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Entropy analysis of buoyancy driven gas–liquid two-phase flow: Analytical and experimental approaches

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HIGHLIGHTS

- An entropy analysis of an airlift pump is investigated analytically and experimentally.
- All effective parameters involved in the airlift entropy generation have been considered.
- A theoretical model will be proposed and according to data collected from experiments.
- Entropy generation of the pump will be calculated in different submergence ratios.
- A complete investigation of effective parameters and their importance has been carried.

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ABSTRACT

Buoyancy-driven two-phase flow is widely utilized in numerous applications, namely for pumping and transport of corrosive industrial liquids, and waste, muddy, or hot water containing sediments as in mining. This pumping method benefits the advantage of transporting unusual fluids that are not easily carried by conventional pumping systems. The airlift pump is one these buoyancy-driven pumping methods. An experimental entropy analysis of an airlift pump is presented in this work. The entropy generation of a pump plays a substantial role in its performance. Analysis of such gas–liquid systems is similar to the problem of modeling two-phase flows. The objective of the paper is to propose a comprehensive entropy analysis method that considers all the effective parameters involved in the entropy generation of an airlift pump, i.e. gas–wall and water–wall frictions, phase interactions, and losses due to relative velocities. A theoretical model is proposed, and entropy generation of the airlift pump is calculated in different submergence ratios, on the basis of experimental data. The results are then compared with those obtained from the authors' previous work, i.e. the thermodynamic approach. Finally, a complete investigation of the importance of each effective parameter is reported for different working conditions. It is concluded that the proposed model is capable of providing comparatively good values for the entropy generation on the basis of the design parameters like the phase flow rates, especially for the cases with submergence ratios above 0.5.

1. Introduction

Gas–liquid two-phase flow is a prevalent phenomenon in the nature and industrial applications. In spite of the inherit complexities associated with the two-phase flow researches, the great importance of such flows in scientific development invites scientists to study the effective parameters. Due to the widespread implementation of two-phase flows in industry and the important role that efficiency plays in the performance of a system, entropy generation, as a thermodynamic property, seems crucial to be analyzed and controlled [1–4]. There is little literature available about the entropy generation of two-phase flows, in which simple methods for analyzing have been used. Revellin et al. [5] proposed two distinct expressions for the local entropy generation of an adiabatic saturated two-phase flow of a pure fluid based on two approaches: the separated flow model using the classical vapor flow quality, and the mixture model, using the thermodynamic vapor quality. In addition, Ezeora [6] used entropy analysis for optimizing the length of two-phase flow evaporator tube with respect to separated fluid model approach. He considered a refrigerant flow to be annular, steady and one-dimensional. In some cases, entropy is used as a

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practical parameter in determining void fraction and other two-phase flow variables [7,8].

A buoyancy-driven two-phase flow system is a device for raising liquids or mixture of liquids and solids through a vertical pipe partially submerged in the liquid, by using compressed air introduced into the pipe at the lower end. By adding air into the mixture, the specific gravity of fluid decreases and tends upwards, because of its lighter density in comparison to the surrounding liquid. The airlift pump is one of the main buoyancy-driven two-phase flow pumping methods which is studied in this paper. Vasandani [9] discussed about the ability of an airlift pump in lifting and transporting corrosive and radioactive liquids. Hanafizadeh and Ghorbani [10] introduced the application of such systems in detail as a review paper. Airlift pumps are very efficient devices for handling difficult pumping operations. Giot [11] has pointed out their usage in transport of corrosive fluids, and solid–liquid mixtures, and also in undersea operation.

Since the concept of the airlift pump was introduced, there have been lots of studies performed on the correlation between a discharge flow rate of a transported fluid and a supply flow rate of a working fluid. However, most of the information is limited to gas lift pumps with submergence ratios of liquid below 0.8 because only pumping work is focused on [12–14].

Apazidis [15] studied the influence of bubble expansion and relative velocity on the performance and stability of an airlift pump. He considered the difference in the velocity of gas bubbles and the liquid. He neglected the wall friction and derived the continuity and momentum equations for each phase without considering phase interactions.

Awari et al. [16] tried to evaluate the performance of a pump under predetermined operating conditions and to optimize the related parameters. They presented the effects of design parameters versus mass flow rate of air, immersion ratio, etc. on the performance of airlift pump. They used the general mathematical expression to determine the effective diameter of nozzle applicable to air lift pump installations. They reported that the slug flow is more predominant for improving the performance of the pump.

Kassab et al. [17] developed a theoretical model to predict airlift pump performance in three phase flow based on the control volume approach. They also investigated the effect of the submergence ratio and size of solid particles on the pump performance. They claimed that predictions of the proposed model are in good agreement with the experimental results of an airlift pump.

Moisidis and Kastrinakis [18] investigated the pressure behavior in riser tubes of a short airlift pump for various submergence ratios, air discharges and riser tube lengths. Their experimental data showed a nonlinear behavior of pressure near the exit of the air ejector due to the increased friction losses in this region. They compared the pressure distributions along the riser tube for various submergence ratios with the predictions of the Stenning–Martin model.

Kim et al. [19] investigated pumping performance and essential hydrodynamic features of an airlift pump with a high submergence ratio experimentally to apply airlift pump principles to direct carbon fuel cell to transport high temperature molten fuel in DCFC system. They reported the effects of submergence ratio and air flow rate on pump's effectiveness.

Hanafizadeh et al. [20] proposed a new definition of performance characteristic for a gas–liquid lifting pump. The definition is based on the actual physical behavior of the pump and the measured experimental data collected from a gas lifting pump with the height and diameter of 6 and 0.05 m, respectively. They also, investigated the effect of important parameters such as the superficial slip ratio, submergence ratio and two-phase flow regimes on the pump performance.

In the present study, authors are about to continue their previous work on entropy generation of buoyancy driven two-phase flow systems [21], and present a model for calculating entropy generation of gas–liquid mixture in an airlift pump with consideration of gas–wall friction, water–wall friction, interactions between phases, and relative velocity effect. The authors believe that relative velocity plays an important role in the entropy generation of the pump at high velocity ranges. First of all, experimental setup is introduced briefly, and the proposed theoretical model is then presented in detail. Afterwards, the importance of each term in the proposed model will be clarified and entropy generation will be calculated from collected experimental data. These results are then compared with those from control volume assumption in thermodynamics approach in authors' previous work. Thus, the work originalities can be summarized in the following items:

- Developing an analytical expression for entropy generation calculation in a buoyancy driven two-phase flow pump.
- The one dimensional proposed model calculates the entropy losses due to gas–wall and water–wall frictions, phase interactions, and losses due to relative velocities.
- Comparison between the entropy generation values calculated from analytical and control volume models.

The experimental results are used as the inputs of both models for entropy generation calculations.

2. Experimental setup

In this study, the large-scale two-phase flow test rig, already used in recent work performed by the authors [21], was employed which has been schematically illustrated in Fig. 1. Air and purified water were utilized as the components of the two-phase mixture in all experiments. The atmospheric air is compressed to 6 bars and stored in the air vessel. The high pressure air is injected through a porous stainless steel plate with holes of 0.5 mm diameter, to the plenum where the mixing process occurs. Then the mixture flows upward in the riser, because of the buoyancy force acting on the air phase as explained in the previous sections. The riser pipe is 6 m in height and 50 mm in diameter. The air flow rate injected into the system is measured by a gas turbine flow meter, while a magnetic flow meter is applied to measure the induced water flow.

At the top of the riser, air and water are separated; air is discharged to atmosphere, and water returns to the airlift tank, and is circulated in the loop. The water level in the airlift tank is determined to be adjusted, in order to create a number of different submergence ratios (SR), which is one of the input variables in our experiment. This ratio is defined as the height of water level in the airlift tank to the length of the riser pipe.

The test rig also consists of four fast and accurate thermocouples, and 16 pressure transmitters, that are located in different sections of the setup, as shown in Fig. 1. The signals produced by these devices, are scaled and fed to a rapid wideband data acquisition card with 1.25 MS/s sampling rate and 16-bit accuracy. These data are processed and recorded for further use. Also, on the riser at the height of 5 m, there has been installed a high speed 1200 fps digital camcorder, for the purpose of flow regime visualization and identification.

3. Methodology of entropy generation analysis

To calculate the entropy generation in airlift pumps, different methods may be proposed. One may treat the system as a control volume, and only consider the flow conditions at the inlet and outlet of the pipe. No matter what happens inside, applying the second law of thermodynamics gives the amount