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A Comprehensive Review of Design and Operational Parameters Influencing Airlift Pump Performance

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ABSTRACT

Airlift pumps find extensive applications across diverse sectors, such as petrochemical and oil industries, mining and hydraulics, abrasive chemicals and hot liquids, and the medical field. Despite their inherent inefficiency, these pumps offer numerous advantages over mechanical counterparts, including reduced initial and maintenance costs, expedited installation, minimized space requirements, and a simplified design and construction. Investigating these systems often presents challenges due to the majority of the flow through the pipe consisting of gas–liquid two-phase flows. Given the numerous influential components in airlift systems, adopting a comprehensive approach is essential. This review article delves into the recent advancements in airlift pump systems, examining their historical context, operation, and diverse applications. Specifically, the article focuses on the design and operational factors that impact the performance of airlift pumps.

1. INTRODUCTION

The airlift pump is a simple device without moving parts, designed for elevating fluid mixtures. These pumps are notable for their ability to transport liquids and gases using compressed air, rendering them suitable for scenarios where conventional pumps are not feasible, such as deep wells with challenging depth and high pressure conditions. Airlift pumps also prove effective for pumping fluids incompatible with traditional pumps, including viscous liquids and liquids containing solids [1]. Moreover, their relatively low-cost and straightforward operation make them a popular choice across a wide range of applications.

Airlift pumps exhibit practical benefits and adaptability across various applications, surpassing conventional mechanical pumps. Their applications span industries such as petrochemical, oil, medical, and aquaculture [1-5]. The operating principle of an airlift pump involves utilizing buoyancy force to propel a two- or three-phase fluid through a vertical pipe that is partially submerged in the fluid, with openings at both ends. Owing to the large pipe size, capillary forces exert minimal influence on the process [1, 6]. Analyzing these systems is complicated due to the challenges associated with modeling two-phase flow, as the majority of the flow through the pipe consists of two phases. In light of the numerous influential factors in airlift systems, a comprehensive approach is essential when considering these characteristics [2, 6].

Despite offering lower efficiency than conventional mechanical pumps, airlift pumps provide several practical advantages, including reduced initial and operating costs, ease of installation, resistance to clogging, minimal space requirements, simplified construction and design, effortless flow rate control, and versatility across various applications [1, 6, 7]. Figure 1 illustrates the research objective and scope of all stages of this study.

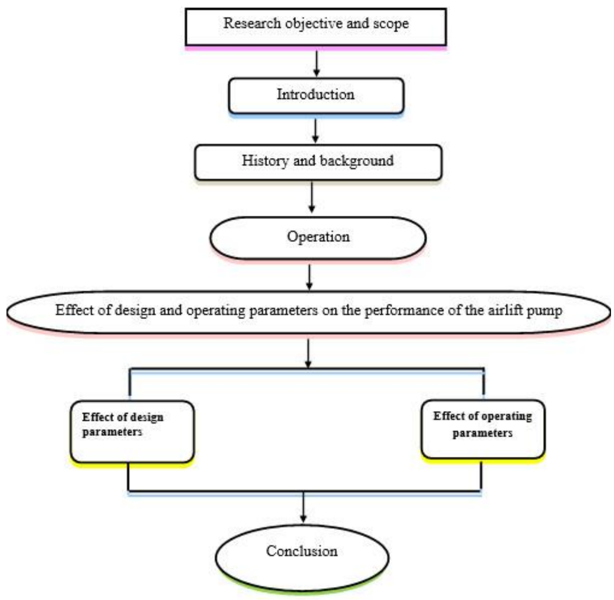

Figure 1. Flowchart for present work

The authors' work is of interest as it offers insights into the influence of operational and design parameters that significantly impact the operation and efficiency of airlift pumps. Research on airlift pumps has primarily focused on their applications in diverse industries, including mining, wastewater treatment, and aquaculture. Studies have demonstrated the cost-effectiveness and energy efficiency of airlift pumps as alternatives to traditional pumping methods.

Furthermore, research has shown that airlift pumps can be utilized for pumping liquids with high solids content, such as sewage and sludge. However, these pumps may not be suitable for high-pressure applications or for liquids with low densities. Several theoretical and practical studies have been conducted on the design and optimization of airlift pumps for specific applications.

2. LITERATURE REVIEW

The inception of the airlift pump can be traced back to 1797 when Carl Emanuel Löscher, a German engineer, developed the first prototype. Its first practical implementation in the United States occurred in 1846, when the oil industry in Pennsylvania adopted the airlift pump technology [6, 8]. Although Professor W. H. Echols provided an early analytical foundation for the subject, the data obtained from his series of experiments could not be directly incorporated into the formulae developed in the current study. A comprehensive summary of the knowledge up to that point can be found in an article titled "Air-Lift Pump," published in the June 8, 1893 issue of Engineering News. However, the article does not delve into the principles governing airlift pump operation beyond acknowledging its functionality.

Prior to the mathematical analysis undertaken by Harris [1], only the effort made by Professor Echols in 1891 at the University of Virginia's Philosophical Society had attempted to scrutinize the topic mathematically. Harris aimed to explore pertinent concepts and examine the inner workings of the air-lift pump, with the objective of deriving a logical formula for intelligent pump construction and laying the groundwork for future experimentation. By applying the conservation of energy principle, an expression was determined for the absolute velocity of water passing through the bubble and the height difference between the water inside and outside the tube, taking into account the buoyancy of the bubble as an upward force.

Subsequent research on airlift pumps was conducted by several investigators, including Ivens [7], Ward and Kessler [9], Stepanoff [10], and others. Stenning and Martin [11] were the first to introduce the fundamental principles of two-phase flow and momentum in their investigation of airlift pumps with relatively small diameters and low lifts. All subsequent research relied heavily on the analytical model initially developed by Stenning and Martin [11]. A one-dimensional study of airlift pump performance in shallow water was established, considering the effects of friction and slip between gas and liquid phases. The theory successfully predicted the performance characteristics of these devices and justified the empirical design principles proposed in earlier works. The one-dimensional theory was deemed adequate for analyzing pneumatic lift pump performance, although additional data were required to determine effective slip ratios and friction factors for larger pumps.

Griffith [12] endorsed the investigation, commending the use of slip models and the foundation in slug flow and flow systems. As slug flow is often observed in airlift pumps, the model provided a valuable basis for subsequent studies. Delano [13] built upon this foundation in his investigation of bubble pumps. Subsequent analytical and experimental studies aimed to enhance airlift pump performance were undertaken by researchers such as Todoroki et al. [3], Castro et al. [8], Parker [14], Kouremenos and Staicos [15], and Oh and Lee [16]. Additional studies examined transitional behavior of gas slug bubbles [17], fluctuating flow characteristics in airlift pumps [18], evaluation of airlift pump performance [19], model development [20, 21], exergy and entropy analyses [22, 23], and the impact of various parameters on airlift pump performance [24-31].

3. OPERATION

Airlift pumps are straightforward machines that operate using pressurized air or gas. An airlift pump consists of a vertical tube open at both ends partially submerged in a liquid [6]. Within the pipe and under the surface of the liquid, an amount of gas is discharged. Assume the pipe is too big for capillary forces to regulate. The bubble rises. It is important for the operation of the pump to have both the impact of the buoyant force that the bubbles exert and the differential pressure that occurs between the injection position and the output location of the pump. The successful operation of these systems is based on both of these characteristics. Since gas has a lower density than liquid, it quickly rises to the top of the pipe after being injected into the bottom of the pipe in its gas phase form. This allows the gas to be injected into the pipe. The liquid phase is forced to travel in the same direction as the rising gas phase due to the pressure and inertia of the gas phase. The gravitational, inertial, and buoyancy forces are the primary ones that are at work in the airlift pump and how they interact with the air and water combination. While the gravity force works as an opposing force, the buoyancy force is the one that does the lifting. As the bubble rises, the liquid that is above it must go through its center in order to reach the level below. As a result, the bubble will not be able to take up the whole cross section of the pipe. In order for the bubble to ascend, it must first become stretched out so that the liquid can flow downward. The absolute velocity of the liquid must meet a particular threshold in order for it to squeeze through the opening left by the bubble as it travels downward. The fact that this speed is there proves beyond a reasonable doubt that there is an uneven head somewhere above. When the pushing forces are strong enough, the liquid travels down the pipe and is discharged at a level that is higher than the level at which it was first immersed. If this does not occur, the liquid will only be raised to the level at which these operating forces will be balanced [1, 6].

In the vast majority of published works, gas–liquid two-phase flow regimes are often broken down into four distinct flow patterns. These flow patterns are referred to as bubbly, slug, churn, and annular regimes, respectively. It has been seen that the two-phase flow regime in the up-riser pipe may result in a variety of different circumstances taking place. Because the air–water combination in the bubbly flow regime is less dense than the single-phase water, it rises to the top of the structure as the bubbly flow regime progresses. The surrounding water is pushed upward to the higher level of the pipe as a result of the water's inertia being displaced by the air bubbles that have been injected. According to the findings of the observations, the size of the inertia force exerted by the bubbles is not sufficiently great to be able to move the water that is all around them a substantial distance. It has been determined that the bubbly flow cannot be employed in the pumping process according to the findings of the previous investigation. The primary justification for this hypothesis is the observation that, under these conditions, the pushing power is insufficient to elevate the water in the opposite direction of gravity. As a result, the bubbly flow can only be used in the airlift pump when large submergence ratios are present. In contrast, for the other flow patterns, such as slug and churn flows, enormous air bubbles function as pneumatic pistons and push the water that is trapped in the slug between them as they move it through the pipe. This is especially true for slug flows. Because of the suction that is caused by the rapid movement of the bubbles, the air bubble not only pushes the water in front of it, but it also pulls water from behind it. In the domain of annular flow, the shear tension at the air–water interface is directly connected to the inertia of high-velocity air that is pushing the water to rise higher. It is required to have a greater air velocity in order to generate an adequate amount of friction force; as a result, the airlift pump is not very effective while operating in an annular flow. It can be shown that three of the primary regimes specifically, slug, churn, and annular flows force the water rather than displace it. As a result, these regimes are more appropriate than the bubbly flow regime in airlift pump, particularly at low submergence ratios [6].

4. APPLICATIONS

One of the first applications of the airlift pump was in mining and hydraulics to raise water from wells and mines. Since sand, silt, gravel, and ponds in the water don't provide any impediments to the functioning of the pump, it's been proposed that it's also good for dredging. It is effectively used for the production of sulfuric acid with high specific gravitates and is well suited for usage in ore leaching works, vinegar works, sugar refineries, dye works, paper pulp works, and other similar establishments. Elevating corrosive chemicals and heated liquids is another use [1-3, 32]. This method of pumping is inefficient but has several benefits over mechanical pumps, including cheaper initial and maintenance costs, quick installation, modest space requirements, and simple design and construction. Airlift pumps may be used to pump corrosive, abrasive, explosive, poisonous, sandy or salted, viscous liquids such hydrocarbons in the oil sector, shaft and mine drilling, under-sea mining, and bioreactors. They don't need lubrication and can remove sludge in sewage treatment facilities [6, 33]. They fit in oddly shaped wells when conventional deep well pumps don't. Recent years have seen an increase in the use of airlift pumps for the transport of boiling liquids that undergo phase changes [34]. Airlift pumps can be used in cages, floating raceways, closed or recirculating systems, pond de-stratification or aeration, return-activated sludge, waste-activated sludge, aerobic digester supernatant return, underwater exploration, dredging river estuaries and harbors, mining minerals from ocean beds, and coal recovery in mine shafts [35]. They are also useful in a broad variety of applications in the chemical and nuclear industries. In petroleum fields, airlift pumps are used in order to raise oil from wells that are considered to be weak [24]. It is possible to make a profit by bringing deep waters from nutrient-rich seas and oceans to the surface, where they may be used to feed phytoplankton and maintain fishing grounds that are among the most productive in the world [28]. There are also medical uses that can prevent certain internal body components from being damaged so that they may be donated into another human body [4, 36].

5. EFFECT OF DESIGN AND OPERATING PARAMETERS ON THE PERFORMANCE OF THE AIRLIFT PUMP

Airlift pumps are equipment that finds widespread use in a variety of industrial contexts. After investigation, analysis, and correction work on the airlift pump theory by several researchers such as Harris [1], Purchas [2], Ivens [7], Swindin [37], Stenning and Martin [11], Spotte [38], Ward and Kessler [9], Hervol and Pyle [39], and others, other researchers studied the factors influencing the work of airlift pumps These pumps' performance may be affected by a variety of parameters, which can be broken down into two distinct classes. The first category consists of design characteristics such as the length and diameter of the pipe, the angle at which the upriser pipe tapers, and the submergence ratio. The submergence ratio is the ratio of the length of the upriser that is submerged to the overall length of the upriser. The second category is made up of operational features like bubble diameter, gas flow rate, bubble distribution, and gas pressure at the input (see Figure 2).

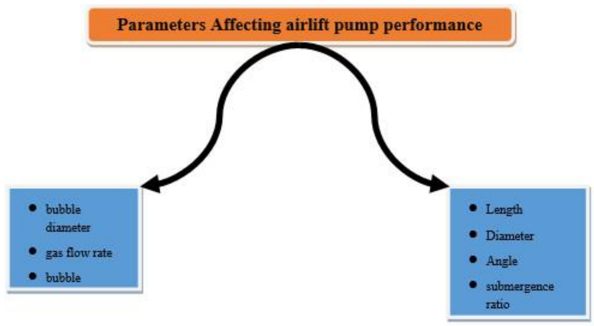

Figure 2. Governing parameters of an airlift pump

5.1 Effect of design parameters

Stenning and Martin [11] established two-phase flow and momentum for studying low-lift air-lift pumps. The internal diameter of the tubing that was used to manufacture the pump was 1 inch. The pump had a total height of 168 inches when it was assembled. The air was introduced to the pump at a point close to its base. The submergence of the pump was measured at H/L ratios of 0.707, 0.629, 0.532, and 0.442 respectively. After beginning with zero and working up to the highest possible value in discrete stages, the rate of air flow was steadily raised, and the water flow rate was determined for each value of air flow. The pump's mean static pressure is shown versus water and air flow rates. Each value of h/l creates a maximum water flow rate. Beyond this point, increasing airflow reduces waterflow. The pump slugged at low airflow rates. As airflow increased, foam flow was detected. The model accurately predicts device performance.

Todoroki et al. [3] derived the basic equation of air-lift pump performance from a simple momentum equation. Throughout the duration of the studies, a pair of pipes made of acrylic resin with internal diameters of 28.3 mm, 7.5 m long and 50.6 mm, 6.8 m long were monitored. Until a specific air rate is attained for a particular submergence ratio, no discharge occurs; however, after the air rate reaches the critical value, the discharge rises quickly with rising air rate up to a maximum. On the other hand, after it has reached its maximum, the discharge drops while the airflow is increased. At a constant air flow rate, the discharge rises as one would anticipate as the submergence ratio rises. In this part of the process, the outcomes predicted by the analysis are compared with the experimental data of both the authors and of other investigators. In the ranges of 25 mm to 100 mm for D, 4 m to 42 m for L, and 0.4 to 0.8 for submergence ratio, the model is in good agreement with the Experimental results.

Castro et al. [8] studied short, small-diameter airlift pumps. Pipes with a smooth exterior were used, ranging in length from 30 centimeters to 3.7 meters. These pipes had an inside diameter of 1.70, 2.50, 5.25, and 7.73 centimeters, respectively. In this investigation, submergence values of 40, 50, 60, and 70% were employed. These values were derived from the ratio of h_s to (h_s+h_d). The pump's foot piece is fed compressed air. Calibrated rotameters measure airflow. Temperature and pressure measurements adjust the rotameter output for compressibility. The air-water combination goes via the education pipe and out of the headpiece. A weigh tank and stopwatch measure water flow. The experimental investigation found that, for a particular pump configuration, the maximum pumping rate occurs at a specified air flow rate. Optimal air flow rates reduce pumping rates. The pump's usable range (air flow rates across which water flow rate stays constant) diminishes with decreasing diameter and increasing submergence. These results show that education pipe length influences low lift pump pumping rate.

Parker [14] constructed a small air lift pump from a glass tube with a diameter of 24.3 millimeters, which has been evaluated with two distinct designs for the air injection foot piece (see Figure 3). In the air-jacket design, air was injected radially inwards, while in the nozzle design, air was injected axially at the intake to the riser. Both designs were intended to inject air. In the air-jacket foot piece, the orifice diameter was 1, 2 and 6 mm and the number of orifices were (4, 8, 16, 32), (4, 8, 22) and (1), respectively, and in the nozzle foot piece, the orifice diameter was 1, 2 and 6 mm and the number of orifices were (4, 8, 16, 24, 36), (4, 8, 6) and (1). The final setup produced a pump that measured a total of 1.278 m in length and had a submergence of 71.1 cm. Therefore, the ratio of depth submerged to total length was 0.556. The bubbles quickly coalesced into slugs, thus flow patterns varied from bubbly-slug at low air flow rates to slug-annular at high air flow rates. Air-jacket foot piece and injection hole configurations didn't affect performance. With the nozzle foot piece, orifice area affected water pumping. The lowest hole examined yielded the maximum pumping rate, and it kept rising. With the air-jacket design, pump discharge was independent of injection hole number and size. At high air flow rates and small orifice area, the nozzle design had increased pumping capabilities but low efficiency.

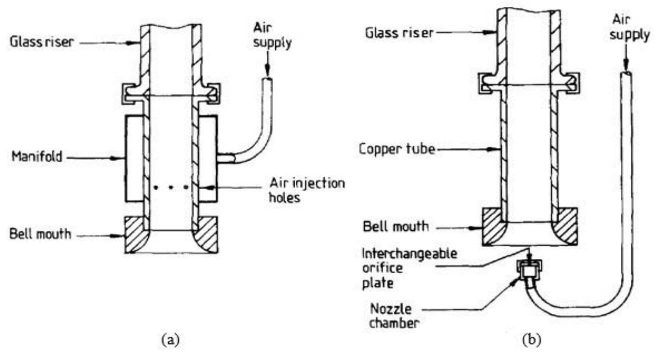

Figure 3. Details of the foot piece designs tested: (a) the air-jacket injector, (b) the nozzle injector

Kouremenos and Staicos [15] tested lifting liquid using two-phase flow in small air-lift pumps. Plexiglass tubes with bore diameters of 12, 14.5, 16, and 19.23 mm were used in the construction of four miniature test pumps. The usual length of the tubes was 933 millimeters. For the purpose of generating and sustaining slug flow in the vertical riser tube, an air injection system was developed. It has been determined that momentum conservation considerations may be used to develop an equation that matches quite well with the data that has been acquired. The volumetric flow rate of the water, also known as Q_w, was measured for a variety of air flow rates (Q_a), depending on which combination of pump, air supply tube, and submergence ratio was being used (0.7, 0.65, 0.6, 0.55). The data indicated a reversal in the pump's characteristic curve, which had been noticed by earlier researchers but could not be anticipated by correlations using fixed friction parameter and slip ratio values.

Morrison et al. [40] studied gas flow rate and diffuser design on air lift pump flow and efficiency. characterized by pump flow zones. Local liquid velocity, void fraction, average gas and slip velocities, and static pressure were measured along the pipe. The air supply, test, and return pipes comprise the air lift pump. Flow tests were conducted in a 38.1-mm-diameter, 3.04-m-long vertical test pipe. The work used air and water. Two diffusers with various air entry ports were tested. When comparing the two different diffuser designs, the performance of the air lift pump was evaluated based on the volume of air that passed through them. Data showed that air volumetric flow rate affects efficiency. At low flow rates, air couldn't raise water to the full lift efficiently. At high flow rates, high air flow increased air-water slip velocity and decreased pump efficiency. The time-averaged local liquid velocities along the pump's lift section were greater for the eight-port diffuser than for the four-port diffuser, and the air-to-water slip velocities were reduced. After reaching a maximum, pump efficiency declined with air flow rate. The eight-port diffuser was more efficient overall, especially in bubbly and slug flow. At a flow rate of 1 m^3/h, the pump was the most efficient.

Reinemann et al. [41] studied tube diameter's influence on vertical slug flow. The inside diameter of the riser tubes ranges from 3.18 mm to 19.1 mm, and their length is 1.80 meters. Airlift pump theory is extended to these tube diameters by considering surface tension's influence on bubble rise velocity. After the flow had steadied for each experiment, volumetric air and water flow rates, bubble rise velocity, submergence, and lift height were measured. Pressure drop measurements across calibrated orifices calculate air and water flows. Timing a bubble over a specified distance determines bubble rise velocities in stationary and flowing liquid. Changing reservoir fluid levels changed submergence ratios. A diaphragm-type compressor pumped air into the system. A valve between the compressor and flow measuring aperture regulates air flow. For all tube diameters evaluated, bubble rise velocity in still fluid matched the prediction equation and previous results. Tube diameter didn't affect pump efficiency or submergence ratio. This is true for air-water systems with tube diameters of >20 mm and low surface tension. As tube diameters become smaller, surface tension increases airlift efficiency and submergence ratio.

Wurts et al. [35] investigated the effects of the diameter and depth of air injection on the pumping rate of an airlift pump. PVC and polyethylene pipes, PVC fittings, stainless steel ring-clamps, and a centrifugal blower were used in the construction of airlift pumps. It was calculated how much of a pumping capacity floating airlift pumps with a centrifugal blower generating 1.9 kw could provide. PVC pipes with inner diameters of 7.6, 10.2, and 15.2 centimeters were used to construct airlift pumps that were 185 centimeters in length. At 50, 65, and 80 centimeters below the discharge outlet, air was injected via a pipe with an inner diameter of 2.5 centimeters and a length of 14.2 meters. The volume of air flowing through the system was changed between 71 and 324 liters per minute (L/min), and the equivalent volume of water flowing through the system was monitored. The diameter of the pipe, the amount of air flow, and the depth of the air injection all contributed to an increase in the individual airlift pumping rates. For each variable that was investigated, individual airlift pumping rates varied anywhere from 66 to 225 liters per minute of water.

Khalil et al. [24] conducted a series of experiments to test the performance of air lift pumps under a variety of submergence ratios, utilizing a variety of air injection foot piece designs. This goal required the development and testing of an air lift pump that had a riser that was 200 cm in length and had a diameter of 2.54 cm. For the purpose of this study, the following submergence ratios were utilized: 0.75, 0.7, 0.6, and 0.5. At each of the four submergence ratios and each of the three air injection pressures, each of the nine possible air injection foot piece designs was used. In order to cover the whole experimental range, a region of 10 millimeters square was selected and partitioned into nine different injection hole configurations (1, 2, 3, 4, 6, 15, 25, 34, and 48 holes). Different injector types and submergence ratios affected pump performance in experiments. The disk with three holes performed well at practically all submergence ratios. A suitable disk design exists for maximum water flow at any submergence ratio. The most efficient submergence ratio was 0.75. Airflow rate, lift ratio, and injection pressure affect pump capacity and efficiency.

Oh and Lee [16] investigated performance data of airlift pumps of relatively short length and small diameter for mariculture operations. In order to collect the necessary information, a set of experimental instruments with inner diameters ranging from 2.1 to 3.4 centimeters and lengths ranging from 40 to 300 centimeters was devised and built. The whole system was outfitted with instrumentation that could monitor water flow rate and air flow rate, in addition to water temperature, air temperature, and pressure. These variables were all measured throughout the system. The findings of this research have a strong correlation with the data on high-lift pumps in the sense that, for any given pump shape, the greatest amount of water flow will occur for a given air flow rate. If you operate the pump with airflows that are either higher or lower than this optimal flow rate, the pumping rate will be reduced. The flows that are optimal for low-lift pumps are quite different from the flows that are optimal for high-lift pumps. However, as the length of the pump increases, the pumping rate for low-lift pumps becomes closer and closer to that of high-lift pumps.

Kassab et al. [42] looked into the effect of the inlet injection region on the air lift pump experimentally because the initial conditions of the pump have a big effect on how well it works. A vertical pipe made of acrylic measuring 24 millimeters on the inside and four meters in length makes up the trial equipment for the air lift pump. Flow visualization is used extensively throughout all of the experimental testing in order to provide an inside view of the differences in flow patterns at the initial injection region as well as along the upriser pipe of the air lift pump. This allows for a more accurate interpretation of the results of the testing. To begin, validate the outcomes of the experiment that were put up by comparing these experimental results with internationally approved data sets. This will allow you to determine whether or not the experiment was successful. Experimental data matches other researchers' flow map. Any change in air system resistance affects pump efficiency but not water production. When compared to the link between water and air flow rates, the sensitivity of the efficiency of the air lift pump to any change in the design or operational parameters is far more evident. The upward injection method has a higher peak efficiency of 34.7% than the downward injection method, which has a peak efficiency of 29.7%, and the side injection method, which has a peak efficiency of 28.9%. Additionally, the larger injector inner diameter has a maximum water capacity of 928 kg/h, which is higher than the 823 kg/h water mass flow rate of the smaller injector inner diameter.

Hanafizadeh et al. [26] performed a numerical investigation of the performance of an airlift pump for a variety of submergence ratios and variations in the diameter of the upriser pipe. For an airlift pump with a riser length of 914mm and three different diameters (6, 8, and 10mm) and seven distinct tapering angles (0°, 0.25°, 0.5°, 1°, 1.5°,2°, and 3°), various submergence ratios (0.4, 0.6, and 0.8) are modeled and analyzed (see Figure 4). The numerical predictions correspond with published experimental data. At fixed submergence ratios, decreasing bubble diameter increases liquid mass flow rate. The pump's performance improves with smaller bubbles and a steeper upriser pipe. The 3° tapered upriser pipe delivers the maximum efficiency at practically all submergence ratios. At constant airflow rates, pump efficiency improves with submergence ratio. In an airlift pump with a narrow intake diameter, the bubbly-slug regime lifts the most water. Pumps with lower upriser pipe intake sizes operate in a restricted range, but increasing the cross-sectional area extends the range.

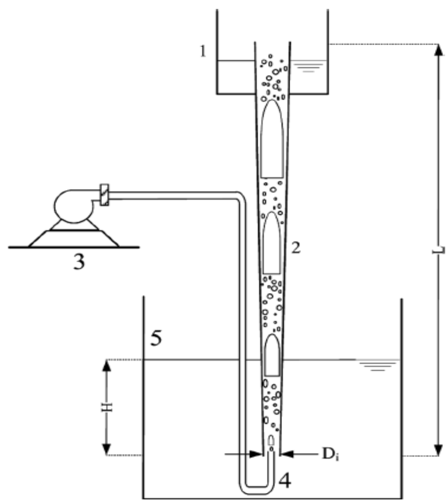

Figure 4. Schematic of airlift pump

Hanafizadeh et al. [31] studied airlift pumps with a vertical riser length of 914 mm, starting diameters of 6 and 8 mm, and step heights from 0.2 to 0.9 m in a 0.6 submergence ratio (see Figure 5). Results demonstrate step airlift pump outperforms regular kind. In constant gas flow rate, there is a precise step height and secondary pipe diameter that may improve pump performance. The optimum phase is when slug flow changes to churn flow in the pipe. The pump lifts the most liquid in the slug flow regime, hence it's also the most efficient. The numerical findings matched the experimental data well. Step airlift pump is more efficient than continuous pipe diameter pump.

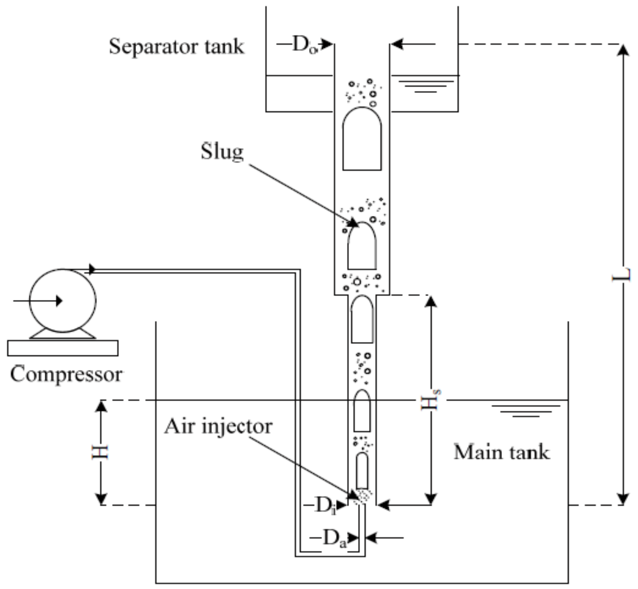

Figure 5. Schematic of airlift pump with step geometry

Tighzert et al. [27] conducted an experimental study on an air-lift system to determine how the submergence ratio and gas flow rate affected the induced liquid flow rate, efficiency, and void fraction. The studies were carried out using a clear riser pipe that was 3.1 meters in length and had an inner diameter of 33 millimeters. The progression of the flow rate of liquid as a function of the flow rate of air reveals an initial stage of exponential growth, which is then followed by a stage in which the flow rate of liquid remains constant regardless of the submergence ratio. The slug flow and the churn flow have been connected to these operating regimes in an analogous manner. Air-lift pump performance is greatest during slug flow and slug-to-churn flow transition. The smallest superficial velocity ratio of the phases correlates with optimum pump efficiency. Air-lift efficiency improves with air flow rate up to a maximum, then transitions to slug flow. Submergence enhances pump efficiency. Submergence ratio for air-lift pump systems should be between 0.4 and 0.75. This research achieves 0.75. Beyond this, it declines. Increasing submergence ratio at a constant air flow rate reduces void fraction. Drift-flux model best predicts air-lift void fraction.

Fan et al. [28] used both practical and theoretical analyses to show that pumping nutrient-rich deep water to the surface to feed phytoplankton might improve the performance of an air-lift pump for artificially upwelling ocean water. Experiments are carried out at a single submerged depth, with a diameter of 0.4 meters and a length of 28.3 meters, using four distinct air injection nozzle designs and varying the volume flow rates of the injected air (see Figure 6). A theoretical model is given considering the flow characteristics of air-lift artificial upwelling. The experimental results validate the model's performance. The results indicate that the air-lift upwelling model can predict pump performance. The study found that pump capacity and efficiency depend on the upwelling pipe's geometry, air flow rate, air injection technique, and vertical water density distribution. Due to less friction, pipe diameter enhances upwelling efficiency. Air injector design affects upwelling efficiency.

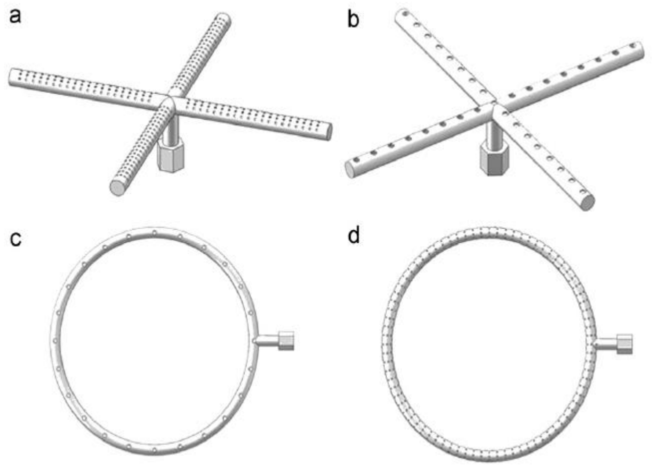

Figure 6. Photos of the air injection nozzles: (a) NozzleNo.1, cross, 384holes; (b) NozzleNo.2, cross, 24holes; (c) NozzleNo.3, circular, 24holes; (d) Nozzle No.4, circular, 384 holes

Tang et al. [29] studied the effect of local pipe mechanisms at the point of flow pattern on water flux and lifting efficiency for airlift pump performance with different air flow rates and submergence ratios (0.32, 0.4, 0.6). The model of the air lift-lift pump's efficient operation was constructed on the basis of the theorem for the conservation of energy. The pipe has a diameter of 40 millimeters, a length of 1.2 meters, a curvature radius of 40 millimeters, a vertical height of 300 millimeters, and it is joined by a flange as well as a straight pipe section. In every pipe construction, water flux and efficiency rise with air flow rate, peak, and then decline when the volume value is between 8– 10m3/h, lifting effect is optimal. Riser tube construction and pipe bend placement affect air-lift performance considerably. In the same circumstances, straight pipe of the same diameter performs better than bent pipe. When local pipe bends are added in the lower air-lift head, air-lift pump performance declines significantly.

Ahmed et al. [43] provided a detailed presentation on the findings of an in-depth experimental examination into the impact that various techniques of air injection have on the performance of airlift pumps (see Figure 7). The influence of air and water two-phase flow patterns, as well as the interaction between phases, is given here. All of the tests were carried out with a submergence ratio of 0.5, and the pipe used was a two-meter-long pipe made of clear acrylic with an inner diameter of 31.75 millimeters for both steady and pulsating air injection. The current airlift pump makes use of a number of different air injectors that have been specifically built to permit air injection in a radial direction, an axial direction, dual (radial and axial), or dual (radial and axial) direction, or with a swirl effect at the air input ports. Additionally, two air injection modes—slow and pulsing—at various injection frequencies are explored at various two-phase flow patterns. These modes include steady and pulsating air injection. The study revealed that airlift pump performance depends on both air injector design and injection technique dynamics. Dual injection beat axial and radial injections in steady air injection regime due to its excellent efficiency throughout the whole air mass flow rate range. In pulsing injection, the liquid flow rate increased at lower air injection rates and the maximum efficiency point changed. The swirl injector functioned like a radial or axial injector, but it didn't supply greater water flow or use less power to raise water. Pulsating axial injection at 1 Hz is 60% more efficient than continuous axial injection and 24% more efficient than dual injection. Synchronizing axial and radial injection ports improves the performance of dual-injector airlift pumps. This configuration improves compressed air usage, axial air penetration, and water reverse flow in the riser pipe. Changing the swirl angle didn't affect the airlift pump's performance.

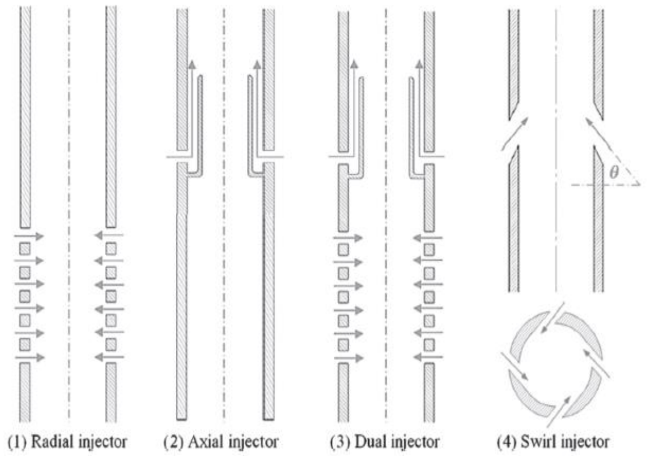

Figure 7. Schematic of air injectors design

Abou Taleb and AI-Jawdat [44] studied the air lift pump's submergence ratio and air jacket. Five submergence ratios and three air jacket kinds were employed. Each air jacket has holes drilled equally around the inner pipe's circumference, with the total hole area maintained constant. By using three different sizes of drilled holes—2 millimeters, 4 millimeters, and 6 millimeters—respectively for the A1, A2, and A3 air jackets, the surface area of the air bubbles may be altered. The lift pipe diameter is 5.08cm and the length is 20 cm. Researchers have discovered that an increase in the submergence ratio results in an increase in the water flow. In addition to this, it was discovered that the minimum air flux necessary for the pump to begin discharging water lowers as the ratio of water to air under the pump grows. The air lift pump had the best possible performance when it was equipped with an air jacket that had a hole of 4 millimeters in diameter. The Air jacket, A2 has the highest water flux and efficiency for the same amount of air flow as it does.

Kassab et al. [25] conducted an analysis of the performance of the airlift pump using nine different submergence ratios from 0.2 to 0.75, three risers of varying lengths of 175, 275, and 375 cm, and nine different air injection pressures with a 25.4 mm inner diameter. Additionally, the pump was evaluated using a variety of different two-phase flow patterns throughout the testing process. The results of this research led to the development of a conceptual model that took into consideration the flow patterns that occurred within the pump's optimal efficiency range of operation. Capacity and efficiency depend on air mass flow rate, submergence ratio, and riser pipe length. As the submerged ratio rises, pump efficiency at the same airflow rate improves. In slug and slug-churn flow regimes, air-lift pumps operate most efficiently. The suggested model predicts liquid volumetric flux for bubbly, slug, and churn flow patterns.

5.2 Effect of operating parameters

Hanafizadeh et al. [45] explored the impacts that the flow regimes had on the performance of an airlift pump experimentally. The data were collected for a two-phase flow of air and water in a vertical pipe with a diameter of 50 mm, an aspect ratio of 120, and a length of 6 m. Image analysis is the method that is used in this research project to conduct an experimental investigation of the gas and liquid upward two-phase flow regime that occurs in the upriser pipe. Using the information obtained from the high-speed camera, the velocity of the gas phase can be determined in a two-phase flow. Slug flow, churn flow, and annular flow are the three primary flow regimes that may be visually identified in the air lift pump. Due to low buoyancy force, bubbly flow can't raise the water phase. In the bubbly flow regime, the airlift pump could only lift water at high submergence ratios. Other flow regimes could lift water at lower submergence ratios. Airlift pump performance was tested and compared to Hewitt and Roberts' flow regime map. For different submergence ratios, the pump's efficiency was determined. The submergence ratio affects efficiency. Slug flow was the best flow regime for airlift pump performance.

Awari et al. [19] tested the performance of the airlift pump for two-phase mixes of air and water under a set of operating and design settings that were previously defined. It has been investigated how the performance of an air-lift pump is affected by a number of different operating and design characteristics. The influence of the air pressure on the discharge of a pump is explored for a variety of nozzle sizes of 3.8, 4, and 5.28 mm, with the diameter of the rising main and the immersion ratio held constant at d=2.5 in and 1.21, respectively. It has been found that a rise in air pressure initially generates an increase in the discharge of a pump for all nozzle diameters, but that this increase is followed by a drop in the discharge. The air pressure that works best for each nozzle will be unique to each nozzle. It is also abundantly evident that the discharge will be larger when the constant air pressure is higher and the nozzle diameter is larger. So, a nozzle with a bigger diameter can help increase the flow to its fullest capacity at any air pressure that may be needed. The effect of diameter, the relative mass flowrates, and immersion ratio was also studied. Experiments show that a bigger rising main improves pump efficiency. Immersion ratio improves pump efficiency.

In conclusion, the comparative analysis of influential parameters used in airlift pumps has produced Table 1, which provides a summary of their conclusions.

Table 1. A comparison of different factors affecting airlift pump performance

Author	Country	Study	Parameters	Variable	Remarks
Stenning and Martin [11] 1968	U.S.A.	Analytical & Experimental	1.d=2.54cm 2.L=4.2672m 3. submergence ratio=0.707, 0.629, 0.532, and 0.442	Q_g & Q_l	One-dimensional theory seems to work well for air-lift pump performance analysis. Larger pump slip ratios and friction factors require more data.

Todoroki et al. [3] 1973	Japan	Theoretical & Experimental	1.d= 28.3 mm, L=7.5 m 2.d= 50.6 mm, L=6.8 m 3.submergence ratio=constant	Q_g & Q_l	1.Momentum equation determines air-lift pump performance. 2. 25≤D≤100 mm, 4≤L≤42 m, and 0.4≤submergence ratio≤0.8 demonstrate good agreement with experimental results.
Castro et al. [8] 1975	U.S.A.	Experimental	1.d= 1.27-7.62 cm 2.L= 30cm-3.7 m	Q_g & Q_l	1.Low lift pumps provide optimal air flow for maximum water flow. Operating the pump with higher or lower air flow reduces water flow. 2.This study's results match high-lift pump data.
Parker [14] 1980	New Zealand	Analytical & Experimental	1.d=24.3mm 2.L=1.278 m 3.submergence ratio=0.556	air injection foot piece designs	1.The air lift pump's air-jacket foot piece discharge characteristic is independent of the number and size of air injection holes. 2.Peak efficiency was achieved with a low air flow rate and a large orifice area.
Kouremenos and Staicos [15] 1985	Greece	Experimental	1.d=12-19.23mm 2.L=933mm 3. submergence ratio=0.7-0.55	Q_a & Q_w	Based on momentum conservation considerations, an equation has been derived, which correlates well with the measurements obtained of small diameters.
Morrison et al. [40] 1987	Texas	Experimental	1.d=38.1-mm 2.L=3.04-m	diffuser design	1.The air flow rate and the way the diffuser is made affect how well the air lift pump works. 2.An increase in diffuser port number also improved efficiency.
Reinemann et al. [41] 1990	U.S.A.	Theoretical & Experimental	1.L=1.8m 2.Q_a & Q_w	d=3-25mm	1.Theoretical airlift efficiency reaches 83% for tubes with dia 6 mm with zero gas flow and 100% submersion. 2.Small-diameter airlift pumps may be designed using the principle.
Wurts et al. [35] 1994	Texas	Experimental	1.L=1.85m 2.Q_a=71-324lit/min	1.d=7.6, 10.2, and 15.2cm	As pipe diameter, air flow, and air injection depth increased, so did the pumping rate of each airlift.
Khalil et al. [24] 1999	Egypt	Experimental	1.d=2.54cm 2.L=2m 3.submergence ratio=0.75-0.5	different injection hole configurations	1.Foot piece design and submergence ratio affect air lift pump performance. 2.Using an appropriate hole distribution in the injection disk for a specific submergence ratio increases pumped water.
Oh and Lee [16] 2000	Korea	Experimental	1.d=2.1-3.4cm 2.L=40-300cm	Q_g & Q_l	Given a pump shape, a certain air flow rate maximizes water flow. Larger or lesser air flows reduce the pumping rate. Low and high lift pumps have varied optimal flows.
Kassab et al. [25] 2008	Egypt	Theoretical & Experimental	d=25.4mm	1.submergence ratio=0.2-0.75 2.L=175, 275, and 375 cm	As the submerged ratio rises, pump efficiency at the same air-flow rate improves. In slug or slug-churn mode, the air-lift pump lifted the most liquid.
Hanafizadeh et al. [26] 2010	Iran	Numerical	L=914mm	1.d=6, 8, and 10mm 2.submergence ratio=0.4, 0.6, and 0.8 3.tapering angles	The 3° tapered upriser pipe delivers the maximum efficiency at practically all submergence ratios.
Hanafizadeh et al. [31] 2011	Iran	Numerical	1.d=6,8mm 2.L=914mm 3.submergence ratio=0.6	step height	In constant gas flow rate, there is a precise step height and secondary pipe diameter that may improve pump performance. The optimum phase is when slug flow changes to churn flow in the pipe.
Tighzert et al. [27] 2013	Algeria	Experimental	1.d=33mm 2.L=3.1m	1.submergence ratio=0.4-0.75 2.Q_a	When using an air-lift pump system, the submergence ratio should fall anywhere between 0.4 and 0.75 for the best possible results.
Fan et al. [28] 2013	China	Theoretical & Experimental	1.d=0.4m 2.L=28.3 m 3.submergence ratio=constant	1.Q_a 2.Air injection nozzle design	Air-lift artificial upwelling efficiency depends on upwelling pipe geometry, air injection nozzle type, and air volume flow rate. Theoretically, increasing the pipe diameter reduces friction in the upwelling pipe, increasing lifting efficiency.
Tang et al. [29] 2014	China	Experimental	1.d=40mm 2.L=1.2m	1.submergence ratio=0.32-0.6 2.Q_a 3.pipe bend	The test findings demonstrate that air-lift pipe type has little influence on flow pattern but a big impact on pump performance.
Ahmed et al. [43] 2016	Canada	Experimental	1.d=31.75mm 2.L=2m 3.submergence ratio=0.5	air injection techniques	The study revealed that airlift pump performance depends on both air injector design and injection technique dynamics.
Abou Taleb and AI-Jawdat [44] 2017	Saudi Arabia	Experimental	1.d=5.08cm 2.L=20cm	1.submergence ratio 2.Air jacket	As submergence ratio rises, maximum water flux and pump efficiency increase for equal air flow. Air jacket affects water efficiency and flux.
Kassab et al. [42] 2022	Egypt	Experimental	1.d=24mm 2.L=4m	inlet injection region	The air lift pump efficiency is more sensitive to changes in geometrical or operational factors than the water and air flow rate relationship.

Awari et al. [19] 2004	India	Experimental	1.d=2.5in	air pressure	The discharge of the pump will rise in response to an increase in the air pressure up to a specific limit, beyond which it will drop.
Hanafizadeh et al. [45] 2010	Iran	Experimental	1.d=50mm 2.L=6m	flow regimes	1.In the bubbly flow regime, the airlift pump could only lift water at high submergence ratios. 2.Slug flow was the best flow regime for airlift pump performance.

6. CONCLUSIONS

All relevant prior research on airlift pumps, both theoretical and numerical, as well as practical work, is discussed in detail. The history, mechanism, uses, and influencing parameters of airlift pumps have been discussed. From this, we may deduce that an airlift pump requires certain conditions in order to function optimally for any given combination of design or operating characteristics. It is possible to draw the conclusion that the modeling of the airlift pump in the flow regime transition does not yet have a sufficient level of understanding. As a pumping device, airlift has not yet been fully figured out in terms of how it works. This is another limitation of the technology. It would appear that the field of theoretical and experimental studies of airlift operational characteristic curves and flow regime transition can be regarded as a step forward in the better understanding of industrial operating, controlling, and upgrading of the airlift pump. This is because these types of studies focus on airlift operational characteristic curves and flow regime transition.

The design and operation parameters of an air lift pump can have a significant effect on its performance. Some of the key factors include:

- Pipe diameter: The diameter of the pipe used in the air lift pump can affect the pumping rate and the power consumption. A smaller diameter pipe can increase the pumping rate, but it can also increase the power consumption and decrease the efficiency.
- Inlet air flow rate: Increasing the inlet air flow rate can increase the pumping rate of the air lift pump, but it can also increase the power consumption and decrease the efficiency of the pump.
- Water flow rate: Increasing the water flow rate will increase the discharge of the pump, but may also increase the required power input.
- Head (vertical distance): The head, or vertical distance that the water is being lifted, will affect the required power input and the maximum discharge capacity of the pump.
- Air-to-liquid ratio: This ratio determines the amount of air that is used to lift the liquid. A higher ratio can increase the pumping rate, but it can also increase the power consumption and decrease the efficiency.
- Operating depth: The operating depth of the pump will affect the required power input and the maximum discharge capacity of the pump.
- Submergence ratio: It is generally desirable to have a high submergence ratio for an air lift pump in order to maintain a high level of efficiency.
- Fluid properties: The properties of the fluid being pumped, such as viscosity, density and surface tension, can also affect the performance of the air lift pump.
- Inlet air pressure: Higher inlet air pressure can increase the pumping rate of the pump, but it can also increase the power consumption and decrease the efficiency.

Overall, the design and operation parameters of an air lift pump can have a significant impact on its performance and efficiency. It is important to carefully consider these factors when designing and operating an air lift pump.

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