4.

3. Conclusions

An experimental investigation was performed in this study. It analyzed the dynamic behavior of solid particles and their implications. Throughout the experiments, a consistent submergence ratio of 70% was maintained. The research focused on assessing the production rate and effectiveness of airlift pumps across a spectrum of 21 input gas flow rates, ranging from 6 to 41 LPM. The liquid production rate was compared between two- and three-phase flow. A noticeable reduction in the three-phase liquid production rate was observed in comparison to that of the two-phase one due to a significant increase in the slurry density. The irregular trajectory of the solid particles was observed. Of notable interest was the downward motion of solid particles within the gas phase. A change in momentum was introduced that influenced the velocity of the subsequent upward-moving solid particles, leading to deceleration. Furthermore, the momentum transfer among the solid particles led to the conclusion that to achieve a steady-state condition, the liquid phase velocity must be approximately 1.5 to 2 times that of the terminal velocity of the solid particles.

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