BUBBLE GENERATION IN A FLOWING LIQUID MEDIUM AND RESULTING TWO-PHASE FLOW IN MICROGRAVITY

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ABSTRACT

An experimental and theoretical research program is described herein to study bubble generation in a liquid flow in a pipe under reduced gravity conditions. The objective of the work is to study the bubble size and frequency of the generation and the resulting two-phase flow but it also concerns the fluid mechanical aspects of boiling in forced flow in microgravity. By injecting a gas into a liquid flow in a pipe through a small hole in the pipe wall we will investigate how the bubble expands and detaches from the wall, without involving the complexities of boiling. The experiments will be conducted both under isothermal conditions and with heat transfer from the wall. In the experiments with heat transfer the effect of thermocapillarity on the bubble formation and detachment will be the main subject.

INTRODUCTION

Two-phase systems including gas/liquid and liquid/liquid contacting systems are common phenomena encountered in many space applications, such as spacecraft thermal control systems, propulsion systems, power generation systems, cryogenic transfer and storage systems, life support systems, and other chemical/material process engineering systems. The design of two-phase systems for space applications requires a knowledge of heat- and mass-transfer processes under microgravity. The distribution and size of the dispersed phase are very essential for the analysis of heat and mass transfer, pressure drop and flow pattern in two-phase systems. Therefore, there is a great need to study how the bubble size and frequency can be controlled in microgravity.

Under microgravity conditions, the body force becomes negligible and surface tension effects become more important, thus very large and more spherical bubble or drop formation is expected. For control of bubble size and frequency, an additional force is needed for detachment of the bubble or drop. One practical way to obtain this additional force is to use the drag force of a flowing liquid near a confined solid boundary (such as the wall of a pipe). There have been numerous experimental and theoretical studies of bubble and drop formation in a quiescent continuous phase in normal gravity. In spite of the fact that in most industrial equipment applications, bubbles and drops are formed in the continuous phase moving past nozzles and orifices, the formation of bubbles and drops in a flowing continuous phase has received much less attention. Kim et al. (ref. 1) reviewed available work on the subject. However, all the empirical correlations developed in normal gravity cannot be applied directly to a microgravity environment by simply setting "g" equal to a low value. Therefore, in refs. 1 and 2 we have developed a theoretical model for the process of bubble and drop formation in flowing liquids, applicable for both terrestrial and microgravity environments. The model deals with two different flow systems; a co-flow and a cross-flow system. The model predictions agree well with available experimental results in normal gravity. They also evaluated the effects of the important dimensionless parameters on bubble and drop size in microgravity based on the model. We are currently conducting experiments in microgravity to test the model.

The current work is an extension of the ongoing work and we will study the process of bubble expansion and detachment from a wall surface which is also related strongly to the basic fluid mechanical phenomena involved in boiling in forced flow. The power demand of spacecraft is expected to increase in the future. The high operating power levels for future space applications require very efficient thermal transport techniques. Two-phase flow systems are considered to be effective in transporting heat in spacecraft where, traditionally, a single-phase flow loop, solid conductor, and heat pipe have been used for thermal management. Two-phase systems take advantage of the heat of vaporization of the cooling liquid. Thus, in order to design efficient two-phase systems for thermal transport we must understand boiling in forced flow in microgravity. A major area of concern deals with how the presence and eventual detachment of vapor bubbles from a solid surface affect heat transfer characteristics in microgravity. Boiling in forced flow is a complex subject and much work is needed to understand the phenomenon. The bubble formation and the detachment from the heating surface during boiling in microgravity are generally quite different from those in normal gravity. Therefore, we will study that aspect of boiling without getting involved directly in the mechanism of boiling.

Another important aspect of boiling in microgravity is that thermocapillarity becomes important under some conditions but the effect of thermocapillarity on boiling in microgravity has not been investigated in detail. Thermocapillarity is usually overwhelmed by buoyancy in normal gravity. However, it is an important driving force for fluid flow in microgravity and we have conducted space experiments on thermocapillary flows (refs. 3 and 4). During boiling the wall is superheated so that the liquid temperature is lower than the wall temperature and there exist interfaces between the liquid and vapor. Then, in the absence of buoyancy, thermocapillary force could become important in the process of bubble generation and detachment. The thermocapillary force is caused by the variation of surface tension along the interface. Since surface tension decreases generally with increasing temperature, the liquid near the interface is pulled toward the colder region, namely away from the wall. The resultant liquid flow near the wall may have an important effect on the bubble behavior.

The thermocapillarity is represented by the dimensionless parameter called surface tension Reynolds number, $R\sigma = \sigma_T \Delta T D_p/\mu_c \nu_c$, where σ_T is the temperature coefficient of surface tension, ΔT the overall temperature variation in the flow, and ν_c the kinematic viscosity. Then the ratio of the liquid flow inertia to thermocapillary forces can be expressed as $Re_p/ R\sigma$. Using the properties of water, the ratio is computed to be about 0.1 for the aforementioned liquid velocity of 10 cm/s and $\Delta T = 10$ °C, which means that the thermocapillary flow actually overwhelms the main liquid flow. Therefore, it is very important to consider the effect on boiling in microgravity. Besides, this thermocapillary effect gives us an additional option to control the size of bubbles in other applications. For example, in case where both the liquid and gas velocities cannot be changed easily because of flow rate constraints, the temperature difference between the wall and the liquid can be adjusted to obtain a desired bubble shape.

DESCRIPTION OF WORK

Experimental Work

In normal gravity one important dimensionless parameter for bubble generation in a flowing liquid is the Froude number, $Fr = \rho_c U_{LS}^2/((\rho_c - \rho_d)g\, D_p)$, where U_{LS} is the superficial liquid velocity, D_p the pipe diameter, ρ_c the liquid density, ρ_d the density of the gas, and g gravitational acceleration. Fr represents the ratio of the inertia forces of the liquid flow to buoyancy. When Fr is much larger than unity, the inertia dominates over buoyancy and thus the flow and the bubble behavior are essentially the same both in one-g and in microgravity. The difference becomes important when Fr is about unity or smaller and that is the situation we will study in microgravity. For example, for a liquid/gas system with a pipe diameter of 2.5 cm in one-g, the liquid velocity is on the order of 50 cm/s or smaller to satisfy the Fr condition. Moreover, we will focus on the laminar flow regime to simplify our analysis, which means the Reynolds number of the liquid flow must be below about 2,500. The Reynolds number is defined as $Re_p = \rho_c U_{LS} D_p/\mu_c$, where μ_c is the viscosity of the liquid. Then, for water flow through a 2.5 cm dia. pipe, for example, the liquid velocity should not go beyond 10 cm/s. As for the gas velocity range, the momentum flux of the gas flow $\rho_d U_G^2$ (U_G = gas velocity at nozzle exit) must be smaller than that of the liquid flow $\rho_c U_{LS}^2$, otherwise the gas flow comes out as a jet. Then, for a water-air system with a liquid velocity of 10 cm/s, the air flow velocity must be less than 3 m/s and if the nozzle diameter is about one-fifth of the pipe diameter, for example, the superficial gas velocity is less than 10 cm/s. For such ranges of liquid and gas superficial velocities the two-phase flow will be in the bubble-flow or slug-flow regime in microgravity. For those flow regimes it is important to understand how an individual bubble is formed and how the bubbles coalesce.

The experimental part is an extension of our current effort. We are conducting microgravity experiments on bubble generation aboard the DC-9 Reduced Gravity Research aircraft at NASA Lewis. In that work, air is injected from a nozzle into water flow in a pipe. The air injection is either in the direction of the water flow (co-flow configuration) or normal to the flow (cross-flow configuration) as illustrated in Fig.1. For both configurations plexiglass pipes of inner diameters 1.27, 1.9, and 2.54 cm are used. Nozzle diameters are 10 and 20 % of a given pipe inner diameter. Superficial gas and liquid velocities are in the range of 5 to 70 cm/s for the 1.27 cm test section and in the range of 5 to 40 cm/s for the 1.9 and 2.54 cm test sections

The main objective of the work is to study the final dimensionless bubble size (ratio of bubble dia. to pipe dia.) under various ranges of the important dimensionless parameters of the problem (ratio of pipe dia.to nozzle dia., ratio of superficial gas velocity to superficial liquid velocity, liquid flow Reynolds number (Re_p defined earlier), and Weber number). The Weber number is defined as $We_p = \rho_c U_{LS}^2 D_p/\sigma$, where σ is the surface tension. In normal gravity the Froude number defined earlier is also important. The process of bubble expansion and detachment is studied mainly photographically. The results will be compared with our model predictions.

The present work will be expanded to study how a bubble is removed from the pipe wall to simulate the conditions during boiling and in other applications. In our present study the injection nozzle tip is placed above the pipe wall in the cross-flow configuration (Fig.1) to minimize the effect of the wall. However, in the proposed work the nozzle tip will be flush with the pipe wall so that the bubble interacts directly with the wall (Fig.2). The experiment will be conducted with and without heating a portion of the pipe wall. Both tests are described below.

Bubble generation without heat transfer---First we will study bubble generation under isothermal conditions. We will investigate the most basic configuration, namely the generation of a single bubble. By using a single hole we will investigate the process of bubble formation and detachment under various conditions as in the present work. We will vary the pipe diameter, the hole diameter, the liquid velocity, and the gas velocity to cover ranges of the dimensionless parameters. The test fluids will be mainly water and air. We will also use a silicone oil-air system in conjunction with the heat transfer experiment discussed later. The process will be videotaped and analyzed. The size and shape of detached bubbles will be determined and compared with the prediction of our model. Since the mechanism of bubble detachment is not well understood in microgravity, the experimental information will help us refine the theoretical model. We will also investigate the relationship between the detached bubble size (relative to the pipe diameter) and the downstream two-phase flow regime. In ref. 2 we have conjectured that if the bubble size relative to the pipe diameter becomes larger than a certain value, the downstream two-phase flow regime changes from the bubble-flow to slug-flow, which seems to agree with available experimental data. Since it is an important transition for two-phase flow, we will study the transition condition in detail. Most of the isothermal experiments will be conducted in parabolic flights using mostly the existing NASA Lewis two-phase flow facilities.

Bubble generation with heat transfer---With bubble generation from a heated wall (without boiling) our main interest will be the effect of thermocapillarity on the process of bubble formation and detachment. In order to study mainly the fundamental nature of the effect, we will use only the single hole arrangement in the proposed experiment. A portion of the pipe around the hole will be heated by heating elements attached to the pipe outside wall. The air injected from the nozzle will have the same temperature as the heated wall. An important new dimensionless parameter in the problem is the aforementioned surface tension Reynolds number, $R\sigma$. Marangoni number, $Ma = R\sigma/Pr$ (Pr = Prandtl number), is also used in thermocapillary flow study. In normal gravity buoyancy is also important but we will focus on reduced gravity conditions. Since it is known that a water-air interface is very sensitive to surface contamination, we will use silicone oil (2 or 5 centistokes kinematic viscosity) as the test liquid in conjunction with air. In addition to the study of bubble expansion and detachment, we will investigate the flow around the bubble in detail. The main diagnostic tool will be flow visualization. For that we will mix a small amount of tracer particles into the test liquid and the flow near the nozzle will be illuminated by a laser light sheet. We will study their motion by a video camera. The motion of individual particle will be analyzed by a PIV technique, from which the flow field will be constructed. The same technique has been used in the aforementioned space experiment on thermocapillary flows. The flow field study will be done with and without heating to see the effect of thermocapillarity on the flow. Also, the size and shape of detached bubble will be compared. The work will be guided by the theoretical analysis discussed below. One complication associated with the flow visualization with heat transfer is that the flow field near the nozzle is blocked form our view by the heating elements. One way to see the flow field is to use thin metallic film heaters through which we can observe the flow field, similar to the heating elements used by Merte (ref.5). We will also investigate other options for the visualization. Experimentally, the pipe diameter will be fixed at about 2.54 cm (1") and the nozzle diameter, the liquid flow rate, the gas flow rate and ΔT will be varied to cover ranges of velocity ratio, diameter ratio, Re_p, We_p, and $R\sigma$.

Although some tests with heat transfer will be conducted in parabolic flights, we will need a longer duration of microgravity to study the effect of thermocapillarity accurately. The reason is that with heating buoyancy flow will be generated during the pull-back period of parabolic flights (the acceleration is about 2-g) and it will interfere with the thermocapillary flow during most of reduced gravity periods.

Theoretical Work

A theoretical modeling is an important part of our bubble generation work. From the modeling work we can learn the basic physical process of bubble expansion and detachment. After an accurate model is developed, it can be used to predict the bubble behavior in other experiments and also, very importantly, it helps us to design a practical system which requires controlled bubble size. We have developed a theoretical model to predict the size of a bubble after its detachment for the configurations illustrated in Fig.1. The model is partly based on available experimental information obtained in one-g tests. We are going to test the model in our ongoing work. The bubble detachment condition from the nozzle is very important in determining the final bubble size. In the current model it is based on observations of bubble detachment under various conditions in one-g. We will study the detachment in the current experiment and, if necessary, we will modify the condition used in the model in this proposed work. We will also analyze the detachment mechanism for the injection from a hole in the pipe wall and develop a theoretical model for bubble expansion and detachment for that situation. The bubble detachment from a wall is different from that from a nozzle because the contact line of the gas bubble is fixed at the nozzle in the latter configuration but it can move along the wall during the bubble expansion in the former configuration. The difference must be taken into account in the modeling.

We will first modify our present model on bubble generation. It is based on a global force balance. The current model will be tested in our ongoing work and will also be used to design the present experiment. In the present model the injected bubble does not interact with the pipe wall and is held at the nozzle tip by surface tension. The bubble is assumed to be spherical in the present model. In the modified model the bubble will be attached to the wall with its neck size independent of the nozzle diameter (Fig.2). Therefore, the bubble shape during the expansion stage is not generally spherical and depends, among other factors, on the contact angle. Also, the condition at the bubble neck at the time of detachment is very important in the model. The current detachment model is based on available ground-based experimental information about bubble detachment from a nozzle without the wall effect. Therefore, we need experimental information regarding the shape of a bubble during the whole process in microgravity to modify our current model. Based on that information we will modify the formula to compute the net hydrodynamic drag on the bubble and the net surface tension force at the contact line between the gas and the wall following the procedure described below.

First, we will characterize the bubble shape under various conditions based on the experimental information. From that information we will develop a formula to compute the net drag on the bubble including the effect of the wall. In the development process we will perform potential flow analysis to obtain information regarding the pressure distribution around the bubble. As for the net surface tension force, we will first characterize the contact line motion during the bubble expansion from the experimental information; we will need information regarding the neck size and contact angle. This contact line characterization is generally a difficult problem because it deals with dynamic contact angle. Since we will be performing a global force balance in this work, it is not necessary to characterize the contact line behavior in detail, so we will develop an approximate model for the contact line behavior. The detachment condition is also complex generally but for the detachment from a nozzle in one-g relatively simple conditions seem to work, namely by checking the bubble neck length relative to the nozzle diameter or the location of the bubble center relative to the nozzle location it is possible to identify the detachment (ref. 2). We will develop a detachment condition based on similar criteria from the data. Finally, we will put those information into the model and compute the final bubble size under various conditions, compare with the experimental data, and refine the model further, if necessary.

With heat transfer we will analyze the effect of thermocapillarity by scaling analysis. We have done scaling analyses in the past on various subjects including thermocapillary flows (e.g. ref. 6). We will follow basically the same procedure as in our past studies to find the important velocity and length scales in various regions and to determine the important forces at various locations. The information will be used to guide the above experimental measurement and also will help us analyze the experimental data. The result from the scaling analysis will also be used in the global force balance to develop a model for bubble generation with thermocapillarity. The procedure for developing the model will be the same as the procedure described above for the isothermal conditions. As mentioned above, the experiments with heat transfer require an extended microgravity of space and the modeling needs the experimental information, so only preliminary work will be done for the model development with thermocapillarity in the proposed four-year period.

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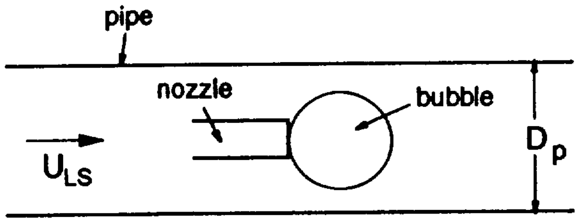
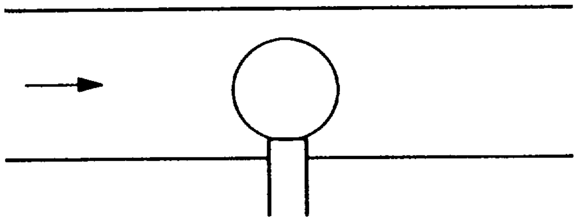


(a) Co-flow system



(b) Cross-flow system

Figure 1. Bubble injection from a nozzle.

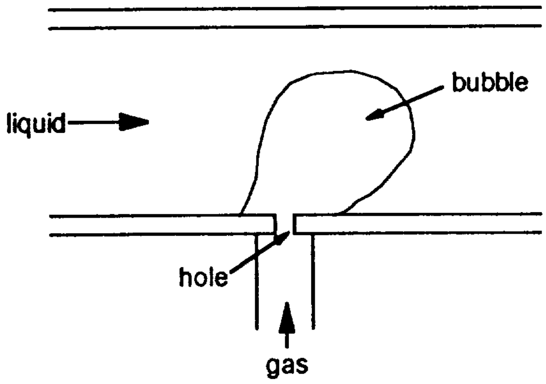


Figure 2. Bubble injection from a hole.