

The Effect of Air Injection System on Airlift Pump Performance

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In the current study, a novel design of an air injection system for an airlift pump was designed and tested. The pump has a circular cross-section and composed of three parts; suction pipe, injection system, and riser pipe. The riser pipe has a diameter of 31.7 mm and a length of 2 m. The performance of the pump was tested using different submergence ratios, ranging from 0.15 to 0.3, and the injected airflow rate was ranging from 1.65 kg/h to 13.32 kg/h. The results showed that both the airflow rate and the submergence ratio have a significant effect on the capacity and performance of the pump. Besides, it was found that the best range of pump efficiency was in the slug and slug-churn flow regimes. Moreover, the highest efficiency was at the most significant submergence ratio of 0.3. A reasonable enhancement in water flow rate was achieved using the current air injection design when compared with the conventional airlift pump injections system.

Keywords: Airlift pump, Injection system, Two-phase flow.

1. INTRODUCTION

Airlift pumps' popularity has increased significantly. They can be used to lift various types of liquids utilizing the buoyancy force that results from an injected fluid, such as air, which has a lower density than the primary liquid. An airlift pump is composed of a vertical pipe, which includes two parts. The first part is known as the suction pipe, which is placed between the bottom and the air injection part and the uprising part, which is placed between the air injection and the discharge parts. The air is injected at a place close to the riser's base, which is partly submerged in the liquid. As a result of air injection, bubbles are formed and expanded as they move upward in the riser part. Thus, a column of liquid and air, which has a lower density than water, is formed. Then, the mixture moves upward in the riser and is pumped out at the top end of the pump. Although these pumps have lower efficiency than the other types, they have been recommended for several applications for many reasons, such as easy to install and maintain, cavitation, and clogging can be avoided and no need for a large area. For these reasons, these pumps are used in several applications, such as lifting corrosive liquids in chemical factories, sludge removal in sewage processing plants, and pumping viscous liquids such as the hydrocarbons in oil industry [1]. In the petroleum section, airlift pumps are used to raise oil from the feeble wells [2].

The performance of the airlift pump is influenced by two main parameters: the geometrical parameters and the operation parameters. Several studies have focused on the effect of the design of the geometrical parameters on the airlift pump performance.

For example, [3] studied the effect of two designs of injectors on the performance of the airlift pump. Two types of air injection systems were investigated; air-jacket and foot-piece air injectors. The results showed that the highest pumping efficiency is achieved at the most significant flow rates when a small area orifice is used.

However, the overall pump efficiency was very low. Another design of the airlift pump is experimentally investigated by [4]. The effect of using 4 and 8 port diffuser as an air injector on the performance of the airlift pumps was investigated. The results revealed that the 8-port diffuser has higher efficiency than the 4-port one. Also, the efficiency is highly affected by the airflow rate as well as the injection technique. The effect of the injection mode on the pump performance was experimentally examined by [2], [5], [6] and [7].

For instance, the effect of a new foot-piece design of an air injection system on the performance of the airlift pump was investigated at different submergence ratios in [2]. It was noticed that the performance of the airlift pump is a function of the size as well as the distribution of the bubbles in the rise section. Considerable enhancement in the performance of the pump was reported using injectors with multiple holes. However, [5] conducted an experimental study to examine the effect of the four different injection nozzles, which have similar injection areas at different airflow rates and fixed submergence ratios. It was found that the design of the injector has a significant influence on the efficiency of the airlift pump. Another design of air injectors was examined by [6]. Three designs of air injectors that enable air injection axially, radially, and both axially and radially at the same time were explored.

Moreover, two injection modes of steady and unsteady injection at various injection frequencies were investigated. It was found that the airlift pump performance with a pulsating axial injection was better than the steady injection. A dual injector was designed and tested by [7]. The results revealed that the most

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significant submergence ratios result in better efficiency and enhanced water flow rate.

An airlift pump with three types of air jacket injectors was investigated by [8] to study the design effect of air jacket types on the performance of the airlift pump. The designed air jackets have drilled holes of different sizes, where the total air injection area is kept constant. The holes were uniformly distributed into rows and columns at the perimeter of the pipe. It was found that the air jacket with a 4 mm hole diameter led to the highest airlift pump performance. Another study reported by [9] showed that air injection angles could affect the performance of the airlift pump. The angles of air injection were from 90° to 22.5° . It was found that an angle of 22.5° is the best among the other tested angles. This angle increased the performance by approximately 11%. Besides, there was no noticeable change in the flow pattern structure when the injection angle was changed.

The effect of a riser pipe with a gradually increasing diameter was tested by [10] and [11]. The reported results showed that the water output within the tapered riser pipe is highly sensitive to the airflow rate than the straight riser pipes. In addition to the geometrical parameters, the influence of the operational parameters such as the submergence ratio and the injected fluid flow rate on the liquid flow rate, efficiency, and void fraction were investigated by [12], [13] and [14]. It was concluded that the capacity and efficiency of airlift pumps are a function of submergence ratio and airflow rates. On the other hand, the pump's dimensionless number (PDN), as well as the lift's dimensionless number (LDN) for capturing flow parameters were presented by [15]. It was noticed that the airlift pump with a riser pipe of small diameter gives a higher lift. It was obtained that fluids of better adhesive characteristics generate greater lift. In addition, enhanced water flow rates were achieved when the submergence ratio was increased.

There are two ways to analyze the distinctive flow regimes of gas-liquid two-phase flow in vertical pipes. One of them is flow regime maps, which are commonly fitted to the database of the observed flow pattern [16] and [17]. At the same time, the other is a theoretical model based on the mass, momentum, and energy balance equations; in this method, the flow regimes are predicted in addition to the transition between them [18].

The flow pattern of the airlift pump was analyzed and discussed by [13], [14], [19] and [20]. It was reported that the main parameters affecting the performance of the airlift pump are the flow pattern inside the riser pipe. Four main regimes can be observed; bubbly, slug, churn, and annular flow. The data showed that the best efficiency range of the airlift pump is within the regimes of slug and slug churn flow. Additionally, the flow structure in the riser pipe was discussed in [21] in which was reported that an unstable flow structure results in a water fallen film (i.e., the film of the water that forms on the inside wall of the riser pipe is falling downwards, and an air-core occupies most of the cross-section of the pipe), a bubbly mixture, an ascendant water film in the riser pipe. Moreover, these

flow structures affect the performance of the airlift pump at the significant airflow rates.

From the literature, one can notice that little work is available on the effect of both the mode of air injection (steady and unsteady) and the design on the airlift pumps' performance. Therefore, the current study aims to investigate the effect of axial air injection on airlift pump performance experimentally. Also, a comparison with available literature is performed for a conventional airlift pump [12], which has a riser pipe of 2 m length and 0.0317 m diameter. Moreover, various operational parameters are taken into consideration during the experiment, such as the flow rates of the injected air and the submergence ratio to study their effect on the performance of the airlift pump. The range of the airflow rate and submergence ratio is 1.65 to 13.32 kg/h and 0.15 up to 0.3, respectively.

2. EXPERIMENTAL APPARATUS

The apparatus used in the experimental work is depicted in Figure 1. It consists of a suction pipe having 750 mm length, a riser pipe of 2000 mm length, and an air injector. The riser pipe has a conical entrance of 175 mm height and 63.5 mm base diameter. The top end of the conical part is attached to the riser pipe, whereas the base is fixed to the exit of the suction pipe by the air injector.

The air injection system that is utilized in the experiment is illustrated in Figure 2. It is composed of an air distribution plate and an axial compartment with a length of 300 mm. The air distribution plate is an annular disk that has 36 holes with a diameter of 3 mm. The holes are uniformly drilled and distributed in the radial direction with an angle of 10° . The plate is mounted at the top end of the axial compartment and supported with a stainless steel liner. The outer and inner diameter of the annular disk is 63.5 mm and 50.8 mm, respectively, with a clearance of 12.7 mm.

The suction pipe is placed in a suction tank and attached to the airlift tank by a rubber tube. Both the riser and suction pipes have an internal diameter of 31.75 mm and 50.8 mm, respectively, and made of stainless steel. The injected air is supplied by an air compressor that delivers air at a peak pressure of 8 bar to an air tank that has a capacity of 2000 liter. The pressurized air is transmitted through a pipeline of 19.05 mm diameter to an on/off valve, then to a pressure-reducing valve (regulator). A rotameter having 0.1% accuracy is used to measure the airflow rate. After that the flow goes to a needle valve for controlling the supplied air pressure, and finally, it passes to a pressure gage (Bourdon Gage) of an accuracy of 2%. The pressurized air enters the air injection system, and axially flows through the cited holes. Then, the airflow merges with water that flows through the suction pipe. Afterward, the two-phase (water and gas) mixture moves upward in the riser pipe and then discharged into the separator. A separated tank is linked to the riser pipe from the upper end.

This tank is used to separate the air from water and to release it to the atmosphere. The discharged water moves to the airlift tank and keeps circulation in a

closed loop. To test various submergence ratios, which is defined as the ratio of the water level in the submergence water tank length (H) to the total length of the riser pipe (L), a movable submergence water tank was used, which was moved up or fell down depending on the value of submergence ratio (H/L). To get a specific submergence ratio, the water tank is kept at a constant level (i.e., the submergence height), which was approximately equal to the water level in the submergence water tank. It is measured by using a scale that is mounted on the support frame, as shown in Figure 1. The scale has a measurement uncertainty of ± 0.01 cm.

The flow rate of the discharged water was measured by collecting the pumped water from the airlift tank in a vessel of a known volume. The volume flow rate is the volume of water during a time, which is measured by utilizing a digital stop watch. The procedure was done five times, ; after that, the volume flow rate of the discharged water was computed with uncertainty ± 0.2 kg/h .

In the current investigation, the submergence ratios (H/L) were varied from 0.15 to 0.3, with an increment of 0.05. At each submergence ratio, the airflow rate was changed from 1.65 kg/h to 13.32 kg/h, and then the corresponding water flow rates were measured.

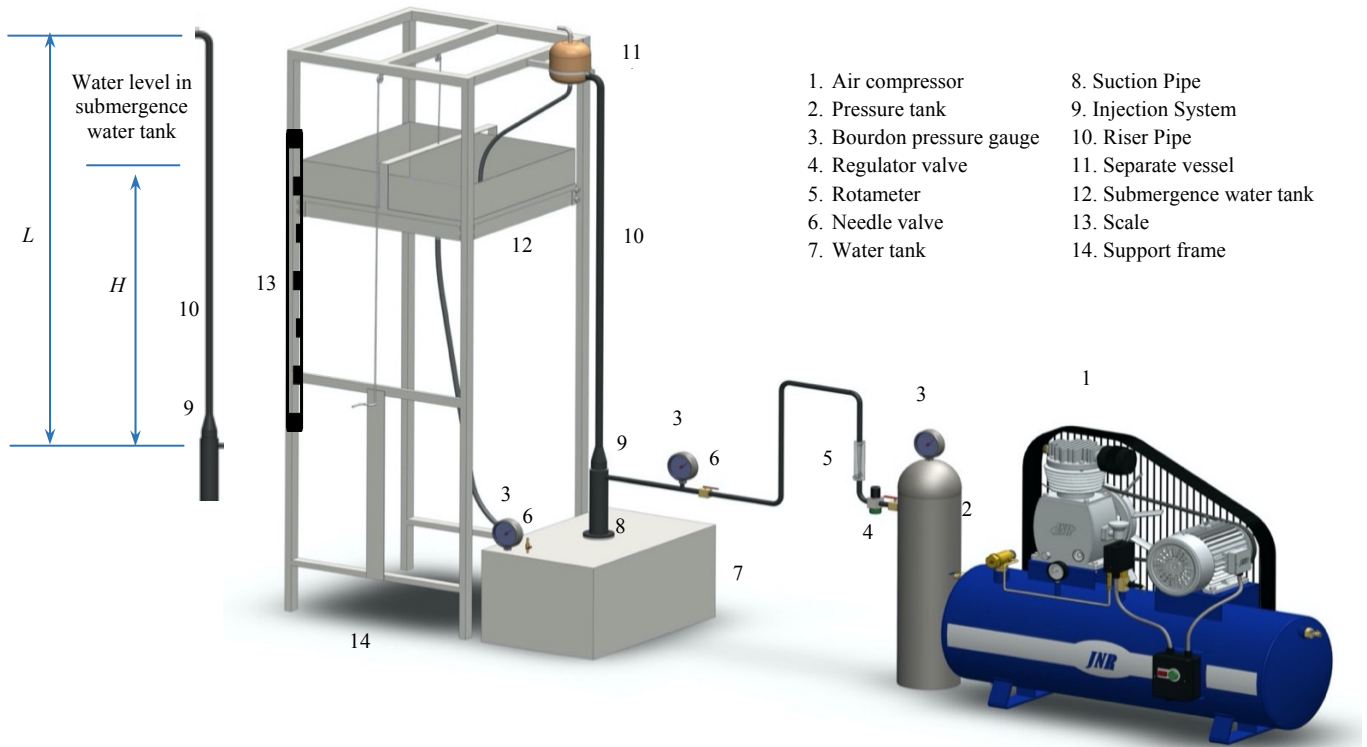


Figure 1. Layout of the Airlift Pump

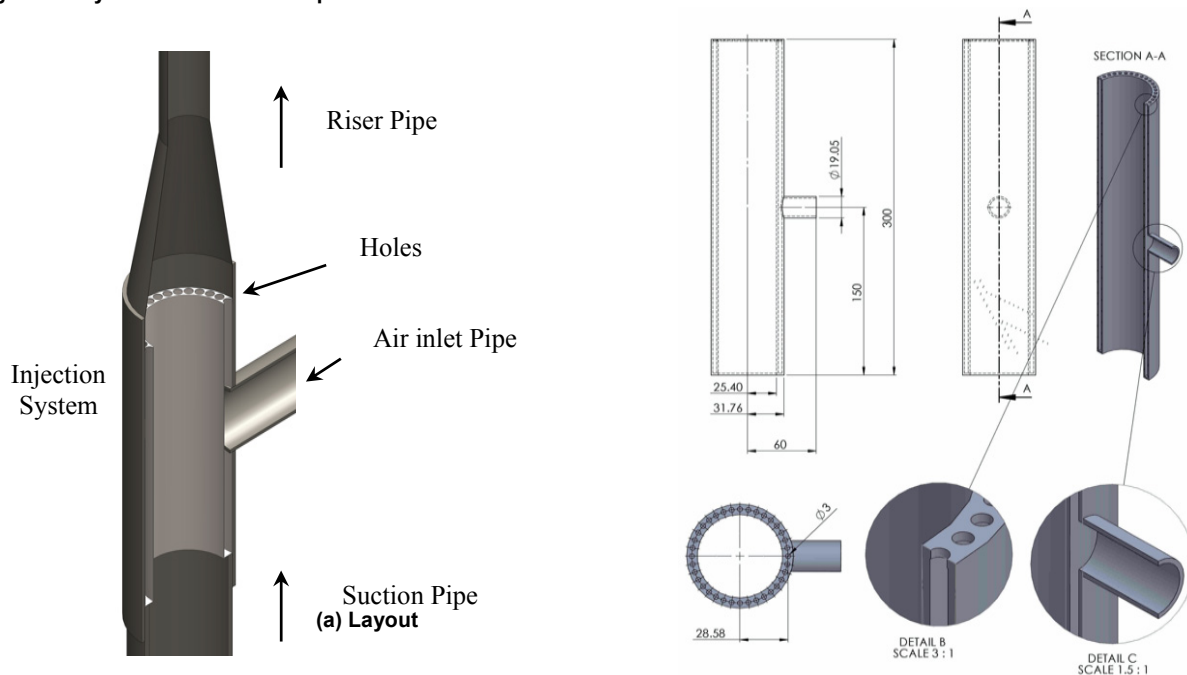


Figure 2. Injection System

3. RESULTS AND DISCUSSION

3.1 Flow Rate

The water pumping rate as a function of the airflow rate at various submergence ratios 0.15, 0.2, 0.25, and 0.3 is presented in Figure 3. It can be noticed that for a specific submergence value, the water flow rate increases as the airflow rate increases. Such behavior continues until reaching a certain peak point, at which the flow rate is maximum. The further increase in the injected airflow rate results in a reduction in the discharged water until it reaches a constant value. Also, for a given airflow rate, the pumped water decreases when the submergence ratio is decreased from 0.3 to 0.15. The highest water flow rate of 0.29 kg/h was obtained at a submergence ratio of 0.3.

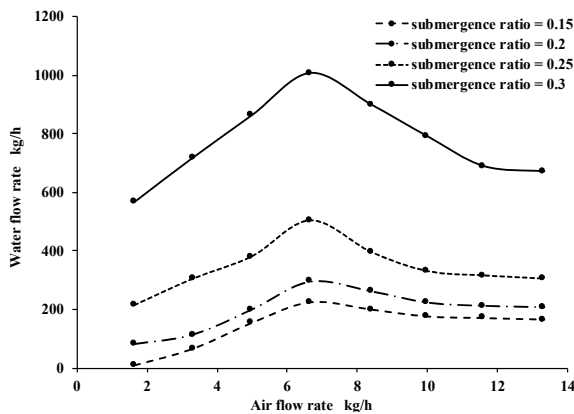


Figure 3. Distribution of the rate of air mass flow versus the rate of water mass flow at different submerged ratios

3.2 Void Fraction

The average void fraction is described as an area or a volume that is occupied by the gas phase inside the whole volume, or the area of the two-phase mixture. Figure 4 illustrates the void fraction against the air mass flow rate for various submergence ratios, which are 0.15, 0.2, 0.25, and 0.3. It can be seen from Figure 4 increasing the submergence ratio at a fixed airflow rate leads to a reduction in the void fraction. This is because increasing the submergence ratio means an increase in the submerged water of the riser pipe. Thus, the level of water that must be lifted by the injected air is low. As a result, the pump needs less compressed air to lift water. Thus, a reduction in the void fraction is occurring. In other words, for a given submergence ratio, as the flow rate rises, the air keeps occupying most of the uprising core cross-section during water lifting.

However, when the void fraction increases, the density of the two-phase flow (the mixture) reduces. This phenomenon can be explained according to the definition of the density of the two-phase flow as:

$$\rho_{TP} = \alpha \rho_a + (1 - \alpha) \rho_w \quad (1)$$

By comparing the two terms in the above equation, it can be clearly seen that the term $((1 - \alpha) \rho_w)$ is more effective than the other one $(\alpha \rho_a)$ as water is denser than air. Regarding the coefficient of the second term, any increase in the void fraction causes a reduction in the two-phase flow density.

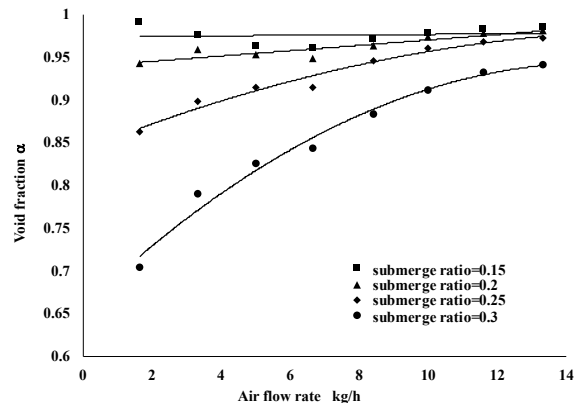


Figure 4. The void fraction variation against the airflow rate at different submerged ratios

3.3 Two-Phase Flow Regime Map

It is reported by many researchers, such as [16], that the structure of flow in a riser pipe has three regimes, such as a slug, a churn, and an annular flow regime. These flow regimes can be traced when the airflow rate is increased using a flow pattern map. Thus, the experimental data distribution presented in Figure 5 is based on a flow regime map that is reported in [16] at different submergence ratios of 0.15, 0.2, 0.25, and 0.3. As can be seen in this figure that, in the zone where water flow raises, the flow pattern is linked to the flow regime of slug, the transition of slug–churn and flow regime of churn. Furthermore, it was found that at the high submergence ratios 0.25 and 0.3, the system of the slug flow seems to be appeared at low airflow rates. However, at low submergence ratios (0.15 and 0.2), the churn flow regime dominates at a low airflow rate.

The slug flow regime is usually characterized by an alternating flow of gas pockets and liquid slug. Most of the gas-phase is concentrated in large bullet shape gas pockets that are known as Taylor bubbles, which are separated from the pipe wall by a thin film of liquid. Besides, these bubbles are separated from each other by an intermediate liquid slug. Inside these large air bubbles, the direction of gas velocity is upward; thus, they act as a pneumatic piston. So, they push the trapped slug water between them along riser pipe, while the thin film around these bubbles is falling down.

However, for the churn flow regime, most of the gas phase is in a gas form, such that it occupies the whole cross-section of the riser pipe due to the increase in void fraction value. This leads to a reduction in the water output due to the drag force. If the pump works in the annular flow regime, then a thin film of water merely ascends along the pipe (i.e., increases the void fraction), increasing flow rate results in a thinner water film.

3.4 Pump Efficiency

Pump efficiency (η) is considered as an essential parameter that characterizes the performance of the different airlift pump models. This parameter can be described as the ratio of the beneficial work conducted in water to the available energy that is resulted from the isothermal expansion of the air from the injection pressure to the atmospheric pressure, [22]. The efficiency can be calculated using the following equation:

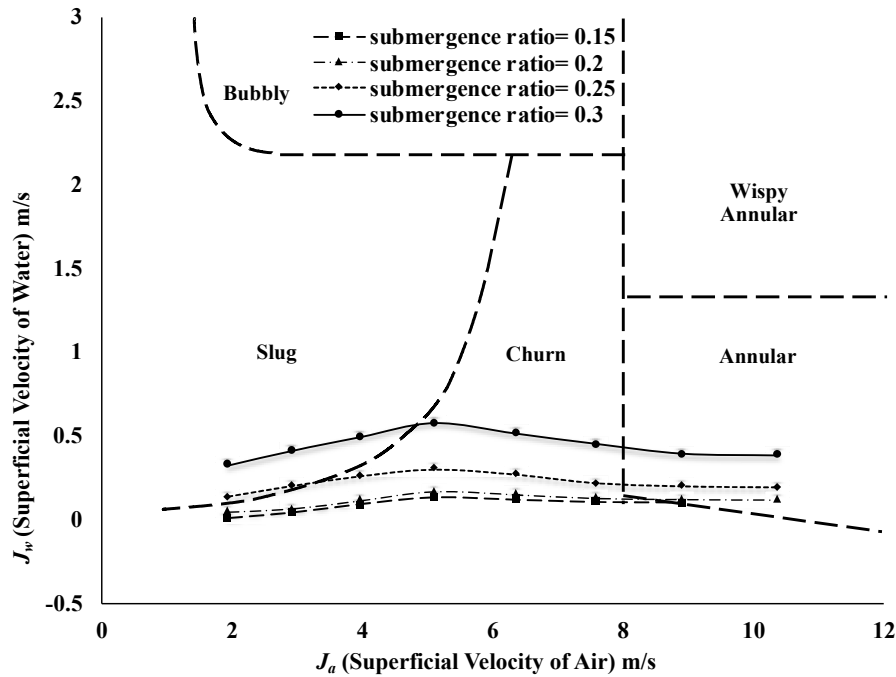


Figure 5. Illustration of performance of the airlift on the map of flow regime, [16]

$$\eta = \frac{\rho_w g Q_w (L - H)}{P_{atm} Q_a \ln(P_{in} / P_{atm})} \quad (2)$$

Figure 6 shows the efficiency variation of the air-flow rate at various submergence ratio values 0.15, 0.2, 0.25, and 0.3. This figure shows that as the airflow rate increases, the efficiency of the pump increases from zero to a maximum value. Then, if the injected airflow rate is further increased, the efficiency of the airlift pump decreases.

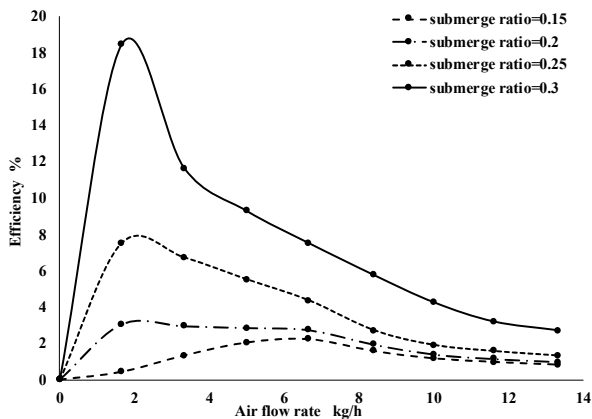


Figure 6. Airlift pump efficiency (%) against the rate of airflow at various submerged ratios

This can be due to the excessive acceleration loss because of the significant values of the void fraction at the upper part of the riser when the airflow rate is increased. Thus, the pump performance is reduced. However, the maximum efficiency that can be achieved is 18.84% at a submergence ratio of 0.3, and an airflow rate of 1.75 kg/h, as presented in Figure 6. At smaller submergence ratios, such as 0.15 and 0.20, the results show that little increase in the pump efficiency can be achieved. These results are in an uneconomical pump operation as the high velocity injected air mixes with

the discharged water outside the rising pipe, and the expelled bubbles lead to an energy loss. However, in comparison with the outcomes of the water mass flow rate depicted in Figure 3, with the efficiency outcomes revealed in Figure 6, can be seen that the best efficiency does not take place at the peak value of the water mass flow rate for all values of the submergence ratios.

3.5 Pump Effectiveness

Pump effectiveness is a significant parameter for the airlift pump usage, and it is commonly used to compare among various designs. It is described by [3] and can be defined as the ratio of water mass flow rate to the injected air mass flow rate. Figure 7 illustrates the effectiveness of the current airlift pump design at different submergence ratios of 0.15, 0.2, 0.25, and 0.3.

It can be observed that two main trends are pre-sented for the pump's effectiveness; one of them is at submergence ratios of 0.3, 0.25 and 0.2, where the pump effectiveness is descending with increasing the flow rate of air, while the other is at the submergence ratio of 0.15. At this trend, the effectiveness is initially increased. Then it is decreased after reaching its maximum value at a certain value of the flow rate of the injected air. These phenomena could be related to the two-phase flow pattern, which is expected at these submergence ratios.

However, when the maximum effectiveness that is presented in Figure 7 is compared with the highest efficiencies shown in Figure 6, it can be noticed that the highest water flow rate values in the two cases are different at a specific value of submergence ratio. This difference can be attributed to the fact that the relation between maximum effectiveness and corresponding airflow rate does not consider the input power that is utilized to compress the air. However, there is a relationship between the pumped water power and the

compressed air power regardless of the amount of the pumped water. Thus, initially, at maximum effectiveness, low efficiency is observed due to the significant input power that is required for air compression.

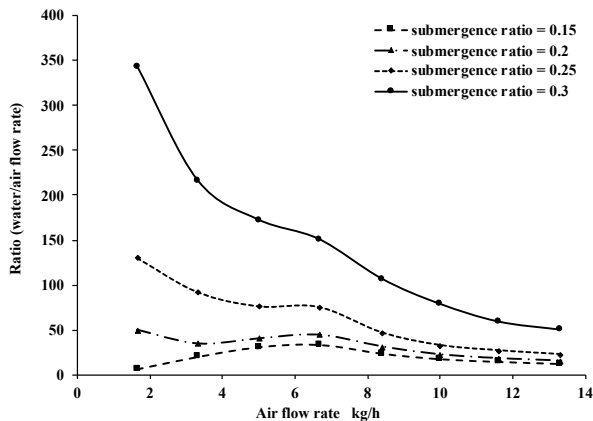


Figure 7. Distribution of ratio (water/airflow rate) against the rate of water mass flow at various submerged ratios

3.6 Influence of Current Air Injection System on the Performance of Pump

The principal characteristic of the air injection system design is the enhancement of the water flow rate that could be achieved at a certain submergence ratio. So, the rate of the discharged water in the present study was compared with the experimental data that were reported in [12] at a submergence ratio of 0.3, as shown in Figure 8.

It can be seen in Figure 8 that the water flow rate in the present study is higher than that in [12] for the same amount of airflow rate. A maximum increase of 18.84% is achieved when the current axial injection system is used when compared with the design that is presented in [12] at a submergence ratio of 0.3. Moreover, the injection method significantly affects the airlift pump efficiency, as shown in Figure 9. In this figure, the current airlift pump efficiency is compared with the experimental data from [12] at the airflow rate ranges from 1.65 to 13.32 kg/h. The results showed that the maximum efficiency for the present work is 18.84%.

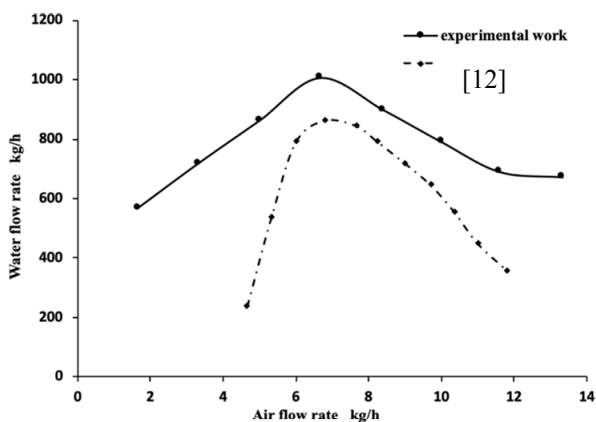


Figure 8 Comparison of the water flow rate versus airflow rate between the result of the present study and [12] at the best submerged ratio, $s = 0.3$

The maximum efficiency of the experimental results in [12] is 11.2%; this means that the current design

shows an enhancement in the pump performance, where maximum efficiency is increased by 42.1% as compared to the previous work [12].

This improvement in pump performance is mainly due to the proposed air injection system.

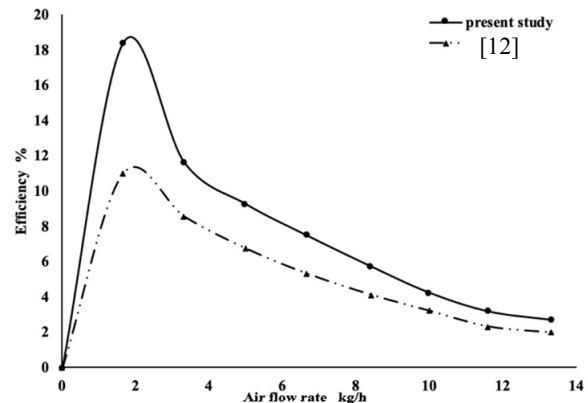


Figure 9 Comparison of airlift performance efficiency for the present study and [12] at submerging ratio, $s = 0.3$

4. CONCLUSIONS

In the present investigation, the effect of the axial air injection method on the performance of the airlift pump was studied. All the experiments were conducted at different submergence ratios, 0.15, 0.2, 0.25, and 0.3, and the airflow rate was between 1.65 and 13.32 kg/h. The concluding remarks that can be drawn are as follows:

- (1) When the submergence ratio rises, the pump maximum pump efficiency increases for a certain flow rate except at the submergence ratio of 0.15.
- (2) The airlift pump can lift an ultimate quantity of liquid when working in the slug or churn slug regimes.
- (3) The highest efficiency does not take place at the ultimate mass flow rate.
- (4) The best efficiency points are located in the slug or slug churn flow regime.
- (5) The results for the axial injection indicates that at 0.3 submergence ratio, the maximum efficiency increases by 42.1% when compared to a the conventional one, and the water flow rate increases by 18.84%.

APPENDIX

ERROR ANALYSIS

For calculating the relative uncertainty of the experimental data, the method that is described by [23] was used. If the variable X is considered as a function of many variables, then

$$X(y) = f(y_1, y_2, \dots, y_n) \quad (3)$$

The uncertainty is defined as

$$U_x^2 = \left(\frac{\partial X}{\partial y_1}\right)^2 U_{y_1}^2 + \left(\frac{\partial X}{\partial y_2}\right)^2 U_{y_2}^2 + \dots + \left(\frac{\partial X}{\partial y_n}\right)^2 U_{y_n}^2 \quad (4)$$

In Equation 4, U_{y_i} is the measured variable y_i uncertainty. If the airlift pump efficiency (that is given

by Equation 2 is considered, the efficiency uncertainty will be computed using the following equation:

$$U_{\eta}^2 = \left(\frac{\partial \eta}{\partial \dot{Q}_w} \right)^2 U_{\dot{Q}_w}^2 + \left(\frac{\partial \eta}{\partial (L-H)} \right)^2 U_{(L-H)}^2 + \left(\frac{\partial \eta}{\partial \dot{Q}_a} \right)^2 U_{\dot{Q}_a}^2 + \left(\frac{\partial \eta}{\partial P_{in}} \right)^2 U_{P_{in}}^2 \quad (5)$$

where, $U_{\dot{Q}_w}^2$, $U_{\dot{Q}_a}^2$, $U_{(L-H)}^2$ and $U_{P_{in}}^2$ are water and the airflow rates uncertainties, the water lifted level, and the inlet pressure, respectively. When the derivative terms are substituted into Equation 5, the following equation is obtained:

$$U_{\eta}^2 = \left(\frac{\rho g (L-H)}{\dot{Q}_a P_{atm} \ln(P_{in}/P_{atm})} \right)^2 U_{\dot{Q}_w}^2 + \left(\frac{\rho g \dot{Q}_w}{\dot{Q}_a P_{atm} \ln(P_{in}/P_{atm})} \right)^2 U_{(L-H)}^2 + \left(\frac{-\rho g (L-H) \dot{Q}_w}{\dot{Q}_a^2 P_{atm} \ln(P_{in}/P_{atm})} \right)^2 U_{\dot{Q}_a}^2 + \left(\frac{-\rho g (L-H) \dot{Q}_w}{\dot{Q}_a P_{atm} (\ln(P_{in}/P_{atm}))^2 P_{in}} \right)^2 U_{P_{in}}^2 \quad (6)$$

By using Equation 6, the relative uncertainty in the efficiency of the airlift pump is found to be $\pm 0.18\%$.

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NOMENCLATURE

H	- water level in the submergence tank	[m]
L	- length of the riser pipe	[m]
J	- superficial velocity	[m/s]
P	- pressure	[N/m ²]
Q	- flow rate	[m ³ /s]

Greek symbols

ρ	- density	[kg/m ³]
α	- void fraction	
η	- efficiency	[%]

subscript

a	- air
atm	- atmospheric
in	- injection
tp	- two phase

w - water

УТИЦАЈ СИСТЕМА ЗА УБРИЗГАВАЊЕ ВАЗДУХА НА ПЕРФОРМАНСЕ ВАЗДУШНЕ ПУМПЕ

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Израђен је и тестиран нови пројекат система за убризгавање ваздуха код ваздушне пумпе. Пумпа има кружни попречни пресек и састоји се од три дела: усисне цеви, система за убризгавање и вертикалног црева. Пречник вертикалног црева је 31,7 мм а дужина 2 м. Перформансе пумпе су испитиване на основу различитих дубина потапања (0,15-0,3) и брзине протока убризганог ваздуха (1,65 кг/х – 13,32 кг/х).

Резултати показују да брзина протока ваздуха и дубина потапања имају значајан утицај на капацитет и перформансе пумпе. Такође је утврђено да се најбоља искоришћеност пумпе постиже при двофазним режимима протока (Slug Flow и Slug-Churn Flow). Највећа искоришћеност је остварена при дубини потапања од 0,3. Значајно побољшање брзине протока воде је постигнуто коришћењем постојећег дизајна убризгавања ваздуха у поређењу са конвенционалним системом убризгавања код ваздушне пумпе.