Modeling of the performances of open loop air-lift pump used for seawater pumping

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Abstract: In this work we have developed equations for predicting the performance of air-lift pumps used for pumping seawater in a closed loop. These equations are based on energy and momentum balances. For a given air mass flow rate and a submersion ratio, these equations allow the seawater mass flow rate and void fraction determination. This simulation allows the evolution of pump efficiency with the gas flow rate and the effect of void fraction and gas flow rate on the results analysis shows that this simulation is a good tool for system sizing and optimization.

Key words: air lift pump, modeling, closed loop, performances, seawater

1. Introduction

A typical airlift pump configuration is illustrated in figure 1. A gas is injected at the base of a submerged riser tube. As a result of the gas bubbles suspended in the fluid, the average density of the two-phase mixture in the tube is less than that of the surrounding fluid. The resulting buoyant force causes a pumping action.

This work is an application of the modified Chisholm’s model [1]. This model is very simple to use. The novel aspect of this model, compared, for example, to that of Stenning and Martin [2] is in the method of predicting the relative motion of the phases. The method leads to simple equations allowing rapid prediction of mass dryness fraction, x, and total mass flow rate, G, at the ‘maximum flow condition’. This procedure is relevant to turbulent liquid flow; air-lift pump operation under laminar liquid flow is described by Jeelani et al [3].

This paper makes use predominantly of the force balance or momentum equation for the two phase pressure drop in the riser tube. Hussain and Spedding [4] used an entirely different approach based on thermodynamic and bubble energy considerations.

2. Experimental test setup and procedure

The experimental test set-up consists mainly of a riser, a down comer, valve, blower and Tank for pumped seawater. The tube which vehicles air from bower to the riser has a conical shape. The blower used with variable rotation speed and 0.8 kW power. A schematic diagram of the test setup is shown in Fig. 1.

The riser is a glass tube with 0.07 m diameter and 2m of length. The down comer is has the same diameter of the riser with 1m of length. The tank used for pumped water has a capacity of 800 L and a valve for discharge. The seawater pumped flowrate is measured by instantaneous level control (6). The uncertainty of liquid flow rate is 5%. The air flow rate is deduced from a specific curve which relates the variations of air flow rate with that of blower rotation speed in minutes (rpm). For each rotation speed we determine, from the specific curve, the volumetric air flowrate and the consumed power.
Fig. 1. Air lift pump where water circulates in an open loop


3. Modeling

The goal of this work is the simulation of an air lift pump, where water circulates in a closed loop. This is based on the modeling of the airlift pumping action. The used model is based on the energy and momentum equations. Two cases can be studied: internal or external closed loop. This latter is the most used for his design simplicity.

In the other hand, the fluid flow and the airlift performances depend on the flow regime. In this study we establish the balance equations independently to the regime map. The design procedure assumes the mixture is incompressible, and with an air density corresponding to the average pressure in the riser. If the mixture fluid is a pure liquid, the pressure drop due to friction is \( \Delta p_{\text{flo}} \). The two-phase pressure drop per unit length in the vertical riser tube is in terms of homogeneous theory for the friction component [5].

\[
-\Delta p = -\Delta p_{\text{flo}} \frac{V_H}{V_L} + g \frac{\rho_L}{V_L} + g \frac{1 - \rho_G}{V_G}
\] (1)

Where the differential operator \( D \) indicates derivatives with respect to length, and the average density of the mixture is given by the following equation:

\[
\frac{1}{\rho_H} = \frac{1-x}{\rho_L} + \frac{x}{\rho_G}
\] (2)

Where:
\( \rho_H, \rho_L \) and \( \rho_G \) are the mixture, liquid and gas densities respectively. They equal to the inverses of specific volumes: \( V_H, V_L \) and \( V_G \) respectively. \( x \), is mass fraction of gas in the riser. This equation can be rewritten as follows:

\[
\frac{V_H}{V_L} = 1 + x \left( \frac{V_G}{V_L} - 1 \right)
\] (3)
The gas density is negligible by comparison to that of water, then, neglecting gravitational forces on the gas:

$$\frac{1}{\rho_g} \cdot g \frac{\alpha_g}{V_L}$$

The equation (1) becomes:

$$-D_p = -D_{p \text{ Flo}} \frac{V_H}{V_L} + g \frac{\alpha_g}{V_L}$$

(4)

The liquid volume fraction is suggested by Chisholm [1] as follows:

$$\alpha_L = \frac{K(1-x)\sqrt{V_L}}{K(1-x)\sqrt{V_L} + x \sqrt{V_G}}$$

(5)

So the gas volume fraction can be calculated by the following equation:

$$\alpha_L + \alpha_G = 1$$

(5b)

In evaluating the liquid fraction it proves convenient to use Chisholm’s [5, 6] equation for the velocity ratio

$$K = \frac{u_G}{u_L} = \left(\frac{V_H}{V_L}\right)^{1/2}$$

(6)

Substituting Eqs (3) and (6) in Eq (5) gives

$$\alpha_L = \frac{1}{\frac{1}{(1-x)\sqrt{V_L}} + 1 - \frac{(1-x)\sqrt{V_L}}{V_H}}$$

(7)

The pressure gradient due to friction if the mixture flows as liquid is given by

$$-D_{p \text{ Flo}} = \frac{\rho^2 V_L}{2D} 4f$$

(8)

And the friction factor can be evaluated from the Blasius equation:

$$\lambda = \frac{0.314}{\Re^{0.25}} = \frac{0.314 \sqrt{D} \Re^{0.25}}{(G \sqrt{D})^{0.25}}$$

(9)

The fluid mixture is in turbulent flow conditions. The inlet momentum in the riser is used for fluid displacement and pressure drop compensation. According to Chisholm [1], the other major pressure drop in the operation of an air-lift pump is that required to accelerate the two-phase mixture at the mixer. With sufficient accuracy for the present purpose this can be evaluated from eq. 10.

$$\Delta P = MF$$

(10)

The sum of the momentum fluxes, MF, of the liquid and gas phases is given by this equation

$$MF = G^2 V_e = G^2 [x V_G + K_e (1-x) V_L] \left[ x + \frac{1-x}{K_e} \right]$$

(11)

Where, Ke, is the effective velocity ratio and evaluated from the following correlation of Chisholm:

$$K_e = K^{0.28}$$

(12)

K is the gas-liquid velocities ratio. It is given by Eq (6). This empirical of Chisholm equation [7] approximates, at the mass dryness fractions of interest in air-lift pumps, to the apparent velocity ratio in the momentum flux measurements of Andeen and Griffith [8] and Wiafe [9].

3.1 Submergence ratio

The driving head for the operation of the air-lift pump comes from the submergence $Z_s$ of the air liquid mixer below the liquid surface. Where $Z_o$ is the length of the riser tube, the submergence ratio is

$$Sr = \frac{Z_s}{Z_T}$$

(13)

An overall force balance gives:

$$g Z_s / V_L = -D_p Z_o + G^2 V_e$$

(14)

From Eqs (13) and (14), neglecting the momentum forces (G^2 V_e),
Combining Eqs (4), (13) and (14), we obtain:

\[-D_p FLO = \frac{g}{V_H} (Sr - \alpha L) - \frac{g^2}{Z_0} V_L \frac{V_L}{V_H} \]

This equation can be solved in conjunction with Eqs (3), (5), (8), (9), (11) and (12) to give the mixture mass flow rate for a given mass dryness fraction. Air-water mixtures at atmospheric pressure were used. The air density was evaluated at the mean pressure in the riser tube. An air density of 1.19 kg/m\(^3\) was assumed at a pressure of 105 N/m\(^2\), and a water density of 103 kg/m\(^3\). Using Eq (14), this leads to the equation for the gas specific volume:

\[
\frac{1}{V_G} = 1.19 \left[ 1 + \frac{0.8 Z_T Sr}{200} \right]
\]

### 3.2 Airlift pump efficiency

The pumping efficiency, \(\eta\), is given by Nicklin (1963) [10]:

\[
\eta = -\frac{g M_L Z_L}{Q_G P_L \ln \left( \frac{P_1}{P_0} \right)}
\]

Where, \(Z_L\) is the total head, \(P_1\) and \(P_0\) denote pressure in and atmospheric pressure respectively, \(Q_G\) is the volume gas flow rate and \(g\) is the gravity.

### 3.3 Maximum fluid flow rate

The maximum fluid flow rate for a given diameter can be obtained by differentiating Eq. (16) and equating the derivative to zero. This leads to a rather cumbersome equation. A more convenient procedure is as follows.

Chisholm [9] proposed the following correlation which relates the ratio \(V_H/V_L\) to liquid volume fraction, \(\alpha_L\):

\[
\frac{V_H}{V_L} = \frac{1}{\alpha_L^2}
\]

Then Eq (4) is written after approximation.

\[-D_p = \frac{-D_p FLO}{\alpha_L^3} + \frac{g \alpha_L}{V_L} \]

The combination of equations (19) and (20) yields:

\[-D_p FLO = -D_p \alpha_L^2 - \frac{g}{V_L} \alpha_L^3 \]

Differentiating with respect to \(\alpha_L\), then equating to zero, gives

\[-2D_p \alpha_L - \frac{g}{V_L} \alpha_L^2 = 0 \]

Hence using Eq (15)

\[\alpha_L = -\frac{2 D_p V_L}{g} = 2 \frac{Sr}{3} \]

From Eqs (7) and (23), taking (1-x) as unity,

\[
\left( \frac{V_H}{V_L} \right)^{1/2} + 1 - \frac{3}{2} - \left( \frac{V_L}{V_H} \right)^{1/2} = 0
\]

This is a quadratic equation, hence
\[
\left( \frac{V_H}{V_L} \right)^{1/2} = \frac{E \pm (E^2 + 4)^{1/2}}{2}
\]

(25)

Where

\[ E = \frac{3}{25r} - 1 \]

(26)

In Eq (25) the positive value of the square root term is the appropriate solution, as \( V_H/V_L \) is always positive. Having evaluated \( V_H/V_L \) from Eq (25), the mass dryness is obtained on rearranging Eq (3)

\[ x = \frac{V_H - 1}{V_L - 1} \]

(27)

The mass dryness fraction can also be evaluated from Eqs (19) and (27), but this introduces further errors due to the approximations. From Eqs (15), (21) and (23):

\[-D_{P FLO} = \frac{4g}{27V_L} S r^3\]

(28)

Combining with Eqs (8) and (9) gives an approximate equation for the maximum flow rate for a given submergence ratio, \( S \).

\[ G = \left[ \frac{8g S r^3 D_{1.25}}{27 - 0.314 \mu_L^{2.25} V_L} \right]^{1/1.75} \]

(29)

4. Results

The calculation of the total mass velocity \( G \), the total and the friction pressure drops, the mass dryness, the volume liquid fraction are calculated by several iterations.

Fig. 2 shows the variation of theoretical and experimental mass liquid flow rate (ML) with the variation of mass gas flow rate for different submerged ratio \( S_r \). It is seen from the figure that, ML increases almost linearly with MG at a constant submerged ratio up to a maximum. After this period, the theoretical curves show a decrease, but the experimental curves stay, almost, in the same level. This is explained by the change in flow regime. This change of regime flow is characterized by the increase of the size and density of great bubbles which called slugs. Consequently, this change of regime is not considered by the basic model of Chisholm.

Fig. 3 shows the variation of friction pressure drop and total pressure drop with the variation of gas mass flow rate for different values of submerged ratio. The figure shows that Total pressure drop is influenced only by the submerged ratio value. Indeed, the submerged ratio value increases, the total pressure increases also. This explained by the fact that the viscosity and the density of liquid water are very high by comparison with of air. So, the submerged ration increases that means the liquid pumped increases also \([11-26]\). Consequently the total pressure drop increases also.

The figure shows also the effect of gas flow rate on the friction pressure drop. This effect is manifested as the decrease of friction pressure drop when the gas flow rate increases. This is explained by the reduction of contact area between wall tube and liquid seawater when the gas flow rate increases. This decrease of friction drop pressure can reach 600 Pa in our conditions test. We know that the pressure drop limits the liquid flow rate. Therefore, the reduction of friction pressure can help to improve the pumped liquid flow rate. But its value is modest by comparison with that of total pressure drop. So, it can be considered as a first step which needs more research for improvement.
Fig. 4 shows the variation of gas volume fraction ($\alpha_G$) and liquid volume fraction ($\alpha_L$) with the variation of mass gas holdup. The figure shows that $\alpha_G$ increases with $MG$. As $MG$ increases, gas fraction, in tube, becomes higher. However, the liquid volume fraction decreases. This fact is explained by the following equations:

\[
\alpha_G = \frac{\text{Volume of Gas}}{\text{Volume of Gas} + \text{Volume of Liquid}} = \frac{V_G}{V_G + V_L}
\]

And

\[
\alpha_L = \frac{\text{Volume of Liquid}}{\text{Volume of Gas} + \text{Volume of Liquid}} = \frac{V_L}{V_G + V_L}
\]

Therefore,

\[
\alpha_G + \alpha_L = 1
\]

So, when $\alpha_G$ increases, then $\alpha_L$ will decreases automatically. This fact is finding at any value of submerged ratio.
Fig. 3. Total and friction pressure drops versus mass gas flow rate.

Fig. 4. Gas and liquid volume fraction versus mass gas flow rate.

Fig. 5 shows the variation of total pressure drop and friction pressure drop with the variation of gas volume fraction. The figure is plotted for open loop airlift pump used for sea water pumping in ambient conditions (T = 23°C). The figure shows that friction pressure drop increases with the increase of gas volume fraction up to a maximum and then decreases. The total pressure drop is not influenced by the gas volume fraction. This fact is explained by the weak effect of gas fraction on the pressure drop by comparison with that of liquid density.
Besides, friction pressure drop is below than 10% of total pressure drop. Therefore, the total pressure drop is controlled, mainly, by the physical characteristics of liquid seawater.

Fig. 5. Total and friction pressure drops versus Gas volume fraction

Fig. 6 represents a sample of the results obtained for the variation of mass liquid flow rate, ML, with the variation of volume gas fraction. It is seen that, Mass liquid flow rate increases up to a maximum and then decreases for different submerged ratios. This result is similar to that obtained in fig. 2. Indeed, the basic model of Chisholm doesn’t consider the flow regime change and the characteristics of seawater.

Fig. 7 shows the variation of airlift pump efficiency with the volume gas fraction for different submerged ratios. The figure is plotted for open loop airlift pump. As volume gas fraction increases the efficiency decreases for any submerged ratio value. However, when the submerged ration value increases, so the pumped liquid flow rate increases also and the efficiency decreases. This fact is explained by the difficulty of gas expansion at high submerged ratio. This result is obtained in previous works [11-26]. We note that the efficiency, of open loop airlift pump used for sea water pumping, doesn’t exceed 22%. However, low efficiency doesn’t means low pumped liquid flow rate.

4. Conclusions

In this work the design equations of air lift pumps have been developed. These equations are based on the energy and momentum balances. The developed model equations have been solved by iteration calculation. They allow the plot of liquid flow rate versus gas flow rate for different submersion ratio values. The total pressure drop is approximately constant with the gas flow rate but increase with the submersion ratio. But the friction pressure drop increases with the gas flow rate up to certain value and then decreases. This decrease is due to the increase of the volume gas fraction. This phenomenon can be explained by the decrease of contact between solid surface and liquid with the increase of volume gas fraction and the reduced value of gas viscosity, therefore the pressure drop decreases also. The curves confirm that the volume gas fraction more than 60% has a negative effect on the liquid flow rate. The total pressure drop is due mainly to gravity, and if we neglect the friction drop, the error will not be more to 19%.
Fig. 6. Mass Liquid Flow rate versus Volume Gas fraction

Fig. 7. Efficiency versus Volume Gas fraction with different submersion ratio (S)

References


