Exergy analysis of Airlift Systems: experimental approach

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Abstract: Airlift Systems (ALS) are widely used in various industrial applications. As the main part of the flow through ALS’s upriser pipe, is formed by gas-liquid flow, the analysis of such systems will be accompanied by problems of two-phase flow modelling. Several effective variables are involved in ALS; thereupon comprehensive method is needed to consider these parameters. Exergy analysis can be considered as a simple solution for the realisation of the preferred domain of ALS’s operation. Here, this method has been proposed to examine the performance of ALS. Based on thermodynamic principles, an analytical model has been implemented in each phase and the respective experimental data have been collected from the test rig. A new efficiency definition for ALS has been proposed and compared with the existing definitions available in the literature. Finally, flow availability and entropy generation have been estimated by this method in the ALS.

Keywords: ALS; airlift system; multiphase flow; exergy analysis; entropy generation; availability.


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1 Introduction

Airlift Systems (ALS) consist of a vertical pipe in which compressed air is injected into its bottom, causing the liquid or the mixture of liquid and solid to be displaced upward. Airlift pump is a unique technology because of its simple structure; however, it has some weaknesses such as low suction head, unstable flow rate and low efficiency in comparison with ordinary pumping systems. The possibility of using airlift pumps in special applications, i.e., pumping corrosive, abrasive, radioactive and chemical fluids, is one of the greatest advantages of these systems. Since no moving part exists in this kind of pump, no lubrication would be needed. Therefore, the maintenance of these pumps is quite simple and the operating costs are low. Due to the simplicity of construction, reliability and low maintenance costs of airlift pumps, these systems are widely used in mines, oil industries, bioreactors and nuclear power plants.

Although airlift pumps have been used since the late 18th century (Castro et al., 1975), the performance of these pumps has remained a great interest to researchers so far. Various studies that have tried to simulate the behaviour of airlift pumps are found in the literature Kato et al. (1975) studied an airlift pump experimentally for solid particles and proposed a model based on the momentum equation. Parker et al. (1984) used an airlift pump for aerating warm water ponds. Apazidis (1985) considered the influence of bubble expansion on the performance and stability of an airlift pump. He considered the stability conditions of an airlift pump within the frame of the more general flow model with the assumption of single-phase flow of an ideal incompressible liquid and taking into account the effect of the expansion of gas bubbles during their lift. Wicomb et al. (1985) used an ALS for perfusion storage of the isolated heart. Parker and Suttle (1987) designed an ALS for aquaculture applications. Chisti (1989) derived the theoretical equations for airlift loop reactors, which described the relation between superficial gas velocity and liquid circulation velocity. Reinemann et al. (1990) experimentally considered the effect of tube diameter on the performance of 3- to 25-mm airlift pumps. They extended Nicklin’s theory into this range of tube diameters by taking into account the effect of surface tension on the bubble velocity. They also claimed airlift efficiency and optimal submergence ratio (which is defined by the ratio of water level to the height of the pipe before the pump operation) increase in this range of tube diameter. Zenz (1993) used various correlations to simulate airlift pumps. De Cachard and Delhaye (1996) proposed a model to predict pressure gradient for slug flow in the airlift pump. Margaris and Papanikas (1997) introduced a pseudoliquid, which was formed by liquid and solid phase, for analysing a three-phase flow airlift pump. Nenes et al. (1997) simulated an airlift pump numerically for deep water well, which was based on the interspersed continua approximation and used appropriate friction correlation for specified flow regimes. Their model could predict either water or air flow rate. A linear stability method was proposed...
by De Cachard and Delhaye (1998) to consider the stability of small-diameter airlift pumps. They noticed that the same variation of the influencing parameters may stabilise or destabilise performance of the pump depending on the value of other parameters. Also, they identified that the effect of compressibility of the gas phase between the regulating valve and injection device is very considerable. White (2001) considered application of airlift pumps in the absorption refrigeration cycles. She compared five different models and verified that the drift flux model was the closest fit to her experimental data. She also found from the experiments that the pump operation was not sensitive to the length of the pipe; however, it was highly dependent on the submergence ratio. Kumar et al. (2003) considered augmentation of airlift pump performance with tapered pipe experimentally. They carried out hydrodynamic investigation to understand the mechanism of improving performance in the pump due to tapered upriser pipe fitted to the pump. They also observed that the water output in the tapered upriser pipe is more sensitive to the air flow rate than that in uniform sized pipe. Abed (2003) used a mathematical model to find operational criteria for the performance of airlift pumps. The performance of a small ALS used for transporting alumina particles of 3-mm diameter was experimentally investigated by Fujimoto et al. (2005). Samaras and Margaris (2005) found a new flow regime map that was appropriate for airlift pump performance and regime transition. They transformed the Hewitt and Roberts regime map for representing the flow performance of an airlift pump. They used gas and liquid superficial velocity as coordinates of the map. They also proposed another map, giving void fraction vs. gas superficial velocity and acclaimed that this map has the advantage of finding void fraction in airlift pump from gas superficial velocity and flow regime, which usually exist in experimental data. Kassab et al. (2007) developed a theoretical model based on the control volume approach to predict airlift pump performance in three-phase flow. The effects of submergence ratio and size of solid particles on the performance of the pump were investigated by them. They perceived that the mass flow rate of solid particle increases with increase in submergence ratio. Also, they concluded that the performance of the airlift pump for lifting solid particle and liquid strongly depends on the flow pattern in which the pump operates. Kassab et al. (2009) evaluated the performance of a pump experimentally and introduced a theoretical model to optimise the operating parameters of the pump. They concluded that the airlift pump will lift the maximum amount of liquid if it is operated in the slug or slug-churn regimes.

Hanafizadeh et al. (2010) developed a new physical numerical approach, called Physical Influence Scheme, to simulate two-phase flow in the airlift pump’s upriser pipe. This method couples the continuity and momentum equations and enforces the role of pressure directly in the continuity equation. Most of the work mentioned above analysed the ALS for nature of two-phase flow and its governing equations. No publication has been reported on exergy analyses of ALS, but there are various research work that have been noticed in the literature about exergy analysis of other systems like vortex tube systems (Saidi and Allaf Yazdi, 1999), PEFC fuel cell systems (Delsman et al., 2006; Saidi et al., 2005) and Magneto Hydrodynamic plasma generators (Saidi and Montazeri, 2007).

Considering the mixing of two phases and energy dissipation caused by friction between phases during the process of lifting liquid phase in the airlift pump’s upriser pipe, exergy analysis can be the most appropriate method to find an optimum efficiency in the ALS. Various parameters such as inlet gas pressure, inlet mass fraction and diameter of gas injection device are effective in mixing phases; as a result, they would affect pump performance. In this article, based on exergy analysis, a novel
approach has been developed to consider the effect of energy dissipating parameters on the behaviour of airlift pumps. Similarly, the second law of thermodynamics was applied to achieve the entropy generation, availability and performance of the pump.

2 Experimental setup

The experiments in this study were carried out in a large-scale two-phase flow test rig. The experimental apparatus is shown schematically in Figure 1. The air and purified water are used as the gas and liquid phases in all experiments. Water supplier is a tank with an adjustable head. Water flow rate is measured by a calibrated magnetic flow metre with an accuracy of ±0.5%. The compressed air is continuously fed by the compressor up to 6 bar. The air flow rates are set and filtered by the filter and regulator valve and measured by calibrated gas turbine flow metre with an accuracy of ±1%. Air and water would be mixed in the plenum made of acrylic glass and placed at the bottom of the upriser pipe. Compressed air is injected into the plenum by the porous stainless steel plate with 108 holes of 0.5-mm diameter. The overall height and inside diameter of the upriser pipe are 6 m and 50 mm, respectively. To observe the two-phase flow patterns, the upriser pipe has been chosen from transparent acrylic glass. Air and water flow upward through the riser and would be separated in the separation tank above the riser.

Figure 1 Schematic of two-phase flow test rig
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Air is discharged into atmosphere, and water, depending on test application, returns to main tank or to airlift tank, and it would be circulated in the loop. In order to apply different submergence ratios, which is defined by the ratio of height of water to the length of the upriser pipe, level of water in the airlift tank should be changed. In the airlift pump, work may be produced or lost simultaneously. Therefore, water temperature may vary during different processes and pumping cycle; these changes are often very small, but since the proposed approach is based on exergy analysis, these apparently small variations may play an important role. Accurate, fast response and calibrated thermocouples were installed in the test loop with the order of accuracy of 0.1°C, and their locations are shown in Figure 1. Sixteen pressure transmitters with an accuracy of 0.3% of full scale were installed at different positions along the upriser pipe to measure the pressure. All the above instruments have a specified signal; these signals are scaled and fed into a rapid and wide-band data acquisition card with the sample rate of 1.25 MS/s and 16-bit accuracy. Recorded data are stored for further postprocessing. A high-speed digital camcorder of 1200 fps at a height of 5 m on the riser is equipped for visualisation, flow regime identification and flow recording.

3 Method of analysing

In this article, exergy method is selected to examine the behaviour of the airlift pump. The upriser pipe is considered as a control volume, and the first and second laws of thermodynamic are applied to it. Figure 2 illustrates the control volume schematically. The first law of thermodynamics for control volume can be written as

\[
\dot{Q}_{CV} + \sum m_i \left( h_i + \frac{V_i^2}{2} + gZ_i \right) = \frac{dE_{CV}}{dt} + \sum m_i \left( h_i + \frac{V_i^2}{2} + gZ_i \right) + \dot{W}_{CV}.
\]

Figure 2 Schematic of control volume
The upriser pipe is made of Plexiglas and has low thermal conductivity. Based on both low thermal conductivity of the pipe and the velocity of mixture in the pipe, it can be concluded that the mixture does not have time to transfer heat to its surrounding. So the assumption of adiabatic control volume is reasonable. Considering adiabatic steady-state flow without work transfer through the boundary of control volume and also neglecting the variation of kinetic energy, equation (1) can be simplified as

$$\sum m_i (h_i + gZ_i) = \sum m_i (h_i + gZ_i).$$  \hspace{1cm} (2)

Implementing this equation for assumed control volume results in

$$\dot{m}_{\text{in}} (h_{\text{in}} + gZ_{\text{in}}) + \dot{m}_{\text{out}} (h_{\text{out}} + gZ_{\text{out}}) = \dot{m}_{\text{in}} (h_{\text{in}} + gZ_{\text{in}}) + \dot{m}_{\text{out}} (h_{\text{out}} + gZ_{\text{out}}).$$  \hspace{1cm} (3)

Considering air as an ideal gas with constant specific heat and assuming equal temperature for air and water at outlet, and dividing equation (3) by water mass flow rate gives

$$\dot{m}_{\text{in}} (h_{\text{in}} + gZ_{\text{in}}) + \dot{m}_{\text{out}} (h_{\text{out}} + gZ_{\text{out}}) = \dot{m}_{\text{in}} (h_{\text{in}} + gZ_{\text{in}}) + \dot{m}_{\text{out}} (h_{\text{out}} + gZ_{\text{out}}).$$  \hspace{1cm} (4)

In equation 4, with assumption of equal outlet temperature for both phases, i.e., $T_{\text{out}} = T_{\text{out}}$, all variables except outlet temperature, $T_{\text{out}}$, are definite; therefore, $T_{\text{out}}$ can be extracted. The second law of thermodynamics for control volume can be written as:

$$\frac{dS}{dT} + \sum \dot{m}_i s_i - \sum \dot{m}_s s_i = \int_0^T \frac{Q_{\text{CV}}}{T} dt + \dot{S}_{\text{gen}}.$$  \hspace{1cm} (5)

In the absence of heat transfer in control volume and assuming steady-state conditions, this equation is reduced to:

$$\sum \dot{m}_i s_i - \sum \dot{m}_s s_i = \dot{S}_{\text{gen}}.$$  \hspace{1cm} (6)

Implementing this formula for ALS’s upriser pipe and rearranging leads to:

$$\dot{S}_{\text{gen}} = \dot{m}_{\text{in}} (s_{\text{in}} - s_{\text{in}}) + \dot{m}_{\text{out}} (s_{\text{out}} - s_{\text{out}}).$$  \hspace{1cm} (7)

Assuming air as an ideal gas with constant specific heat, it follows that

$$\dot{S}_{\text{gen}} = \dot{m}_{\text{in}} \left( C_{p,\text{air}} \ln \frac{T_{\text{in}}}{T_{\text{in}}} - R \ln \frac{P_{\text{in}}}{P_{\text{in}}} \right) + \dot{m}_{\text{out}} \frac{T_{\text{out}}}{T_{\text{in}}}. $$  \hspace{1cm} (8)

The entropy generation could be obtained through equation (8), provided that the temperature of outlet phases is known. As it was mentioned before, the outlet temperature can be obtained through equation (4). Similarly, the rate of irreversibility can be linked to the variation of the availability as:

$$I_{\text{CV}} = \left( \sum \dot{m}_w \Psi_i - \sum \dot{m}_w \Psi_i \right) + \sum \left( 1 - \frac{T_i}{T_i} \right) \dot{Q}_{\text{CV,j}} - \dot{W}_{\text{CV}}.$$  \hspace{1cm} (9)
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In the absence of heat transfer and actual work, the rate of irreversibility is considered to be equal to the rate of destruction of flow availability, which is also proportional to the entropy generation.

\[ \dot{I}_{CV} = \left( \sum \dot{m}_i \psi_i - \sum \dot{m}_r \psi_r \right) = \dot{T}_0 \dot{S}_{gen, CV}. \quad (10) \]

where, \( \psi \) is exergy or flow availability, which is defined as

\[ \psi = (h - T_s s + gZ) - (h_0 - T_0 s_0 + gZ_0). \quad (11) \]

Equation (10) can be rewritten for upriser of airlift pump as follows:

\[ \dot{I}_{CV} = (\dot{m}_{a_i} \psi_{a_i} + \dot{m}_{w_i} \psi_{w_i}) - (\dot{m}_{a_o} \psi_{a_o} + \dot{m}_{w_o} \psi_{w_o}). \quad (12) \]

Using the definition of exergy, equation (11), the exergy of inlet air can be defined as

\[ \psi_{a_i} = (h_{a_i} - h_{w_i}) - T_0 (s_{a_i} - s_{w_i}) + g(Z_{a_i} - Z_{w_i}). \quad (13) \]

It is noticed that assuming constant specific heat for the air and considering it as an ideal gas lead to modification of equation (13):

\[ \psi_{a_i} = C_p a (T_{a_i} - T_0) - T_0 \left( \frac{T_{a_i}}{T_0} - R \ln \left( \frac{P_{a_i}}{P_0} \right) \right) + g(Z_{a_i} - Z_{w_i}). \quad (14) \]

Using equation (11) and assuming constant specific heat for inlet water result in

\[ \psi_{w_i} = C_v w (T_{w_i} - T_0) - T_0 \left( \frac{T_{w_i}}{T_0} \right) + g(Z_{w_i} - Z_0). \quad (15) \]

As \( P_{out} = P_{atm} = P_0 \), then the term of \( \ln(P_{out}/P_0) \) in the exergy of outlet air will be zero. Consequently, the exergy of air at the outlet would be given by

\[ \psi_{a_o} = C_p a (T_{a_o} - T_0) - T_0 \left( \frac{T_{a_o}}{T_0} \right) + g(Z_{a_o} - Z_{w_o}). \quad (16) \]

Similarly, the exergy of outlet water can be expressed as

\[ \psi_{w_o} = C_v w (T_{w_o} - T_0) - T_0 \left( \frac{T_{w_o}}{T_0} \right) + g(Z_{w_o} - Z_{w_o}). \quad (17) \]

3.1 Efficiency

For the device that does not involve the input or output work, such as airlift upriser pipe, the second law efficiency is defined in terms of ratio of output to input availabilities. Thus, given the definition of the second law efficiency in this case, efficiency of airlift pump can be stated as:

\[ \eta_{2nd\ law} = \frac{\dot{m}_{a_o} \psi_{a_o} + \dot{m}_{w_o} \psi_{w_o}}{\dot{m}_{a_i} \psi_{a_i} + \dot{m}_{w_i} \psi_{w_i}}. \quad (19) \]
However, this kind of efficiency is typically defined for devices that include heat interaction between the two inlet and outlet flows. Therefore, it seems that the second law efficiency is not quite appropriate for remarking the state of efficiency of ALS. Since the main goal in airlift pump is related to the outlet water mass flow rate and the main source of energy is in the inlet air mass flow rate, combining the first and the second law efficiencies can lead to redefining efficiency of ALS. In this study, the efficiency of ALS is defined as

\[
\eta_{\text{airlift}} = \frac{m_w \left( \psi_{w_{\text{out}}} - \psi_{w_{\text{in}}} \right)}{m_{\text{air}} \psi_{\text{sls}}}. \tag{20}
\]

In the literature, efficiency of ALS is described as the ratio of outlet water flow rate to the inlet airflow rate (White, 2001; Kassab et al., 2007). This efficiency is defined as

\[
\eta_{\text{Air}} = \frac{m_{\text{w_{out}}}}{m_{\text{w_{in}}}}. \tag{21}
\]

The main drawback of such a definition is that the efficiency is not between 0 and 1, and it is independent of injected air pressure and temperature, but the new definition of efficiency of an ALS is in the mentioned range and takes all the effective variables into account.

4 Result and discussion

The prevailing flow regimes identified in the gas–liquid vertical upward pipe are bubbly, slug, churn, annular and mist flow (Taitel et al., 1980). In the bubbly flow, the gas phase is composed of discrete bubbles in the continuous liquid phase. An increase in gas phase causes the coalescence of bubbles and consequently the formation of the slug flow in the pipe. The size of slugs is approximately equal to the diameter of the pipe with the round heads. The large bubbles in the slug flow breakdown and churn flow is constructed. The churn flow is the oscillatory regime that varies with time. With more increases in gas flow rate, annular flow regime appears. In the annular flow, the continuous gas phase exists at the centre of the pipe and the liquid films are formed at the pipe wall. The annular flow in which the gas phase is accompanied by the separate tiny droplets is called mist flow. In the ALS, the bubbly flow regime cannot lift water completely due to the low buoyant force exerted by the air bubbles. In this study, the main flow regimes that are detected by flow visualisation with high-speed camera (1200 fps) are slug, churn and annular, which are shown in Figure 3.

Using new definition of efficiency based on the exergy analysis tends that the effect of pressure and temperature of the inlet injected air be introduced directly into the efficiency of ALS. As the ALS operates nearly in adiabatic condition, the effect of pressure is greater than that of the temperature. The exergy point of view considers the pressurised air as an available energy that leads the ALS to operate and lift the water to the upper level. Moreover, this method considers that the energy is lost due to the interaction of the phases with each other and with walls. However, this consideration is internally seen when the second law of thermodynamics is written down for the ALS control volume. Therefore, the consideration of the above-mentioned effects is not
needed to confront with the complexity of interaction of two-phase flow. So the exergy efficiency is more accurate than the conventional definition of the efficiency while it enjoys the simplicity of exergy analysis.

**Figure 3** Picture of three main flow regimes that are detected in the airlift pump

Figure 4 shows the efficiency of airlift pump, which is defined by equation (20) in terms of injected air flow rate for different submergence ratios of 0.34, 0.42, 0.5, 0.58 and 0.67. In this article, the submergence ratio is defined by:

\[
SR = \frac{L_s - L_g}{L - L_g}
\]  

(22)

where \( L \) is the total height of the upriser pipe, \( L = 6 \text{ m} \), \( L_g \) is the height of the gas injector from the bottom of the upriser pipe, \( L_g = 0.3 \text{ m} \) and \( L_s \) is the vertical distance between the water level in the airlift tank and the bottom of upriser pipe (see Figure 2).

**Figure 4** Efficiency of airlift pump in terms of air flow rate for different submergence ratios
As shown in Figure 4, two major trends exist for efficiency of the pump. High submergence ratios have a descending trajectory and low submergence ratios have at first ascending and then descending trend. The reason can be explained by two-phase flow patterns associated with these submergence ratios. The performance curves of the airlift pump are depicted on the flow regime map. In Figure 5, the superficial velocity \( (J_g) \) and void fraction \( (\alpha_g) \) of gas phase correspond to x and y axis, respectively. As it can be clearly seen in Figure 5, starting points of the two-phase flow in ALS with submergence ratios of 0.58 and 0.67 are in the region of slug flow pattern, but those of flows with lower submergence ratios are located in the region of churn flow. The ALS experiences its highest efficiency in the slug region, provided that the flow passes through that regime. Thus, it can be concluded that the most efficient flow pattern for the airlift pump is the slug flow regime. Moreover, Figure 4 illustrates that an increase in submergence ratio promotes the efficiency of the ALS. This concept is in complete accord with the physics of the system because at high submergence ratios the amount of augmentation of water is lower; consequently, less power is needed for lifting water.

**Figure 5  Presentation of airlift performance on void fraction regime map**

Figure 5 indicates the performance curves of the airlift pump with inner diameter of 50 mm and the height of 6 m for air–water two-phase upward flows in the different submergence ratios depicted on the void fraction regime map (Samaras and Margaris, 2005). In the present map, the superficial velocity of air and void fraction correspond to the x and y axis, respectively, and the range of the submergence ratio varies from 0.34 to 0.67.

Figure 6 illustrates the efficiency of ALS that already exits in the literature. The comparison made between Figures 4 and 6 reveals that the overall behaviours of curves in both figures have the same form. Two major trends indicated in Figure 4 are repeated in Figure 6. The main weakness of the old efficiency is its range. As shown in Figure 6, the quantity of efficiency crosses 100, which is in contradiction to the concept of efficiency.
Figure 6  Old definition of efficiency of airlift pump in terms of air flow rate for different submergence ratios

Figure 7 displays the second law efficiency of the airlift pump defined by equation (19) in terms of injected air flow rate. As it was expected, this efficiency cannot exactly predict the behaviour of the pump. The trends observed in Figure 7 are quite similar to those in Figures 4 and 6. Again in this figure, lower submergence ratios have lower efficiencies, but the predicted values are higher than those calculated by equation (20). The reason may be that the outlet air exergy is considered as a gain in the numerator of equation (19), which leads to overestimating the amount of efficiency, while the purpose of using airlift pump is solely lifting the water phase. Also in equation (19), the exergy of inlet water is seen as a driving factor used in denominator of the fraction, while the inlet water is moved by the aid of injected air. Therefore, based on the second law, this definition of efficiency somewhat contradicts the physics of airlift pumps and cannot predict the efficiency of ALS appropriately.

Figure 7  Second law efficiency of airlift pump in terms of air flow rate for different submergence ratios
Figure 8 shows entropy generation in terms of inlet air pressure. These results are depicted for different submergence ratios in the range of 0.25–0.75. It is obviously seen that for constant submergence ratios, the increase in inlet pressure enhances the rate of entropy generation in pump. As it is clear from the recent figure, slopes of curves are very steep and therefore the entropy generation in the ALS is completely dependent on the pressure of injected air. Since entropy generation is in conflict with efficiency, pumps are preferred to operate in the minimum possible pressure while the submergence ratio is constant.

**Figure 8** Entropy generation in airlift pump in terms of air inlet pressure for different submergence ratios

Variation of entropy generation is illustrated in terms of water level in the upriser pipe in Figure 9. As it can be seen, entropy generation diminishes with the increase in submergence ratio. As a result, the pump operating in higher submergence ratios enjoys higher efficiency. This conclusion was previously indicated in the efficiency diagram of Figure 4.

**Figure 9** Entropy generation in airlift pump in terms of water head
In Figure 10, the airlift entropy generation is demonstrated in terms of both injected air flow rate and two-phase flow regimes. As shown in Figure 10(a), an increase in air flow rate enhances the generated entropy. Figure 10(b)–(d) shows that the minimum entropy generation occurs in the slug flow regime. Also, the comparison between these figures reveals the fact that the highest submergence ratio (0.75) has the least entropy generation in this flow regime. It can be concluded that, from the point of view of entropy generation, the best suitable flow regime for operating the ALS is slug flow. The least entropy generation in slug flow regime can be attributed to the fact that the two phases mix less in this regime than in the churn and annular flow regimes; hence, the pump has its lowest entropy generation and highest efficiency.

**Figure 10** Entropy generation for different flow patterns: (a) entropy generation in terms of air flow rate for different submergence ratios; (b) entropy generation in different flow patterns for submergence ratio of 0.58; (c) entropy generation in different flow patterns for submergence ratio of 0.67 and (d) entropy generation in different flow patterns for submergence ratio of 0.75
5 Error analysis

According to the definition of the uncertainty of variable $F$, which is a function of $n$ independent variables $X_i$, experimentally measured, is calculated by

$$U_F^2 = \left( \frac{\partial F}{\partial X_1} \right)^2 U_{X_1}^2 + \left( \frac{\partial F}{\partial X_2} \right)^2 U_{X_2}^2 + \cdots + \left( \frac{\partial F}{\partial X_n} \right)^2 U_{X_n}^2 \quad (23)$$
where

\[ F = \text{fun}(X_1, X_2, \ldots, X_n) \]  

and, \( U_{\chi} \) is the uncertainty of measured variable \( X_i \). In equation (24), the uncertainties of variables are independent of each other. Equation (22) can be summarised as

\[ U_F^2 = \sum_{i} \theta_i^2 U_{X_i}^2 \]  

where \( \theta_i \) is defined by the partial derivation of \( F \) as a sensitivity factor. The main parameters considered in this work are efficiency and entropy generation. These two parameters are functions of the following measured variables

\[ \eta_{\text{airlift}} = \text{fun}(\dot{m}_a, \dot{m}_w, \psi_{a_i}, \psi_{w_i}, \psi_{a_w}) \]  

and

\[ S_{\text{gen}} = \text{fun}(\dot{m}_a, \dot{m}_w, T_{a_i}, T_{w_i}, T_{\text{out}}, T_{a_w}). \]  

where \( \dot{m}_a \) was measured by turbine flow metre with the accuracy of 1% and \( \dot{m}_w \) was measured by magnetic flow metre with the accuracy of 0.5%. All temperatures were measured by thermocouple with the accuracy of 0.1°C and pressure by the pressure transmitters with accuracy of 0.3%. \( T_{\text{out}} \) is calculated from equation (4), so the amount of its uncertainty must be calculated before being used in equation (24). It can be seen from equation (4) that the outlet temperature is a function of the following variables

\[ T_{\text{out}} = \text{fun}(\dot{m}_a, \dot{m}_w, T_{a_i}, T_{w_i}, T_{\text{out}}, T_{a_w}). \]  

The uncertainties of measured and calculated variables are summarised in Table 1, in which the amount of uncertainty is \( U_F \), which is defined by equation (23), and the approximate error is defined as the ratio of the value of uncertainty to the value of the variable, which is expressed in percent.

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<tr>
<th>Quantity</th>
<th>Amount of uncertainty</th>
<th>Approximate error (%)</th>
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<td>Efficiency</td>
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<td>20</td>
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<tr>
<td>Flow availability (gas and water)</td>
<td>±0.82 and 5.05</td>
<td>0.05 and 0.5</td>
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<tr>
<td>Rate of entropy generation</td>
<td>±0.24</td>
<td>10</td>
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</table>

6 Conclusions

An exergy analysis was used to study the effects of some parameters on the performance of ALS. The experimental data were collected from the airlift with diameter of 50 mm and length of 6 m. The results were used to investigate both the entropy generation and efficiency in the ALS. It was observed that the flow regime in the upriser pipe has the dominant role in the efficiency of the pump, so it was concluded that the best flow regime for airlift pump is the slug flow regime. It was also shown that lower entropy generation
occurs in lower inlet air pressure and flow rate. In addition, it was demonstrated that using high submergence ratios decreases the entropy generation and hence increases the efficiency of the ALS.

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References


**Nomenclature**

\[ C \] Specific heat capacity [J/kg K]

\[ E \] Energy [J]

\[ G \] Gravity acceleration [m/s²]

\[ H \] Enthalpy [J/kg K]

\[ I \] Irreversibility [J]

\[ \dot{m} \] Mass flow rate [kg/s]

\[ P \] Pressure [Pa]

\[ \dot{Q} \] Rate of heat transfer [W]

\[ R \] Constant of gas [J/kg K]

\[ S \] Entropy [J/K]

\[ T \] Time [s]

\[ T \] Temperature [K]

\[ V \] Velocity [m/s]

\[ W \] Work [J]

\[ y \] Ratio of air mass flow rate to water mass flow rate

\[ z \] Height [m]
### Subscripts

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### Greek letters

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