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EXPERIMENTAL CHARACTERIZATION OF A MODIFIED AIRLIFT PUMP

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ABSTRACT

This paper presents an experimental investigation on a modified airlift pump. Experiments were undertaken as a function of air-water flow rate for two submergence ratios (ε=0.58 and 0.74), and two different riser geometries (i) straight pipe with a constant inner diameter of 19 mm and (ii) enlarged pipe with a sudden expanded diameter of 19 to 32 mm. These transparent vertical pipes, of 1 m length, were submerged in a transparent rectangular tank (0.45×0.45×1.1 m^3). The compressed air was injected into the vertical pipe to lift the water from the reservoir. The flow map regime is established for both configurations and compared with previous studies. The two phase air-water flow structure at the expansion region is experimentally characterized. Pipeline geometry is found to have a significant influence on the output water flow rate. Using high speed photography and electrical conductivity probes, new flow regimes, such as "slug to churn" and "annular to churn" flow, are observed and their influence on the output water flow rate and efficiency are discussed. These experimental results provide fundamental insights into the physics of modified airlift pump.

INTRODUCTION

Airlift pumps are widely used in the oil and gas industry for improving the efficiency of oil wells. Compressed air is used to transport liquid inside a vertical pipe. The injection of air from the bottom of the riser pipe generates bubbles which carry the liquid particles upward due to interfacial friction.

The hydrodynamic properties of two-phase liquid-gas flow within the vertical riser pipe have been extensively reported over the last two decades [1-5]. Lawniczak et al. [1] studied the overall performance of airlift pumps and came to the conclusion that as the input air flow rate increases, the water flow rate increases until reaching a constant value. Additionally, they found that for low air flow rates the response water flow rate is linearly related, and that at higher air flow rates there is an exponential relation. Hanafizadeh et al. [2] studied the effects of flow regimes on the performance of airlift pumps. They used high speed camera to observe the flow of air and water traveling through the vertical transparent pipe. They classified four flow regimes, bubbly, slug, churn, and annular, with slug flow the most effective flow regime. Furthermore, they showed that as submergence ratio increases, the performance of the pump improves. Tighzert et al. [3] found that the maximum efficiency of an airlift pump occurs with slug flow, and soon falls during the transition from slug to churn flow. They also found that the optimal range for the pump is between a submergence ratio of 0.40 and 0.75. The effects of suction pipe diameter were studied by AlMaliky and AlAjawi [4]; they found that the pumping rate of the airlift pump increases as the suction diameter increases, due to the increase of static pressure and decrease of water velocity leading to lower friction losses. Kassab et al. [5] developed an analytical model to predict experimental results based on the relation between water and air flow rates provided by Stenning and

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Martin [6]. Mahrous [7-10] developed models for the study of air injection types, single stage versus multi stage [7], as well as for airlift pumps with a bent riser [8], solid particles [9] or gradually enlarged segment in the riser tube [10]. Similarly, Hanafizadeh et al. [11] developed a numerical model to study the effect of step geometry in the riser pipe, where they found that a sudden increase in diameter can increase the efficiency and the water flow rate. Weismann [12] established the flow regime map for air-water in a 25 mm vertical pipe and Nicklin [13] developed and analytical equation for efficiency. The effect of air injection, tube diameter, submergence ratio and riser inclination were also investigated experimentally [14-20].

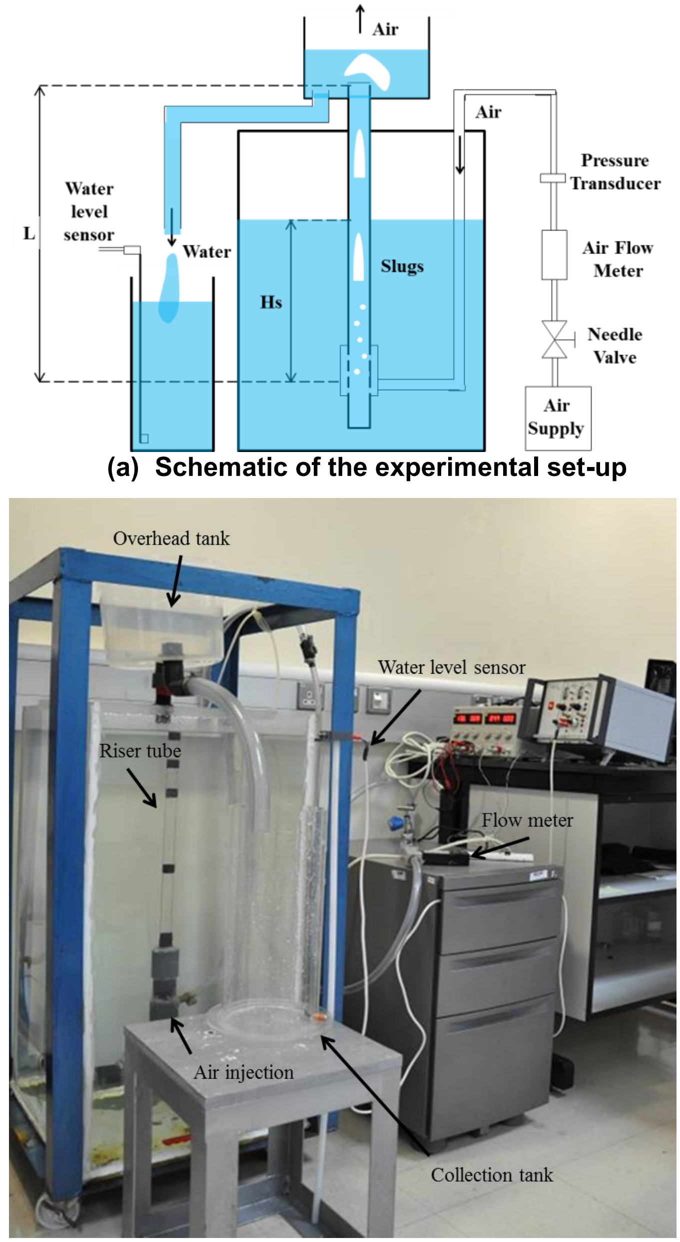
However, the experimental studies of liquid-gas flows for the geometric case of the sudden expansion of the riser inner pipe diameter have not been extensively assessed. Hence, the purpose of this study is to characterize experimentally the influence of the sudden expansion on both water flow rates and efficiency of the airlift pump as well as to observe the effect of flow regimes on the output water flow rate.

The paper is structured as follows. The experimental setup and the flow visualization system employed are described. Measurements of the superficial velocities are presented. The influence of sudden expansion on two-phase water-air flow regime map is discussed. The flow rate performance curve and the efficiency are measured and presented for different geometries and submergence ratios.

EXPERIMENTAL SETUP

The experimental setup consists of a vertical square tank, a transparent Plexiglas riser tube, an air supply, an overhead tank, and a collection tank. The tank was fabricated from Plexiglas and has a height of 1.1 m and square section of 0.45 m. In this experiment the tank was filled with water as a working fluid, with a constant temperature of 21°C. The height of water was between 0.73 to 0.85 m and remains approximately constant during the experiment. Transparent Plexiglas pipes, with different diameters and geometries are used as pipe risers and suspended vertically at the center of the tank. An injector is placed at 0.21 m from the bottom of the pipe in order to provide air to the system. The air injection system consists of a compressor, a mass flow controller and an injector having 48 holes, each 2 mm in diameter, evenly distributed in six rows and eight columns, to ensure even air input.

Air is supplied to the system from a compressor (with a maximum capacity of 7 bars). The air flow rate



(a) Schematic of the experimental set-up

(b) Airlift pump experiment

Fig. 1: Experimental setup and data acquisition system

is controlled by a needle valve and monitored using a mass air flow meter (Cole Parmer RK-32712-44). The air pressure is also measured using a pressure transducer (OMEGA PX40-15G5V). Injected air is rising in the vertical pipe generating a transport of water inside the riser tube. An open overhead tank is placed at the top of the riser tube to collect both fluids. The air is allowed to vent and water is then directed to the collection tank where a water level sensor is used to measure the quantity of water transported in the system.

Submergence ratio is defined as: $\varepsilon = \frac{H_s}{L}$, where H_s is the height of the water above the air injection area (Fig. 1.a) and L is the length of the riser tube. The submergence ratio is altered by adjusting the level of water in the tank.

Experiments were conducted for two different pipe configurations reported in Table 1. Riser pipe 1 has a constant inner diameter along the vertical axis, D=19 mm. The inner diameter of the riser pipe 2 increases suddenly at L=0.4 m from the air injector. The inner diameter of this pipe before the expansion area is 19 mm and 32 mm after the expansion. All pipes have 1 m length and consist of a 0.2 m suction segment and a 0.8 m riser segment. All experiments were undertaken with two different submergence ratios of 0.58 and 0.74 and using several different air flow rates from 0.04×10^{-3} m^3/s to 1.6×10^{-3} m^3/s.

Table 1 Characteristics of pipe geometry

Riser pipe	Type	Inner diameter (mm)
1	Straight	19
2	Expanded	19 to 32

The two phase air-water flow was examined using a high speed camera. To illuminate the central area of the tank, a lamp was installed at the right side of the tank and a high speed camera (Photron FASTCAM SA3) was installed perpendicular to the vertical wall of the tank at the distance of 0.70 m. Full-frame images of 1024 × 1024 pixels were acquired and transferred to a computer via a frame grabber. The measurements were focused on the center of the riser pipes.

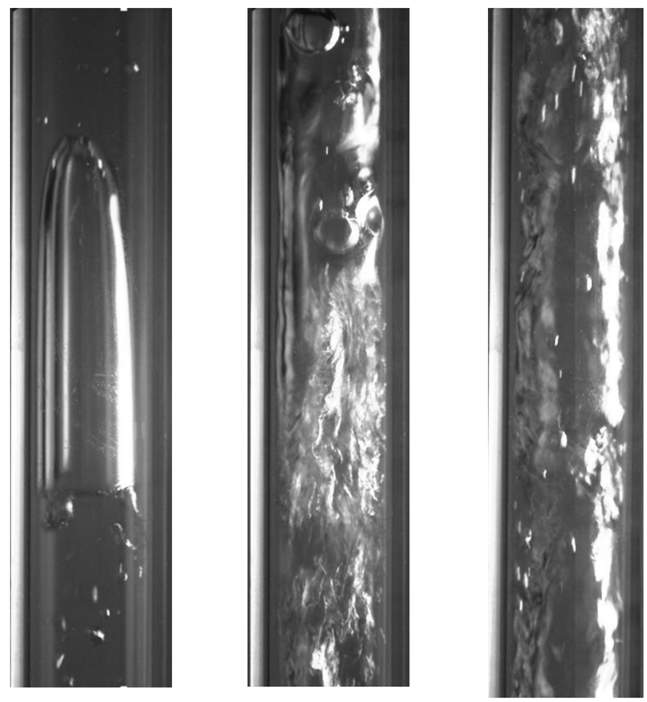
Measurements Uncertainty

The key parameters contributing to the measurements uncertainty were mass flow rates, water level, time and pressure. Air flow rate measurement was obtained using Cole Parmer gas mass flow meter (RK-32712-44). The estimated error, provided from the supplier in mass flow measurement was 2% of full scale. For water flow rates, the sensor level is used to measure the height of water displaced by the airlift pump for a certain period of time. The error in the determination of the water flow rate including the level sensor and time measurements was approximately 7%. The pressure measurements was obtained using as pressure transducer (OMEGA PX40-15G5V) having a measurement uncertainty of ±0.15% full scale.

RESULTS

Test Facility Validation

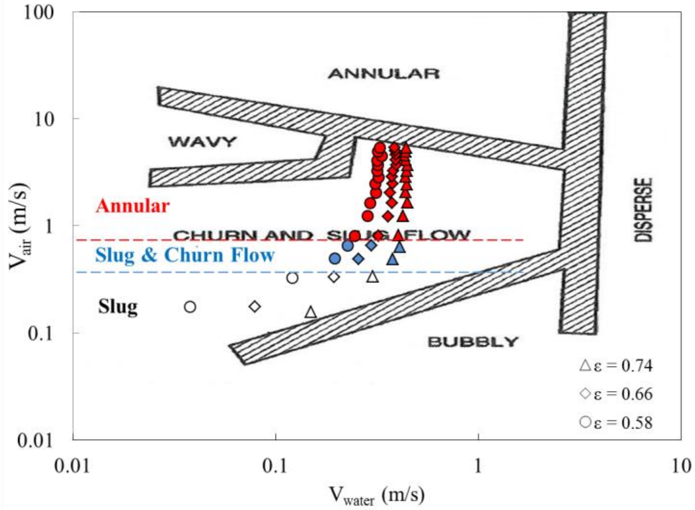
By using flow visualization, three distinct flow regimes are observed in the straight pipe (19 mm inner diameter) and are presented in Fig. 2. The first regime is characterised by the vertical motion of alternate elongated bubbles and water columns and is named slug flow (Fig. 2-a). For higher airflow rates, the slug flow is replaced by churn flow in which bubbles appear more chaotic and unstable as the slugs tend to break apart and no longer hold their shape (Fig. 2-b). At large air flow rates, air and water are displaced using an annular configuration where air is concentrated in the middle area of the pipe surrounded by a thin layer of water around it. The flow is named annular flow and is presented in Fig. 2-c.



(a) Slug flow **(b) Churn flow** **(c) Annular flow**

Fig. 2: Photographs of flow regimes for straight pipe (ε=0.74 and D=19 mm)

In order to validate our experiment, a flow regime map is established for the present experiment and is compared with a reference flow regime map for air-water in a 25 mm vertical pipe [12]. Results of different patterns are presented in Fig. 3 in terms of superficial velocities of water and air. As shown in Fig. 3, the slug and churn flows are approximately matching with the reference flow regime map. However, in the present experiment, the annular flow appears at lower superficial air velocity than the reference experiment.



Dashed lines and points are experimental data provided from the current study while the hatched zones represent the experimental predictions of Weisman [12].

Fig. 3: Comparison of measured flow regimes of air/water mixture in vertical riser pipes for the current test facility with the reference data

This discrepancy can be mainly attributed to the difference of inner pipe diameter (19 mm diameter in the present experiment compared to 25 mm in Weisman's [12] experiment). This smaller diameter could cause bubbles to coalesce much faster causing slug and annular flow to occur more rapidly or at lower velocities. Another potential cause for this difference could be that the experiment done in this study took place in a submerged environment versus Weismann's experiment [12] which was performed in a long vertical pipe where two phase water-air flow was generated using a water pump and air compressor.

Influence of an expanded inner pipe diameter on flow patterns

The comparisons of flow regimes between different pipe configurations (straight and expanded) are presented in Fig. 4. It was observed that all three flow regimes (slug, churn and annular) exist in both straight and expanded pipes. However, the expanded pipe influences the characteristics of these flow regimes, particularly at the critical flow rates where the flow regime is expected to change in a straight pipe.

For the riser pipe 2, the sudden expansion of the inner diameter from 19 mm to 32 mm, increases the turbulence of pipe flow in this expanded area. This transition causes two additional flow regimes to form:

(i) Slug to Churn Flow: characterized by a co-existence of slug flow and churn flow. Slug bubbles passing through the expansion area are disrupted and break apart forming churn flow (Fig. 5.a).

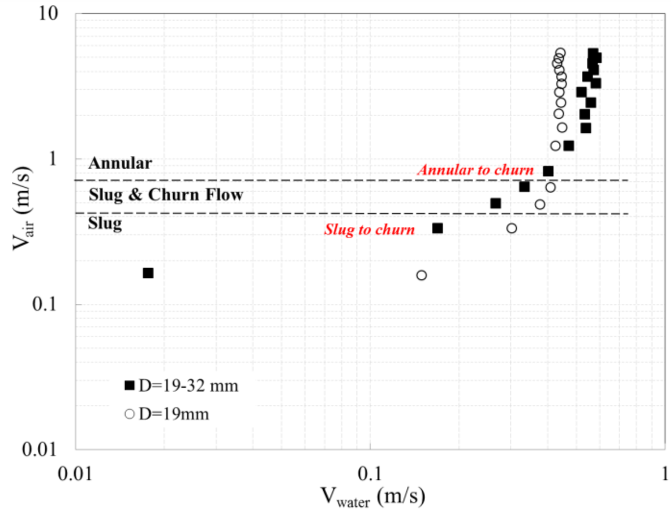
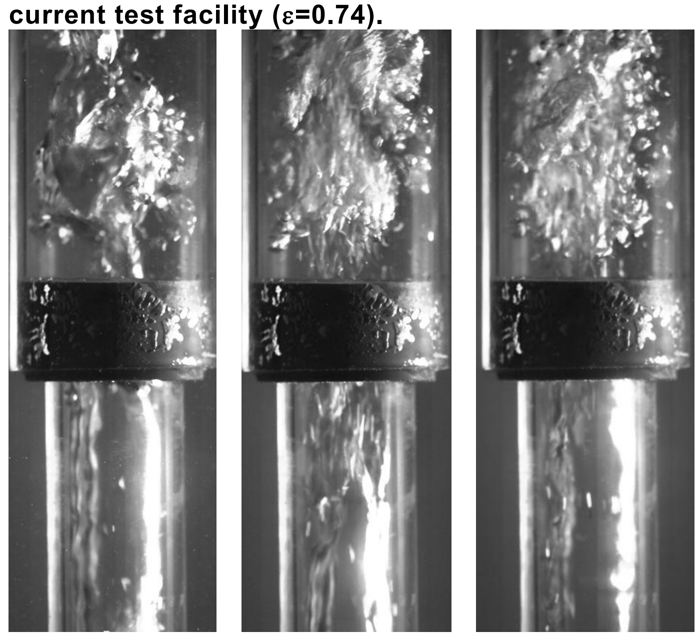


Fig. 4: Measured flow regimes of air/water mixture in vertical expanded and straight pipes for the current test facility (ε=0.74).



(a) Slug to churn **(b) Churn to churn** **(c) Annular to churn**

Fig. 5: Photographs of flow regimes for expanded pipe (ε=0.74 and D=19-32 mm)

(ii) Annular to Churn Flow: characterized by a co-existence of annular and churn flow. Annular flow which represents a stable regime is disturbed when it passes through the expansion area forming a more chaotic regime of churn flow (Fig. 5-c).

It is important to notice that far from the critical flow rates where the flow regimes map changes for the straight pipes, it possible to obtain slug to slug as well as churn to churn (Fig. 5-b) and annular to annular flow regimes.

Influence of an expanded inner pipe diameter on flow rate performance curve

Fig. 6 shows the flow rate performance comparison between the straight and expanded pipes. The water flow rates increase and depend strongly on air flow rates. For the case of a straight pipe (D=19mm), for both submergence ratios (ε=0.58 and 0.74), flow rate performance curves can be divided to two parts (i) at low air flow rates $0<Q_g<0.2\times10^{-3}$ m^3/s, Q_w increases drastically with Q_g, corresponding to slug and churn flow regimes, (ii) for $Q_g>0.2\times10^{-3}$ m^3/s water flow rates increase slowly until reaching constant value corresponding to the case of annular flow regimes in the pipe.

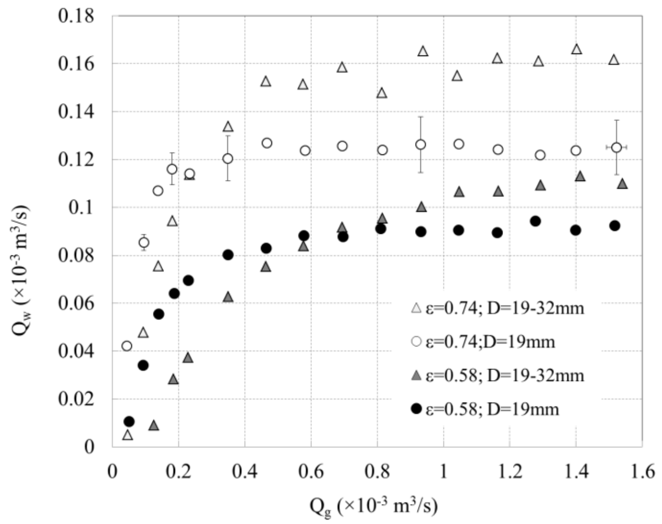


Fig. 6: Flow rate performance curve of the airlift pump for different submergence ratio ε and geometry

Regarding expanded pipes, at low air flow rates $0<Q_g<0.2\times10^{-3}$m^3/s, Q_w increases with Q_g, with lower values than the case of straight pipes. The flow rate performance curve of expanded pipes, increases continuously with Q_g until crossing a critical point where the curve of the straight pipe reaches a constant value. It is observed that the straight pipe has a better output water flow rate at lower air flow rates. However, at flow rates above a critical point, which varies for different pipe parameters, the expanded pipe has the higher output water flow rate.

This could be explained by the additional flow regimes observed in the expanded pipe (Fig. 4 & 5). It has been shown that slug flow is more desirable than churn flow and churn flow more desirable than annular flow [2-3]. Therefore, it could be assumed that the expanded pipe has a lower output rate at low air flow rates. This is due to its ability to have a slug to churn regime, as this would cause the more efficient slugs to be broken down into churn and so lowers the output rate. The other difference in output rate could be due to the fact that the expanded area breaks down long slugs to multiple small slugs, which have less buoyant force to lift up water. Similarly, the higher output rate of expanded pipes, for high air flow rates, could be attributed to the annular to churn flow regime, as the less efficient annular flow is converted into churn flow.

Influence of an expanded inner pipe diameter on efficiency of the airlift pump

The efficiency of the airlift pump for different submergence ratios and pipe geometries are presented in Fig. 7. The equation used to calculate efficiency is given by Nicklin [13]:

$$\eta = \frac{\rho g Q_w (L - H_s)}{P_a Q_g Ln \frac{P_{in}}{P_a}} \qquad \text{Eq.1}$$

where η is the efficiency, ρ is the liquid density in kg/m^3, g is the gravitational acceleration in m/s^2, Q_w and Q_g are the water and air discharge rate respectively, both in m^3/s, L is the length of the riser pipe in m, H_s is the height of the pipe that is submerged in m, P_a is the atmospheric pressure in N/m^2, and P_{in} is the pressure at the injection point in N/m^2.

It is observed that all curves have a maximum efficiency corresponding to a drastic increase at low air flow rates $0<Q_g<0.4\times10^{-3}$ m^3/s and smooth decrease after the maximum point, where the air flow rate increases. This trend is comparable to previous experimental results [1-5]. It is important to notice that the geometry of the pipe affects significantly the maximum efficiency point of the airlift pump. The efficiency of the expanded pipe is lower compared to that of straight pipes for low flow rates ($0<Q_g<0.4\times10^{-3}$m^3/s).

For higher flow rates ($Q_g>0.4\times10^{-3}$m^3/s) the geometry of the pipes and submergence ratio do not significantly affect the efficiency of the airlift pump. The large difference in efficiency for the lower flow rates can be attributed to equation 1.

From this equation it is noticed that only three variables can affect the system, (i) the injection pressure (P_{in}), (ii) the water flowrate (Q_w) and (iii) the air flow rate (Q_g). The ratio of injection pressure to atmospheric pressure is close to one for all cases. Therefore, the efficiency is significantly affected by

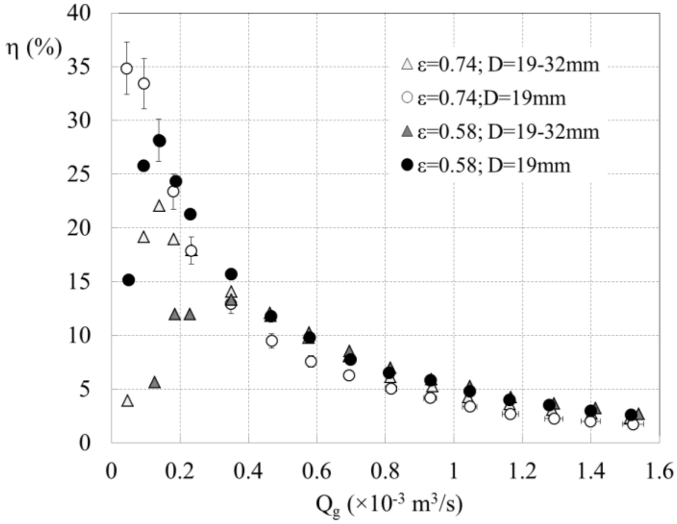


Fig. 7: Efficiency curve of the airlift pump for different submergence ratio ε and geometry

the ratio of flow rates, as seen in the equation provided. From Fig. 6 it can be seen that this ratio has a notably high value at low air flow rates ($0<Q_g<0.4\times10^{-3}m^3/s$) and the ratio converges to a constant value for high flow rates. Consequently, the influence of geometry cannot be observed on the efficiency for higher flow rates ($Q_g>0.4\times10^{-3}m^3/s$).

CONCLUSIONS

In this study, the influence of an expanded inner diameter of riser pipe on the airlift pump is investigated. Experiments were undertaken as a function of air-water flow rate for two submergence ratios (ε=0.58 and 0.74), and two different riser geometries (i) straight pipe with a constant inner diameter of 19 mm and (ii) enlarged pipe with sudden inward expanded diameter of 19 to 32 mm. The flow map regime is established for both configuration and compared with previous studies. For the straight pipe, the flow regime map of slug and churn flows approximately match the reference flow regime map [12]. For the expanded pipe, new flow regimes, such as "slug to churn" and "annular to churn" flow, are observed and their influence on the output water flow rate and efficiency are discussed. Based on the visualized air-water flow, pipeline geometry is found to have a significant influence on the output water flow rate. The influence of both submergence ratio and geometry are negligible on the efficiency for high flow rates. Future experimental analysis related to gradual expansion will be conducted to complete this study.

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