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Performance of Airlift Pumps: Single-Stage *vs.* Multistage Air Injection

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Abstract Airlift pumps provide reliable means of artificially lifting of liquids or liquid-solid mixtures from deep wells or vessels. This paper presents a numerical investigation into the effects of air injection strategy, single-stage vs. multistage air injection, on the airlift pump performance. A numerical model of airlift pump, based on the concept of momentum balance, was developed and validated against available experimental data. Predictive studies on model airlift pump with different arrangements of injected compressed air were numerically carried out. Numerical results showed that applying the commonly used single-stage air injection causes a steep change in the pump output-input characteristic curve followed by a fast decay after the optimum point. Injecting the compressed air in a number of air injection stages, on the other hand, was shown to increase the range of bubbly-slug flow regime as well as the pump operating window close to the optimum conditions. Improvement in the pump performance at higher degrees of air input mass flow rates is expected when employing multistage air injection.

Keywords: *airlift pumps, two-phase flow, multistage air injection*

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1. Introduction

Airlift pump is a type of deep well pumps. Sometimes, it is used for removing water from mines or pumping slurry of sand and water or other solutions. Use of airlift pump has been promoted for a number of reasons such as: lower initial cost and maintenance, easy installation, small space requirements, simplistic design and construction, ease of flow rate regulation, and ability to handle corrosive, highly toxic and radioactive fluids. In the airlift system, air (or gas) is injected through an injection system at (or near) the base of a vertical pipe (the riser tube) that is partially submerged in a liquid or slurry. Bubbles, therefore, form and expand as they rise in the riser tube. A two- (or three-) phase column containing air phase has a lower density than a column of liquid alone and therefore the mixture formed in the airlift tube rises and is expelled at the top of the pump.

Theoretical and experimental analysis of airlift pump performance was extensively studied through a number of publications. Parker [1] made a comprehensive experimental study to determine the effects of foot piece design on the lifting characteristics of the airlift pump used for hydraulic transport of liquids. The effects of air injection method on the airlift pump performance were experimentally investigated by Mansour and Khalil [2] and by Khalil et al. [3]. It was concluded that, initial bubble size and distribution in the riser tube could have great effects on the pump performance. Khalil and Mansour [4] carried out an experimental investigation on the airlift pump performance by studying the effect of introducing a surfactant to the pumped liquid. Results showed that an improvement in the pump capacity and pump efficiency can be obtained when using a surfactant with low concentration. They studied the influence of riser tube diameter and injector design on the efficiency characteristics of the airlift pump. Mahrous [5] numerically investigated the performance of airlift pump lifting solids under various geometrical and operational conditions. The predictive studies showed that the solid particles volumetric concentration in the suction section of the airlift tube significantly affects the airlift pump efficiency based on solids as the main gain of the pump. Mahrous [6,7] carried out numerical investigations into the effects of riser tube configuration on the airlift pump performance. Different ways necessary to reduce momentum loss followed the expansion of air phase in the riser tube section were numerically investigated. Numerical results showed that the airlift pump performance is improved by gradually enlarging the riser tube at some distances near the air injection level.

The expansion of air in the riser tube of the airlift pump from the air injection pressure to the pump outlet pressure causes the two-phase air-liquid (or air-slurry) flow to distribute in a number of patterns [8]. The basic flow patterns are bubbly, slug, churn and annular flows. At low air input velocity, the air phase can rise in bubbles of different and variable shape and size. This type of flow is called bubbly flow. As the input air rate increases, the smaller bubbles begin to coalesce into larger bubbles or air slugs which in essence separate the water column into the slug flow regime. The transition between these two flow regimes is termed as the bubbly-slug flow regime where small bubbles are found suspended within the liquid slugs between the larger air slugs [9]. In case of very high input air velocities, the liquid can be pushed to the wall of the tube and the air streams separate in the middle of the tube and loaded with droplets of liquid. This type of flow regime is called annular flow. In annular flow, the continuity of air along the pipe appears in the core and no liquid is being lifted. Moreover, the pressure losses and power losses of flow are extremely high. So, for the design purpose of airlift pumps, it is advisable to avoid the ranges of annular flow, which is characterized by poor pumping efficiency. If the difference between the air injection pressure and pressure at pump outlet, which usually is atmospheric, is high, annular flow can occur in the upper part of the riser tube. While in the lower part, just above the air injection zone, bubbly flow is dominating. In such cases, the pump performance may be highly improved if the pipe diameter is enlarged at certain distances [6,7,10,11]. The graduation in the riser tube section may ensure slug flow along its height.

The main objective of this work was to numerically study the effects of multistage air injection on the airlift pump performance. In order to reduce the pumping energy loss due to the expansion of air phase on the riser tube, the compressed air is evenly distributed in a number of injection stages in the riser tube section. The model airlift pump performance is investigated under different arrangements of air injection stages to figure out the appropriate air distribution with regards to pump performance.

2. Method

Based on the principles of theoretical treatment, different calculation methods of airlift pump performance were offered. Among others, Clauss [12], Boës *et al*. [13], Yoshinaga and Sato [14], Margris and Papanikas [15], and Hatta *et al*. [16] developed fairly reliable theoretical analysis for the calculations of airlift pumps. Each of these models allowed a general calculation for the pumping action required by the airlift pump. In the present work, a numerical analysis of the performance of airlift pump based on the principle of momentum balance is presented under steady state operating conditions. The airlift pump performance is studied according to the analysis of Yoshinaga and Sato [14]. The assumptions made for the mathematical formulation of the airlift mechanism were: compressible and ideal gas flow for the air phase, the planes of equal velocity and equal pressure are normal to the pipe axis, no exchange of mass between phases, and isothermal flow for all phases. The assumption of isothermal flow is justified only if the two phases flow slowly through the airlift tube so that a continuous heat exchange with the environment is no longer possible, Margaris and Papanikas [15].

A schematic diagram of the proposed model of the air lifting system is shown in Figure 1. The body of the airlift pump illustrated in Figure 1 consists of two main parts. The first lower part is a suction pipe of length (L_S) between the bottom end (level E) and the start of air injection (level I), while the second part is the riser tube of length (L_R) between the start of air injection ports and the discharge ports. Compressed air, uniformly distributed in a number of injection stages, is injected starting from the water depth of (L_I). The ratio between the submerged depth (L_I) and the total riser tube length (L_R) is defined as the submergence ratio (α).

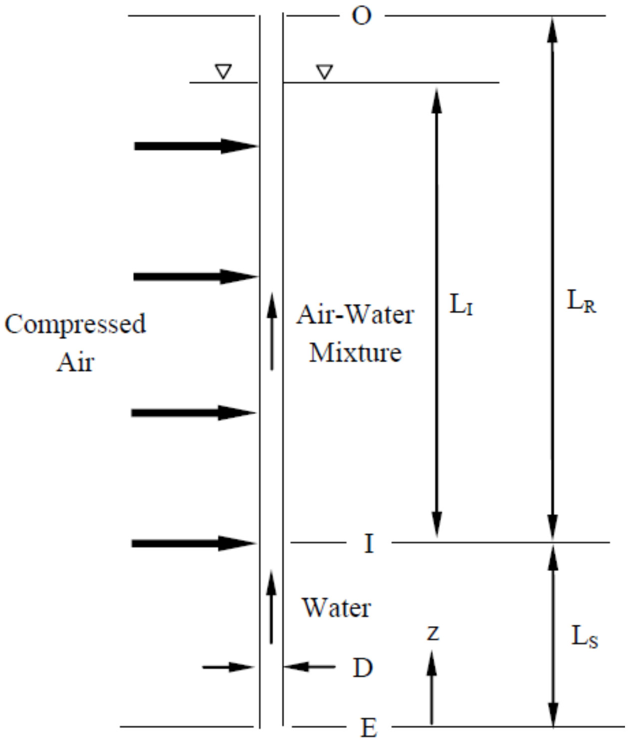

Figure 1. Model of numerically tested airlift pump

Applying the concept of momentum balance to a control volume bounded by the tube wall and tube cross sections at the suction and discharge levels (levels E and O, respectively) results in the momentum equation.

$$\begin{aligned} & A\rho_L j_L u_{L,E} - A\left(\rho_{G,O} j_{G,O} u_{G,O} + \rho_L j_L u_{L,O}\right) \\ & -\pi D\int_E^I \tau_L d_Z - \pi D\int_I^O \tau_{LG} d_Z \\ & -A\int_E^I \rho_L \varepsilon_L g d_Z - A\int_I^O \left(\rho_G \varepsilon_G + \rho_L \varepsilon_{L,2}\right) g d_Z \\ & + A\rho_L g\left(L_S + L_I\right) = 0 \end{aligned} \quad (1)$$

where ρ is the density, j is the volumetric flux, u is the velocity, A is pipe cross-sectional area, D is pipe diameter, τ is the shear stress, ε is the volumetric fraction, P is the pressure, and g is the acceleration due to gravity. The subscripts L and G denote the liquid and gas (air) phases, respectively. In addition, the subscripts z and LG respectively refer to the co-ordinate z and the two- phase air-water mixture.

In Equation 1, the first and second terms respectively denote the momentum of flow that enters through E and leaves through O, the third and fourth terms denote the frictional forces in the suction and riser tubes, respectively, the fifth and sixth terms respectively refer to the weight of the water phase in the suction tube and the weight of the two-phase air-water mixture in the riser tube, and the seventh term implies the hydrostatic pressure force of the surrounding water, acting at the bottom end of the lifting tube at section E. It is noted that the interaction forces between phases, such as the drag and virtual mass forces, appear in the mathematical formulation only if the conservation equations of mass and momentum are applied for each phase separately.

Since both the air pressure and airflow rate vary throughout the pump, owing to the expansion of air, the frictional and body forces in the riser tube section cannot be estimated at the mid section of the riser tube and, therefore, the riser tube should be divided into a number of short segments in the flow direction. The length of each segment is chosen such that the nodes pressure ratio for any segment is the same for all segments. Assuming that the pressure distribution for each segment is linear, the frictional pressure gradient at such a segment and the flow local conditions are calculated at the middle of this segment. The terms of frictional and body forces in the momentum equation, Equation 1, are then calculated using step-by-step integration procedure throughout the riser tube.

An iterative solution is required for the calculation of air and water volumetric ratio and also for other flow parameters that are involved in the momentum equation. During the calculations, the air temperature at the injection point is assumed to be the same as the temperature of the water. Moreover, the temperature gradient is neglected throughout the riser tube. Therefore, an isothermal expansion of gas from the air injection pressure to the pump outlet pressure (P_O) is applied. Performing the momentum balance over the entire length of the airlift tube, the airflow rate ($j_{G,O}$) aimed to achieve a specific gain of water output rate (j_L) can be numerically predicted. The numerical computations are also necessary for calculating the variations in air and water conditions throughout the individual sections of the airlift tube. Detailed information about the definition of different terms of Equation 1 can be found in reference [14] and reference [17].

3. Results and Discussion

3.1. Model Validation

To verify the validity of the present modelling approach, the predicted results obtained by the developed numerical model were compared with the experimental data measured by Weber and Dedegil [18], Yoshinaga *et al*. [14,19], and Fujimoto et al. [21]. The theoretical predictions and the experimental data of the performance of airlift pump while lifting pure water have been compared through Figure 2 to Figure 4 at uniform tube cross-sectional area and at different values of submergence ratio (α). Figures 2, 3, and 4 show a typical example of the water pumped rate (water volumetric flux, $j_L = Q_L / A$, where A is the uniform cross sectional area of the riser tube) as a function of air supplying rate based on standard atmospheric conditions (air volumetric flux, jGa= $j_{G,O} = Q_{G,O} / A$). For each degree of submergence ratio, the airflow was systematically varied and the corresponding water flow rates were numerically predicted. As illustrated in Figure 2, for a constant value of submergence ratio, the water flow rate increases by increasing the airflow rate. Depending on the degree of pump submergence, such behaviour continues until a limiting point is reached, where the water flow rate reaches a maximum value. Further increase in the airflow rate causes a decrease in the water flow rate. This reduction in the water flow rate can be attributed to the fact that the flow pattern in the riser tube at higher rates of airflow tends to become annular. At lower airflow rates, however, slug flow regime is dominating in the airlift tube. In the bubbly-slug flow regime, the water pumped rate is directly proportional to the airflow rate [20]. The results for the presented submergence ratios indicate a common pattern of variation. It is clear that, the submergence ratio has a strong effect on the lifting characteristics of the airlift pump. As illustrated in Figure 2, Figure 3, and Figure 4, the performance of airlift pump is well predicted by the developed numerical code over the entire range of presented submergence ratios. The comparison between the numerical and measured data, therefore, demonstrates a high degree of agreement that is sufficient to justify the use of this simulation tool for parametric predictive studies.

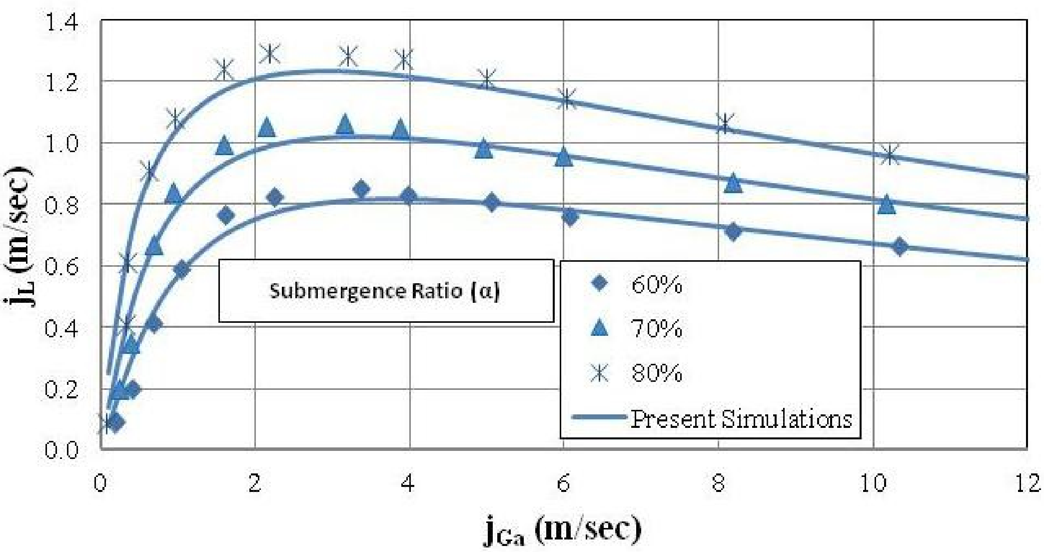

Figure 2. Validation of numerical results calculated based on present simulations with experimental data of Yoshinaga *et al*. [14, 19]. Conditions are: D =26 mm, L_R=6.74m, and L_S=1.12m

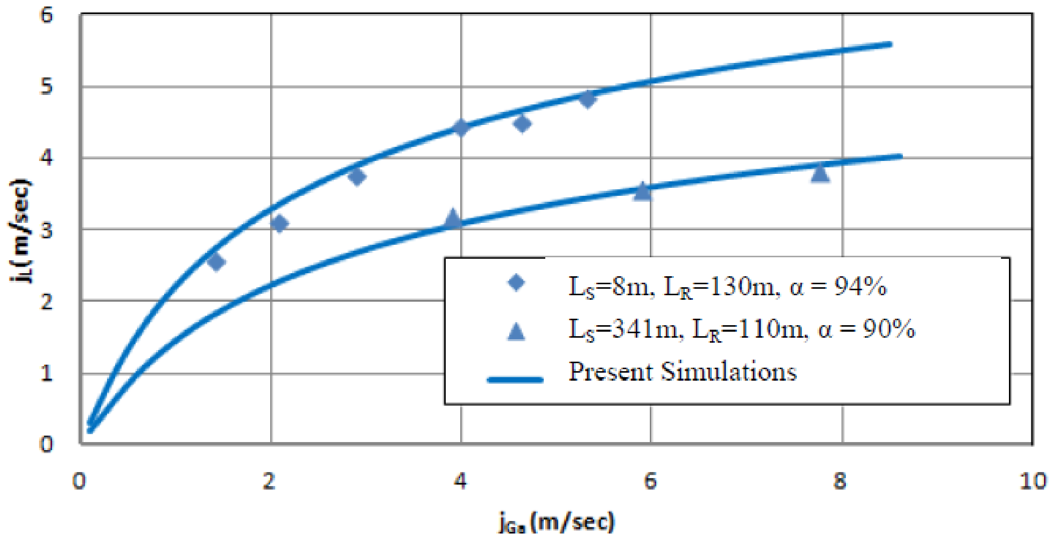

Figure 3. Validation of numerical results calculated based on present simulations with experimental data of Weber and Dedegil [18]

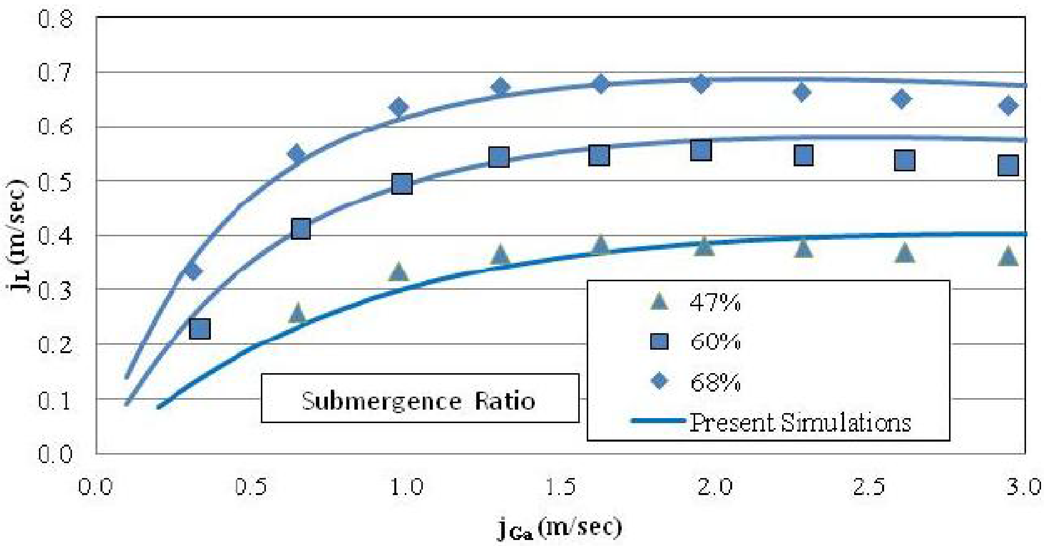

Figure 4. Validation of numerical results calculated based on present simulations with experimental data by Fujimoto et al. [21]. Conditions are: D = 18 mm, L_R=2.4m, L_S=0.8m

3.2. Single-Stage *vs.* Multistage Air Injection

Figure 5 compares the effect of injecting the compressed air in a number of injection stages on the pump output water volumetric flux. In this case, a model airlift pump having specifications of D = 26 mm, riser length (L_R) = 6.74 m, suction length (L_S) = 1.12 m, and Submergence Ratio (α) = 70% is numerically tested. The compressed air is evenly distributed in a number of injection stages through the riser tube length starting from level I in Figure 1; namely 1, 2, 3 or 5 injection stages.

For all cases displayed in Figure 5, it is clear that for reasonably low air flow rates, the water discharge rate is directly proportional to air input rate. For higher airflow rates, however, the pump output is decreased when increasing the air input rate. This behaviour could be attributed to the fact that at low air flow rates, bubbly-slug flow regime is dominating in the riser tube, while at higher airflow rates; the flow pattern tends to become annular.

The results in Figure 5 show that, for the model airlift pump with a single-stage air injection, the pump output rate increases rapidly to reach a peak value, while that with more than one injection stage, the pump discharge rate increases at a slower rate to reach a slightly lower peak value than that of the single-stage case. Increasing the air input rate beyond the point of optimum pump output results in a faster decay of the pump discharge in the case of single-stage air injection as compared to that of multiple air injection airlift models. As illustrated, increasing the number of air injection stages expands the range of bubbly-slug flow regime. The slower decay in the pump discharge rate at high air input rates in the case of multiple air injection stages makes the operating window close to the optimum discharge much wider in comparison with the single-stage air injection. Increasing both the range of bubbly-slug flow regime and the domain of optimum operation, therefore, is expected to increase the stability of the airlift pump as compared to the single-stage injection case. This behaviour may be attributed to the reduction in energy loss due to flow acceleration when injecting compressed air in a number of injection stages. As the number of air injection stages increases, the air input rate corresponding to pump optimum discharge point also increases. Thereafter, the pump characteristic curve becomes nearly flat.

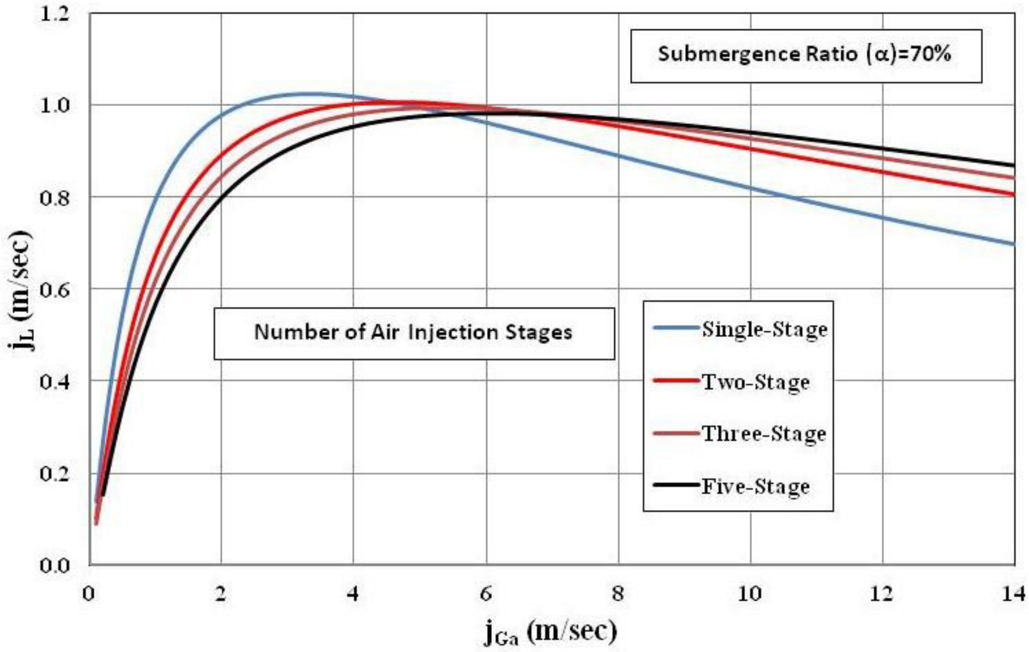

Figure 5. Effects of air injection stages on the pump discharge rate (α=70%)

The development of air phase in the riser tube corresponding to different air injection stages is shown in Figure 6 in terms of variations in the gas holdup (ε_G) at jGa = 10 m/sec of Figure 5. For the single-stage air injection, the gas holdup is gradually increasing as the air expands vertically in the riser tube. Results in Figure 6 demonstrate that by increasing the number of air injection stages, the air volume fraction at the start of injection and along the riser tube decreases. This definitely reduces the acceleration energy loss associated with the expansion of the air phase in the riser tube section till the next air injection stage, as compared to the single-stage air injection. Incremental reduction in the air volumetric fraction due to the multiple air injection stages decreases as the number of stages increases.

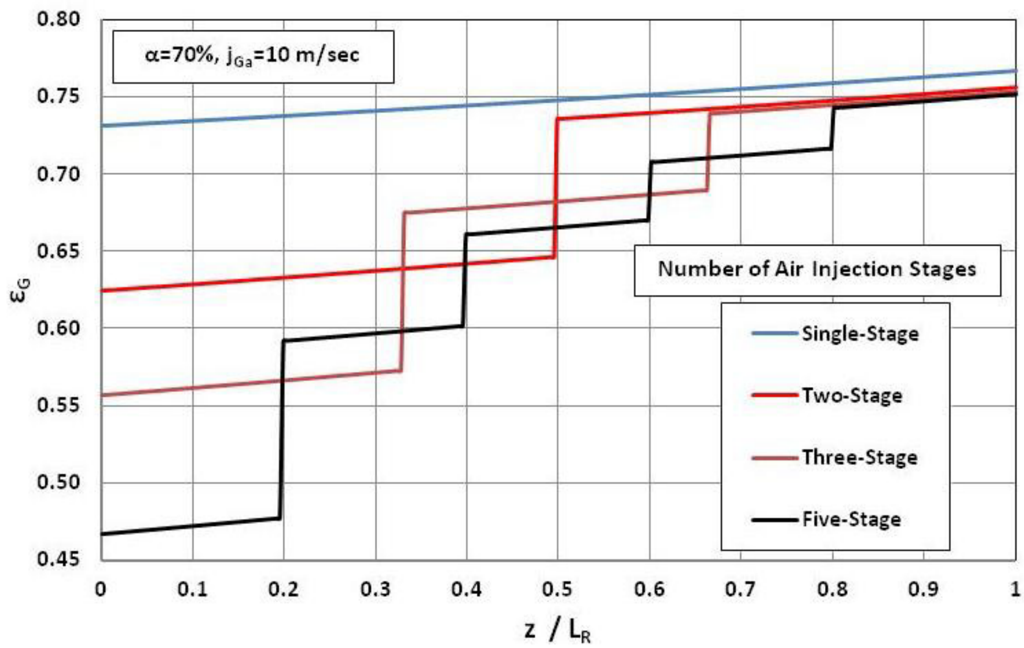

Figure 6. Variation of gas volumetric fraction along the riser tube at α=70% and j_{Ga}=10 m/s

4. Conclusions

This research compares through a numerical predictive study the performance of airlift pump with single- and multistage-stage air injection. The numerical model was assessed and verified through a comparison with available experimental data. The numerical results showed that increasing the number of air injection stages expands the range of bubbly-slug flow regime in the riser tube of airlift pump. Also using multiple air injection stages was shown to widen the pump operating range that is close to the optimum discharge. Increasing both the range of bubbly-slug flow regime and domain of optimum operation while applying multistage air injection are believed to increase the stability of the airlift pump as compared to the single-stage air injection case.

Nomenclature

A	Pipe cross sectional area
D	Pipe diameter
g	Acceleration due to gravity
j	Average volumetric flux
L_I	Submergence height
L_R	Riser tube length
L_S	Suction tube length
P	Pressure
Q	Volumetric flow rate
u	Velocity
z	Elevation of the mixture level in the pipe
Greek symbols:	
α	Submergence ratio (L_I / L_R)
ε	Volumetric fraction
ρ	Density
τ	Shear stress
Subscripts:	
a	Atmospheric conditions
E	Pipe inlet section
G	Gas phase
L	Liquid phase
L_G	Two-phase air-water mixture
O	Pipe outlet section

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