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3-dimensional Simulation of an Air-lift Pump from Bubbly to Slug Flow

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0. Nomenclature

A : Tube cross-sectional area (m^2)
C_o : Liquid slug velocity profile coefficient
D : Tube diameter (m)
f : Friction factor
g : Acceleration due to gravity (m/s^2)
P_s : Single phase frictional pressure drop (N/m^3)
Q_G : Volumetric gas flow rate (m^3/s)
Q_L : Volumetric liquid flow rate (m^3/s)
Q'_G : Dimensionless volumetric gas flow
Q'_L : Dimensionless volumetric liquid flow
Re : Reynolds number
V_m : Mean velocity of the liquid slug (m/s)
V_T : Rise velocity of the Tatlor bubble (m/s)
V_{T_s} : Rise velocity of the Taylor bubble in still fluid (m/s)
V'_{T_s} : Dimensionless bubble rise velocity in still fluid
Z_l : Length of tube unsubmerged / Lift height (m)
Z_s : Length of tube submerged (m)
α : Submerged ratio
ϵ : Gas void ratio
ν : Kinematic fluid viscosity
ρ : Fluid density (kg/m^3)
σ : Surface tension (kg/s^2)
E : Inverse Eötvös number / Surface tension number

1. Introduction

The air-lift pump is the equipment that pump liquid such as water, petroleum, etc. by injecting compressed air, vapor, or any material being in gaseous state. The air-lift pump has been used in various applications with its merit that it can pump up without any moving parts. E.g. coffee percolator, petroleum industry, suction dredge, OTEC i.e. ocean thermal energy conversion and so on. By the merit, it has high durability for high temperature water or vapor, and fluid-solid mixture like waste water, muddy water and crude, which cause problems when it's pumped up with general pumps. In this regard, the air-lift pump has been one of the most desirable technology.

A typical air-lift pump configuration is illustrated in Figure 01. The principle of this pump is very simple. When air is injected from the injector at bottom of a submerged tube, i.e., air bubbles are suspended in the liquid, the average density of the mixture in the tube is less than that of the surrounding fluid in the reservoir. Then hydrostatic pressure over the length of the tube is decreased. This buoyancy force causes a pumping action. [1]

2. Methodology

This study describes the simulation using ANSYS CFX how much mass of liquid pulled out during changing of mass of injected air in the simple air-lift pump. After simulation, the result is going to be compared to theoretical model and experimental result.

2.1 Theoretical Review

Basic theory of air-lift pump was founded by Reinemann at al.'s work. The essential part of this theoretical model is reviewed here. [1, 2]

First of all, the rise velocity of gas slug in a vertical tube relative to that of liquid slug has been described by:

$$V_T = C_0 V_m + V_{T_s} \tag{01}$$

and mean velocity of the liquid slug (V_m), given by:

$$V_m = \frac{Q_L + Q_G}{A} \tag{02}$$

The Taylor bubble, also called gas slug and long bubble, is formed in the tube which usually have an approximately hemispherical leading nose, a long cylindrical body region surrounded by a liquid film, and a trailing tail with either rounded, or flattened, or dimpled shape. The velocity of the Taylor bubble is set equal to the average linear velocity of the gas in the riser tube:

$$V_T = \frac{Q_G}{\epsilon A} \tag{03}$$

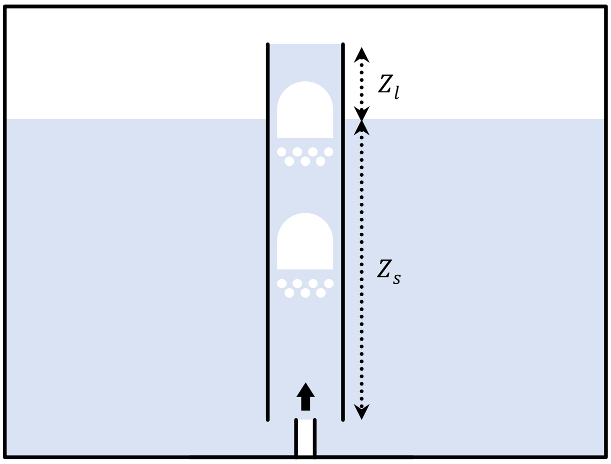

Figure 01. Typical air-lift pump

It is more convenient that modeling a pumping performance by using Froude number which is a dimensionless number comparing gravitational and inertial forces. By this concept of Froude number, the volumetric flow rates of Q_L, and Q_G, and the velocity V_{T_s} are non-dimensionalized to be Q'_L, Q'_G, and V'_{T_s} respectively, as follows:

$$Q'_L = \frac{Q_L}{A\sqrt{gD}}; \quad Q'_G = \frac{Q_G}{A\sqrt{gD}}; \quad V'_{T_s} = \frac{V_{T_s}}{\sqrt{gD}}; \qquad (04)$$

From (1) – (4), the gas void fraction in the riser tube can be expressed as:

$$\epsilon = \frac{Q'_G}{C_o(Q'_L+Q'_G)+V'_{T_s}} \qquad (05)$$

A velocity profile coefficient of liquid slug (C_o), which is ratio of liquid velocity at the center of the tube to mean velocity of the liquid slug, is 1.2 when the Reynolds number (Re) of the liquid slug is more than 8,000. The Reynolds number is usually bigger than 8,000, for the diameter of the tube, however, for air-lift pump with diameter less than 20 mm, the Reynolds number can be less than 8,000. The limiting value of the velocity profile coefficient has been found to be about 2 for the Reynold number approaching zero.

There is important effect besides the Reynolds number when the tube diameter is below about 20 mm, that surface tension. The effect of surface tension can be characterized by the inverse Eötvös number, i.e., surface tension number defined as:

$$E = \frac{\sigma}{\rho g D^2} \qquad (06)$$

When the surface tension number is above about 0.2, the effect of viscosity can be neglected, and the bubble Froude number in still fluid can be expressed as a function of the surface tension parameter alone. This corresponds to tube diameter less than about 20mm in air-water system:

$$V'_{T_s} = (0.352)\{1-(3.18)E-(14.77)E^2\} \qquad (07)$$

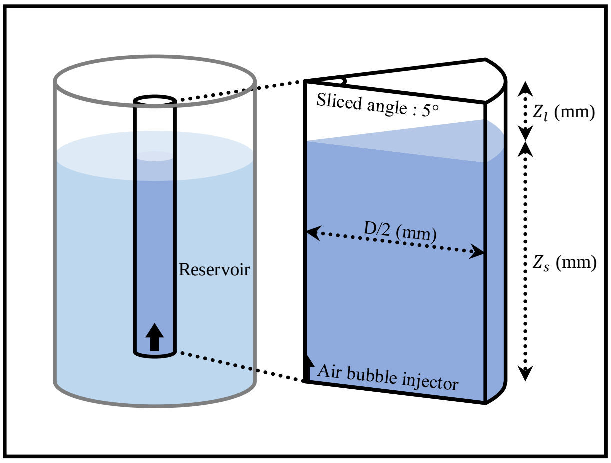

Figure 02. Schematic of the air-lift pump

Second, the submergence ratio is a parameter commonly found in airlift analysis and is defined as:

$$\alpha = \frac{Z_s}{Z_l+Z_s} \qquad (08)$$

The submergence ratio corresponds to the pressure gradient which is made up of components due to the weight of the two phase mixture and frictional losses.

A hydrostatic pressure balance on a vertical tube which is submerged in fluid, follows that:

$$\rho g Z_s = \rho g(1-\epsilon)(Z_l+Z_s) \qquad (09)$$

This assumes that the weight of the gas is negligible relative to the weight of the liquid.

When the fluid in the tube is flowing, there is an additional pressure drop due to frictional losses, and it should be added to the Equation 09. The frictional pressure drop on single phase can be calculated based on the mean slug velocity as:

$$P_s = f\frac{(Z_l+Z_s)\rho V_m^2}{2D} \qquad (10)$$

$$f = (64)/Re \ (Re \le 2100) \qquad (11)$$

$$f = (0.316)/Re^{0.25} \ (Re \ge 3500) \qquad (12)$$

$$Re = \frac{DV_m}{\nu} \qquad (13)$$

Including the frictional effect in the Equation 09 result:

$$\rho g Z_s = \rho g(Z_l+Z_s) + f\frac{(Z_l+Z_s)\rho V_m^2}{2D}(1-\epsilon) \qquad (14)$$

The frictional loss must be multiplied by $(1-\epsilon)$, the fraction of the tube occupied by liquid, to obtain the total frictional pressure drop in the riser tube. The frictional effects in the liquids film around the gas bubble have been shown to be small compared to those in the liquid slug and are therefore neglected.

2.2 Simulation Statement

As shown in the preceding section, the imaginary apparatus is designed for knowing the flows of bubbles and the discharge flow rate of water. The shape of the equipment which is used to this simulation corresponds to the schematic in Figure 02 and it's based on typical model of the air-lift pump.

A tube which length is 500mm is placed in the center of a cylindrical reservoir and this is replaceable with the other tubes with a diameters 11mm. The water reservoir feeding water is connected to drain part of the tube, for that the level of water adjusting enables to set up the submergence ratio as desired.

The simulation domain can be a simplification as a sliced arc column as shown in Figure 02, due to the shape of apparatus. As the air-lift pump tube can be drawn cylindrical shaped, it is axial symmetric with respect to the centerline. The sliced arc column is 1/72 of the original tube, so the angle between two plates is 5°.

This simulation doesn't use any fluid models for turbulence to establish clear the phenomenon of drag force, lift force, and pressure drop which is basic principles of air-lift pump. The materials used in this simulation are the air at 25℃ and the water at 25℃ which has density 1.185kg/m^3 and 997 kg/m^3 respectively.

This study is set up with conditions depending on tube diameter and submergence ratio 0.8, 0.9, and 1.0. These parameters are based on the existing experiment of S. H. Kim, et al., from Sejong Univ., and Kitech, i.e., Korea institute of industrial technology. [2]

2.3 Boundary Conditions

Boundary conditions are shown in Figure 03 and the information of each boundaries is as follows.

At the inlet, only the air bubble flows in and the mass flow rate is given as defined by the conditions which is calculated between dimensionless data from the above equations and density of the materials. The temperature of the air at the inlet is set to be 25℃.

At the top, the air flows out by same mass flow rate with that of the inlet boundary for the mass conservation at each iteration level, and there is no water exchange.

At the outer wall, the boundary imposes free slip condition for the air and no slip condition for the water. There is no heat or mass transfer and the thickness is assumed to be negligible in the simulation. On the other hand, the wall of the inner tube has a 1mm thickness and imposes same slip condition with the other walls.

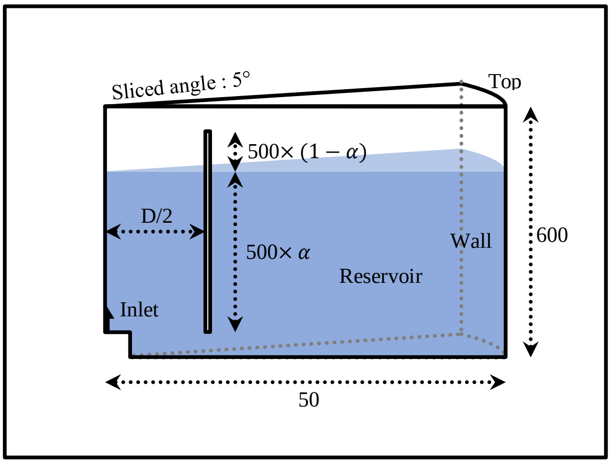

Figure 03. Schematic of the boundaries for the simulation

3. Results and Conclusions

The comparison of the simulated results, experimental result, and theoretical result is been able by data shown as Figure 04. They have similar trends but they also have a little differences because there are some limits of simulating the flow regimes.

As Figure 04, there is a linear relation part which has low air flow rate, and it can be predicted to slug flow regime. Beyond this regime, water discharge does not increase, because of the property of churn-annular flow which is called when the most of inner volume of the tube is filled with air.

At the different flow condition, different coefficients for friction factor or pressure drop should be used, but this simulation uses a laminar condition and the theoretical equations are valid only for slug regime

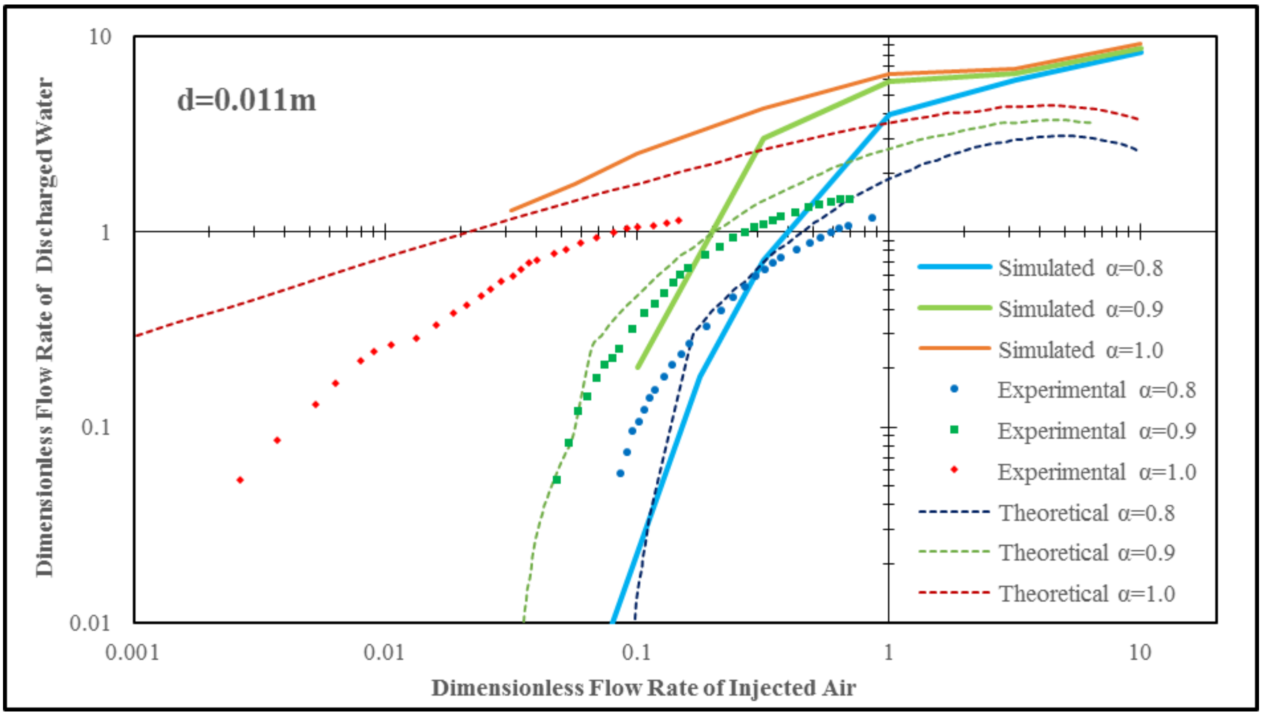

Figure 04. Dimensionless flow rate of discharged water as a function of injected air for different tube diameter 0.011m and 0.008m and various submergence ratio 0.8, 0.9, and 1.0

where the air flow rate is lower than the other regimes. From these causes, the differences has arisen, and difference comes bigger as the air flow rate increases, i.e., becoming annular flow regime or churn flow regime.

4. Further Works

There are some needs for optimizing the effectiveness of air-lift pump such as diameter of the tube, practically useful submergence ratio, kind of injected gas, and various flow conditions, after comparing the result which generated from the simulation during slug flow regime with theoretical result and experimental result. Also during designing the simulation, it should be applied that some conditions e.g., turbulence condition which appear in churn, annular, and annular mist flow regime, and bubble diameter following the depth from the surface of working liquid.

REFERENCES

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