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Experimental and analytical investigations of airlift pumps operating in three-phase flow

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Abstract

Based on the control volume approach, a theoretical model is developed to predict the airlift-pump performance in air–water–solid three-phase flow. Experiments were performed using coarse, irregular non-uniform crushed pink limestone particles. The effect of the submergence ratio and size of solid particles on the pump performance are investigated. The predictions of the proposed model are in good agreement with the experimental results of an airlift pump conveying solid particles. In addition, the comparison with the experimental results shows that the proposed model can be used, with good accuracy, to predict the performance of airlift pumps operating in air–water two-phase flow when the solid mass flow rate is set to zero.

Keywords: Airlift pump; Three-phase flow; Multi-phase flow in a vertical pipe; Solid transport

1. Introduction

The principles of airlift pumping were understood since about 1882, but practical use of airlift did not appear until around the beginning of the twentieth century. In comparison with other pumps, the particular merit of the airlift pump is the mechanical simplicity. Moreover, airlift pumps have several advantages over other pumps. They do not have any moving parts, no lubrication or wear problems. Thus, theoretically, the maintenance of this kind of pumps has a lower cost and higher reliability. Airlift pumps can be used for lifting corrosive and/or toxic substances in chemical industries, conveying slurries in mining, lifting manganese nodules from deep-sea bed at about 4000–6000 m [1], sludge removal in sewage treatment plants [2], operating continuous sand filters, and lifting life fish in airlift fish pumps. Moreover, they are easy to use in irregularly shaped wells where other deep well pumps do not fit. Airlift pumps are not available from suppliers, but they are very simple to build. Generally, airlift pumping is most efficient when the static liquid level is high. The main disadvantages of airlift pumps are their low efficiencies and requirement of a very large submergence to obtain high efficiency as compared to other pumps.

Many studies were performed to investigate the performance of airlift pumps operating in two-phase flow [3–5]. For airlift pumps conveying solid particles, several experimental studies were reported in the literature, however, only few studies were carried out to analyze their performance theoretically. Moreover, only uniform solid particles were used to investigate the pump performance.

An early study of airlift pumps lifting solids was performed by Kato et al. [6] for a low-head airlift pump used to lift uniform solid particles. They analyzed the pump based on an existing theory of two-phase flow. The model was developed by coupling the momentum equation of two-phase flow and the equation of motion of a single solid particle. The performance of a typical airlift pump was computed and its fundamental characteristics were obtained with neglecting the compressibility of air. They validated their model by comparing its results with the results obtained using a 19 mm diameter pipe as a riser and small glass balls (density = 2600 kg/m^3) of 3.75 and 7.57 mm diameters as test solid particles.

Kato et al. [7] extended the study of Kato et al. [6] for high-head airlift pumps where the compressibility of air was taken into consideration. The test particles used in the experiments were

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Nomenclature

A	pipe cross sectional area (m^2)
c	distribution coefficient
D	pipe diameter (m)
f	coefficient of friction
g	gravitational acceleration (m/s^2)
h_d	static lift
H_s	static head (m)
J	volumetric flux (m/s)
K	friction factor
L	length along the pipe (m)
L_2	suction part (two-phase flow) (m)
L_3	delivery part (three-phase flow) (m)
m	flux of three-phase mixture
P	pressure (N/m^2)
Q	volume flow rate (m^3/s)
Re	Reynolds number
S	slip ratio
S_r	submergence ratio
u	velocity (m/s)
x	quality

Greek letters

ε	void fraction (volumetric fraction)
ρ	density (kg/m^3)
τ	shear stress (N/m^2)

Subscripts

f	friction
G	gas
L	liquid
LS	liquid–solid
S	solid
3	three-phase flow

glass balls of 50 mm diameter. They concluded that, the flow of high-head airlift pumps for solid particles could be analyzed by extending the analysis of the low-head case study.

Yoshinaga and Sato [8] questioned the validity of the momentum balance method and the empirical correlations used by previous investigators because they were not universally confirmed. Moreover, the multi-fluid model is not satisfactory applicable because several constitutive equations for three-phase flow are not sufficient to model the performance of airlift pumps lifting solids. As a result, none of the models, together with their relating constitutive equations, have been sufficiently successful to be used in engineering applications. They developed a theoretical model based on the momentum equation combined with some empirical correlations from pervious studies of three-phase flow. They studied also the effects of pipe diameter, the submergence ratio, and the size and density of the solid balls on the pump performance. In their experimental work, they used ceramic spheres of diameters of 6.1 and 9.9 mm (density = 3630 kg/m^3). Two pipes of 26 and 40 mm diameters were used with the uniform ceramic balls. Several combinations of the ceramic balls were lifted using the 40 mm diameter pipe. Submergence ratios of 0.6, 0.7, and 0.8 were tested. The theoretical model was validated by comparison with the experimental results.

Gas–liquid–solid three-phase flow in an airlift pump was also modeled by Margaris and Papanikas [9] by a system of differential equations driven from the fundamental conservation equations of continuity and momentum. Their approach led to a more general mathematical model that is applicable to a wide range of installations, from small airlift pump to very large systems. The analysis is based on a separated flow model. The set of equations were programmed in a computer code, which they used as a tool for optimizing the design of airlift pump installations. They concluded that their model is capable of obtaining the important parameters such as drag coefficients of both solid and liquid; pump efficiency, and optimum values of pipe diameter, length, and injection point.

Another theoretical analysis of the three-phase flow in a vertical pipe was presented by Hatta et al. [1]. The system of governing equations used is based on the one-dimensional multi-fluid model. The transitions of gas flow patterns are taken into account in the system of governing equations. The analysis was later extended to include the effects of the air compressibility Hatta et al. [10], where a sudden change of the pipe diameter was introduced to account for the compressibility of air. They found that the motion of the solid particles depends strongly on the volumetric flux of the gas-phase as well as the submergence ratio.

In the present work, a theoretical model is developed to predict the airlift pump performance when operating in three-phase flow regime. The capability of the model in predicting the performance of the airlift pump lifting coarse irregular particles is examined by comparing its results with the experimental results of Ahmed [11].

It is known that airlift pump is not a fluid transport installation but it is only a fluid transfer device essentially short. Therefore, in practice, there is no need to know the pipe losses in an airlift pump installation. As a pumping device, however, the airlift pump has a large variation in efficiency, and any reduction of flow below its optimum range increases hydraulic losses, irrespective of a lower pipe friction loss. For this reason a familiarity with the hydraulic performance of the airlift pump is much more important than the knowledge of the pipe friction loss. Therefore, the present work is concentrated on studying the parameters affecting the design of airlift installations. These parameters are:

- The ratio between the submergence (static lift) and the total length of the pipe (the sum of the static head and static lift), which is known as the submergence ratio, S_r. The submergence ratio is the most important factor in the pump design.
- Volume flow rate of the fluid (pump capacity), Q.
- Static lift, h_d, which is the height to which water or solid–water mixture is to be raised.
- The important solid characteristics, such as the particle size.