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RESEARCH ARTICLE

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A STUDY ON EFFECT OF OPERATING CONDITIONS ON THE PERFORMANCE OF THE BUBBLE PUMP OF ABSORPTION-DIFFUSION REFRIGERATION CYCLES

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ABSTRACT

A diffusion-absorption refrigeration cycle or a pump less vapour absorption refrigeration cycle holds a great significance in noiseless refrigeration applications. The diffusion-absorption cycle is unique in that it runs without any mechanical work input. The cycle utilizes ammonia-water as working fluids. The diffusion-absorption cycle relies on a bubble pump to pump the solution from the absorber to the boiler. A bubble pump is a fluid pump that operates on thermal energy to pump liquid from lower level to the higher level. It does not contain any moving parts. Heat is applied at the bottom of the tube at a rate sufficient to boil some of the liquid in the tube. The resulting vapour bubbles rise in the tube. Due to the small diameter of the pump tube, the vapour bubbles occupy complete cross-section of the tube and are separated by small liquid slugs. Each bubble acts as a gas piston and lifts the corresponding liquid slug to the top of the pump tube. The bubble pump operates most efficiently in the slug flow regime in which the vapour bubbles are approximately the diameter of the tube. A mathematical model of the bubble pump by using simple analytical equations such as the continuity equation and the momentum equation will be able to predict the operated condition, required tube diameters, heat input…).The model assumes slug flow in the bubble pump. This model is used to find out the outlet liquid and vapor velocities for different heat flux input.

Keys words: Bubble pump, two-fluid model, simulation, heat flux, operating conditions

INTRODUCTION

A diffusion-absorption refrigeration cycle or a pump less vapour absorption refrigeration cycle holds a great significance in noiseless refrigeration applications. The diffusion-absorption cycle relies on a bubble pump to pump the solution from the absorber to the boiler . A bubble pump is a fluid pump that operates on thermal energy to pump liquid from lower level to the higher level.

Heat applied to the pump causes formation of bubbles and the density of strong solution in the vertical pump tube is reduced so that the solution is forced to the top by the static head of solution in the absorber vessel. The vapor which is released by boiling the solution will eventually become the condensed refrigerant, and its mass rate will dictate the refrigeration capacity of the refrigerator. According to established theory of absorption refrigeration, this mass rate of refrigerant is supported by the circulation rates of the strong and weak solutions and their concentration difference.

BUBBLE PUMP

The diffusion-absorption cycle relies on a bubble pump to pump the solution from the absorber to the boiler. A bubble pump is a fluid pump that operates on thermal energy to pump liquid from lower level to the higher level. It does not contain any moving parts. The bubble pump operates on the same principle that lifts coffee to the top of a coffee percolator. The bubble pump, as shown in Fig. 1, is nothing but a vertical tube of small circular cross-section.

The liquid in the liquid reservoir initially fills the tube to the same level (h). Heat is applied at the bottom of the tube at a rate sufficient to evaporate some of the liquid in the tube. The resulting vapour bubbles rise in the tube. Due to the small diameter of the pump tube, the vapour bubbles occupy complete cross-section of the tube and are separated by small liquid slugs. Each bubble acts as a gas piston and lifts the corresponding liquid slug to the top of the pump tube. The bulk density of the liquid and vapour mixture in the pump tube is reduced relative to the liquid in the liquid reservoir, thereby creating an overall buoyancy lift. The energy sources generally used are (i) electric heat and (ii) flame heat. In the latter case, the entire length of the bubble pump or boiler is heated to increase the heat transfer area.

Depending on the bubble pump tube, system pressure and properties of the pumped solution, two different kinds of flow are possible, namely slug flow and mixed vapour bubble-liquid (bubbly) flow. At the bottom of the pump tube small bubbles form and join together forming bigger vapour bubbles. The rising vapour bubble acts like a piston and lifts a corresponding liquid slug to the top of the bubble pump tube. After a certain pump tube diameter is exceeded, the flow behaviour changes from the slug flow regime to that of the mixed flow. The important parameters of the bubble pump are pump tube diameter (dp), driving head (h), pump lift (L) and pump heat input (Qp). The main characteristic values to judge the performance of the bubble pump are solution flow rate and the pumping ratio

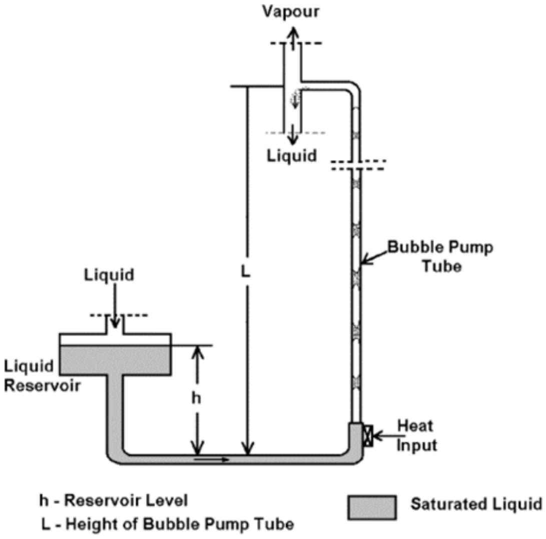


Figure.1

Two phase flow :

A two-phase flow is defined as a flow of two separate parts of a heterogeneous body or system. Vapour-liquid mixtures, where the vapour and liquid are phases of the same fluid are referred to as two-phase single component mixtures (e. g. vapour-liquid mixture in a bubble pump) while gas-liquid mixtures where the vapour and liquid are different fluids are referred to as two-phase two component systems (e. g. air-liquid mixture in an air-lift pump). Following are some commonly used terms in two-phase flow.

Dryness fraction:- It is defined as a ratio of mass flow of gas to the total mass flow.

Void fraction: The void fraction is the ratio of the gas flow cross-sectional area to the total flow cross-sectional area

Mass velocity: In two-phase flow literature, mass velocity is extensively used. It is the ratio of mass flow rate to the total flow cross-section area of the mixture.

Pressure drop: The calculation of two-phase pressure drop involves some complex calculations. Various correlations and charts are used to calculate the pressure gradients developed due to friction in the flow and change in momentum.

Flow Patterns: The flow patterns encountered in vertical upwards co-current flow are shown in Fig. Following flow patterns are encountered when a mixture of vapour and liquid flows through a vertical pipe.

1. Bubbly flow**.** In bubbly flow, the gas or vapour phase is distributed as discrete bubbles in a continuous liquid phase. At one extreme, the bubbles may be small and spherical and at the other extreme the bubbles may be large with a spherical cap and a flat tail. In this latter state although the size of bubbles does not approach the diameter of pipe, there may be some confusion with slug flow.

2. Slug Flow. In slug flow the gas or vapour bubbles are approximately the diameter of the pipe. The nose of the bubble has a characteristic spherical cap and the gas in the bubble is separated from the pipe wall by a slowly descending film of liquid. The liquid flow is contained in liquid slugs which separate successive gas bubbles. These slugs may or may not contain smaller entrained gas bubbles carried in the wake of the large bubble. The length of the main gas bubble can vary considerably.

3. Churn flow. Churn flow is formed by the breakdown of the large vapour bubble in the slug flow. The gas or vapour flows in a more or less chaotic manner through the liquid which is mainly displaced to the channel wall. The flow has an oscillatory or time varying character, hence the descriptive name ?churn? flow. This region is also sometimes referred to as semi-annular or slug annular flow.

4. Wispy annular flow. Wispy-annular flow has been identified as a distinct flow pattern. The flow in this region takes the form of a relatively thick liquid film on the walls of the pipe together with a considerable amount of liquid entrained in a central gas or vapour core. The liquid in the film is aerated by small gas bubbles and the entrained liquid phase appears as large droplets which have agglomerated into long irregular filaments or wisps. This region occurs at high mass velocities and because of the aerated nature of liquid film could be confused with high velocity bubbly flow.

5. Annular flow.. In annular flow a liquid film forms at the pipe wall with a continuous central gas or vapour core. Large amplitude coherent waves are usually present on the surface of the film and the continuous break up of these waves forms a source for droplet entrainment which occurs in varying amounts in the central gas core. In this case, as distinct from the wispy-annular pattern, the droplets are separate rather than agglomerated.

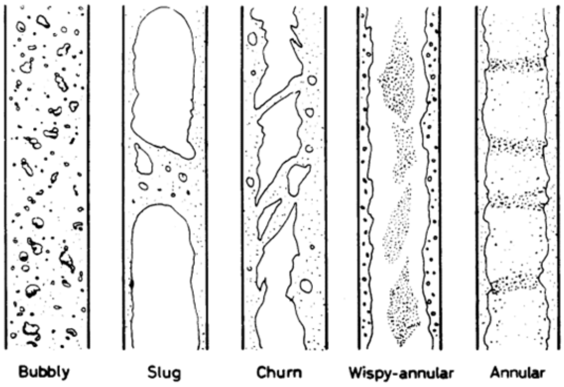


Figure .2

Information on bubble pumps, also known as vapor-lift pumps, is sparse in the open literature. Percolating coffee makers are a well-known application of bubble pumps. Heat addition to the fluid at the base of a vertical tube creates vapour, thereby increasing the buoyancy of the fluid causing it to rise through the vertical tube under two phase flow conditions, as seen in figure . Only the work of one author (Delano 1998) has addressed the design of a bubble pump for use in a single pressure absorption refrigeration cycle, with others (Schaeffer 2000, Sathe 2001) referencing this model.

Air-lift pumps are very similar to vapour-lift pumps, with a different mechanism to increase the buoyancy of the fluid. There is much more information available in the open literature on air-lift pumps. Most are based on the assumption of two-phase slug flow. Additionally, few have the same range of lift (~0.5 to 1 m) and diameters (~6 to 10 mm) that are applicable to the current study. Both air and vapor-lift pumps, however, are simply two-phase flow in a vertical tube; therefore two-phase flow models can be used to analyze the system.

Einstein Cycle Bubble Pump: Delano (1998) designed a model, based on the air-lift pump analysis of Stenning and Martin (1968), and analyzed the performance of the bubble pump of the Einstein cycle. It uses momentum balances and assigns a value recommended by Stenning and Martin (1968) for the slip (*S=VG/VL*) between phase velocities to model the two-phases involved. Schaefer (2000) used Delano's (1998) model with a turbulent single-phase friction factor instead of an experimentally determined one. In addition, Schaeffer analyzed the relationship of diameter, submergence ratio, mass flow rate, and heat input to maximize performance.

Platen-Munters Cycle Bubble Pump: Recently there has been a lot of interest in the Platen and Munters cycle. Herold et. al (1996) gives a review of the details of its operation and performance. Chen et. Al (1996) investigated the diffusion-absorption cycle for enhancing its performance. The result was a new design for the bubble pump/generator configuration. The original design combines the generator and the bubble pump into one component, with only one heat addition. The modified version heats the strong ammonia solution first, extracting most of the ammonia from the water so that a weak ammonia solution is sent to the bubble pump where another heater causes the solution to boil and rise, due to increased buoyancy, through the lift tube. This design is virtually identical to the bubble pump/generator configuration in the Einstein cycle; therefore the same bubble pump model can be used for both cycles.

Chen et al (1996) experimentally found that this new configuration increased the cycle COP by about 50%, however a detailed theoretical model was not developed in this publication. Earlier, Hassoon (1991) provided a theoretical model and experimental results for a bubble pump that used injected steam for lift instead of vaporizing the liquid in the tube. However, it modeled a lift tube that was cooled along its length. Its application was for an ammonia-water absorption heat pump. More recently, Sathe (2001) used Delano's (1998) methodology applied to the Platen-Munters' bubble pump.

Mathematical Analysis

The diffusion-absorption refrigeration cycle consists of a generator bubble pump, an absorber, an evaporator and a con-denser, and usually operates with ammonia/water/hydrogen or helium as working fluid. Fig shows the main components of an absorption-diffusion refrigeration cycle and flow configurations in the bubble pump .

In the diffusion-absorption cycle, the bubble pump is a heated tube that lifts fluid from a lower reservoir to a higher one . The generator configuration is of great importance. Heat is usually supplied at the bottom of the tube [3, 7, 9]. In the present work, heat is applied along all the tube length. This configuration of the bubble pump has two advantageous.

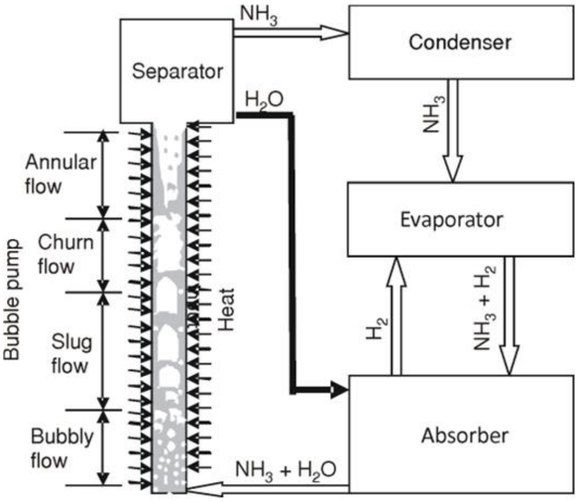


Figure.3 Main components of an absorption- -diffusion refrigeration cycle and flow configurations in the bubble pump

In the present work, the two-fluid model was used for the two-phase flow region considering the hydrodynamic non-equilibrium between the liquid and vapour phases. The flow configuration was not limited to the slug regime [8, 9], starting as bubbly and ending as annular.

Governing Equations : In the two-phase region, the general conservation equations of mass, momentum, and energy were formulated by Ishii et al. For the steady-state with negligible kinetic and potential energy, the conservation equations are reduced to the following equations:

Mass phase equations:

$$\frac{d}{dz}\alpha\rho_G u_G = V_G$$

$$\frac{d}{dz}(1-\alpha)\rho_L u_L = V_L$$

Momentum phase equations:

$$\frac{d}{dz}(\alpha\rho_G u_G{}^2)+\alpha\frac{dP}{dz}+\alpha\rho_G g=-F_{WL}-F_{GL}-F_{GL}$$

$$\frac{d}{dz}((1-\alpha)\rho_L u_L{}^2)+(1-\alpha)\frac{dP}{dz}+(1-\alpha)\rho_L g=-F_{WL}+F_{LG}-F_{LI}$$

Mixture energy equation:

$$\frac{d}{dz}(1-\alpha)\rho_L u_L H_L+\alpha\rho_G u_G H_G=\frac{q_W P_h}{A}$$

Vapour generation rate:

The heat transfer rate q_e due to evaporation

$$q_e=C_2\left(q_w-C_1 h_{sp}(T_w-T_L)\right)$$

Where C_1 and C_2 are,

$$C_1=1-\frac{\pi}{16}\frac{\alpha}{\alpha_{osv}}\quad for\ \alpha\le\frac{16\alpha_{osv}}{\pi}$$

$$C_1=0\ for\ \alpha>\frac{16\alpha_{osv}}{\pi}$$

$$C_2=\left(\frac{T_W-T_{sat}}{T_W-T_L}\right)^2$$

Where, h_{sp} = Single liquid heat transfer coefficient is,

$$h_{sp}=0.023\frac{\gamma_L}{D}Re_L{}^{0.8}Pr_L{}^{0.4}$$

Reynolds number in the liquid phase is,

$$Re_L=\frac{GD(1-x)}{\mu_L}$$

Where T_w = wall temperature is calculated from,

$$q_w=h_{tp}(T_w-T_L)$$

The convective boiling heat transfer coefficient, h_{tp} can be expressed as the arithmetic summation of the two -phase convection contribution, h_{cv} and the boiling contribution, h_{nb} :

$$h_{tp}=h_{cv}+h_{nb}$$

$$h_{cv}=F h_{sp}\quad\text{and}\quad h_{nb}=S h_{npb}$$

Where the factor F represents the acceleration effect of liquid due to vapour shear stress and the factor S represents the suppression of nucleate boiling due to the liquid flow.

$$F=1\quad\text{for}\ \frac{1}{Xtt}\le 0.1$$

$$F=2.35\left(\frac{1}{Xtt}-0.213\right)^{.736}\quad\text{for}\ \frac{1}{Xtt}>0.1$$

The Lockhart-Martinelli parameter is expressed by :

$$\frac{1}{Xtt}=\left(\frac{\rho_L}{\rho_g}\right)^{0.5}\left(\frac{\mu_g}{\mu_L}\right)^{0.1}\left(\frac{x}{x-1}\right)^{0.9}$$

$$S=\frac{1}{1+2.35.10^{-6}Re_{tp}{}^{1.17}}$$

$$h_{npb}=0.00122\frac{\mu_L{}^{0.79}C_{PL}{}^{0.45}\rho^{0.49}}{\sigma^{0.5}\mu_L{}^{0.29}h_{fg}{}^{0.24}\rho_g{}^{0.24}}\Delta T_{sat}{}^{0.24}\Delta P_{sat}{}^{0.75}$$

Where Re_{tp} is the two-phase Reynolds number expressed by:

$$Re_{tp}=F^{1.25}\frac{G(1-x)D}{\mu_L}$$

$\Delta T_{sat}=T_W-T_{sat}$ and

$\Delta P_{sat}=P_{sat}(T_w)-P_{sat}(T_{sat})$

The vapour generation rate is given by the following expression:

$$V_G=-V_L=\frac{q_e}{h_{fg}+C_{PL}\Delta T_{sat}}$$

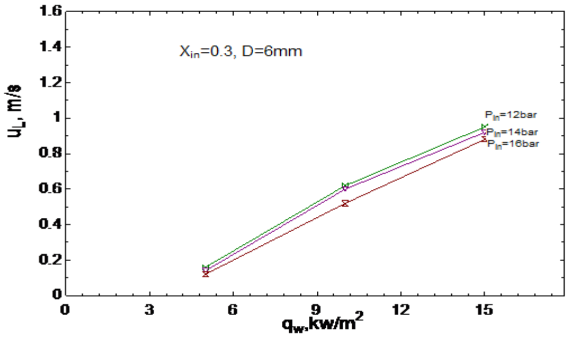
Operating conditions considered:

Parameters	Values
Heat flux ,q	1-30 kwm^{-2}
Tube diameters ,D	6-10mm
Mass flow rate ,G	50kgm^{-2} s^{-1}
Tube Length ,L	0.9m
Ammonia fraction , X_{in}	0.3 – 0.5
Inlet pressure ,Pin	12-18 bar

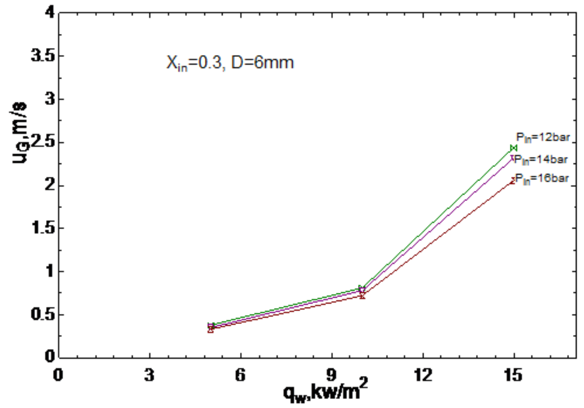
RESULTS AND DISCUSSIONS

The governing equations are solved using REFPROP and EES and for operated conditions illustrates in table at different diameters, different inlet solution, different pressure inputs and different heat flux. The mixture is assumed to be saturated in inlet of bubble pump tube. The results are tabulated and graphs are drawn as follows:

Influence of heat flux on liquid and vapour velocities for different operating pressures :



Graph 1 : Liquid velocity Vs Heat flux for X_{in}=0.3, D=6mm

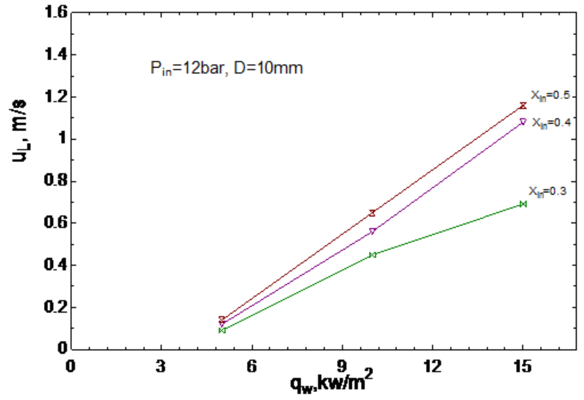


Graph 2 : Vapour velocity Vs Heat flux for X_{in}=0.3, D=6mm

Similarly for different diameters (8mm,10mm) , different inlet fractions (0.4.0.5) for these different three pressures .

- The influence of the operating pressure on liquid velocity and vapour velocity is shown in the above graphs
- The liquid velocity increases with increasing heat flux , reaches a maximum and the it may decreases
- As the operating pressure increases, liquid velocity decreases with increasing heat flux
- The vapour velocity increases linearly with the heat flux

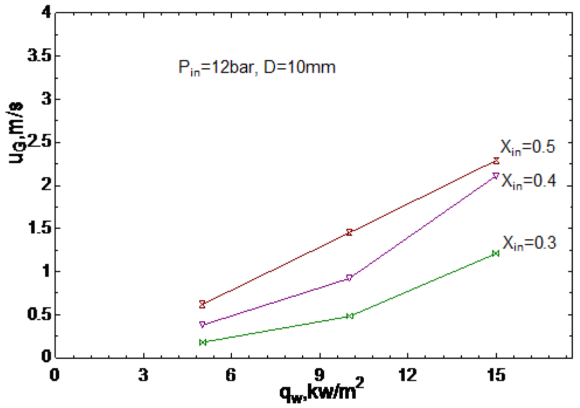
Influence of heat flux on liquid and vapour velocities for different ammonia fractions in inlet solution :



Graph 3: Liquid velocity Vs Heat flux for P_{in}=12bar, D=10mm

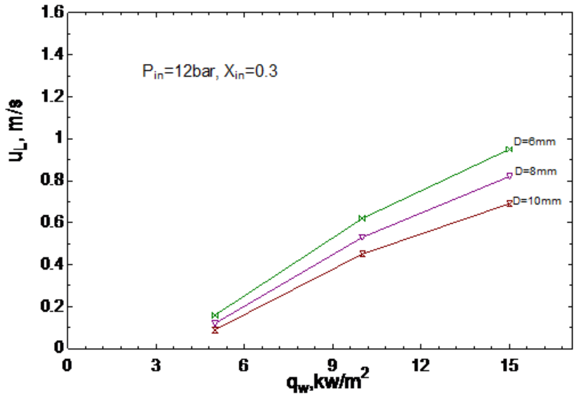
Similarly for different diameters (6mm,8mm) , different pressures(14bar,16bar) for these different inlet fractions .

- The influence of the operating pressure on liquid velocity and vapour velocity is shown in the above graphs
- The liquid velocity increases with increasing heat flux , reaches a maximum and the it may decreases
- As the operating pressure increases, liquid velocity decreases with increasing heat flux
- The vapour velocity increases linearly with the heat flux



Graph 4: Vapour velocity Vs Heat flux for P_{in}=12bar, D=10mm

Influence of heat flux on liquid and vapour velocities for different tube diameters:



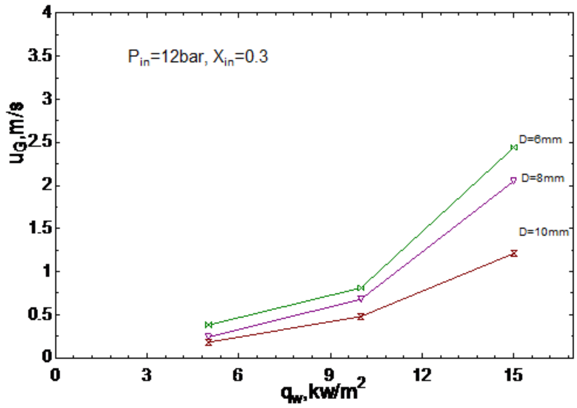
Graph 5 : Liquid velocity Vs Heat flux for P_{in}=12bar, X_{in}=0.3

Similarly for different pressures(14bar,16bar) different inlet fractions (0.4,0.5) for these different diameters .

- The influence of the tube diameter on liquid velocity and vapour velocity is shown in the above graphs
- The value of heat flux that corresponds to the maximum liquid velocity depends on

tube diameter. As the diameter increases, the liquid velocity decreases with increasing heat flux

- The vapour velocity increases linearly with increasing heat flux



Graph 6 : Vapour velocity Vs Heat flux for P_{in}=12bar, X_{in}=0.3

CONCLUSIONS

- The objective of the current study was to find optimum design parameters of the bubble pump using two phase flow correlations
- It was found that there is an optimum condition for which to operate the bubble pump , which is slug regime
- The influence of the heat flux and operating conditions on the flow characteristics was examined
- The liquid velocity variations present a maximum values that depend on operating conditions , whereas the vapour velocity varies linearly with heat flux

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