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Review

Two-phase flow and pool boiling heat transfer in microgravity

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ABSTRACT

Researches on two-phase flow and pool boiling heat transfer in microgravity, which included ground-based tests, flight experiments, and theoretical analyses, were conducted in the National Microgravity Laboratory/CAS. A semi-theoretical Weber number model was proposed to predict the slug-to-annular flow transition of two-phase gas–liquid flows in microgravity, while the influence of the initial bubble size on the bubble-to-slug flow transition was investigated numerically using the Monte Carlo method. Two-phase flow pattern maps in microgravity were obtained in the experiments both aboard the Russian space station Mir and aboard IL-76 reduced gravity airplane. Mini-scale modeling was also used to simulate the behavior of microgravity two-phase flow on the ground. Pressure drops of two-phase flow in microgravity were also measured experimentally and correlated successfully based on its characteristics. Two space experiments on pool boiling phenomena in microgravity were performed aboard the Chinese recoverable satellites. Steady pool boiling of R113 on a thin wire with a temperature-controlled heating method was studied aboard RS-22, while quasi-steady pool boiling of FC-72 on a plate was studied aboard SJ-8. Ground-based experiments were also performed both in normal gravity and in short-term microgravity in the drop tower Beijing. Only slight enhancement of heat transfer was observed in the wire case, while enhancement in low heat flux and deterioration in high heat flux were observed in the plate case. Lateral motions of vapor bubbles were observed before their departure in microgravity. The relationship between bubble behavior and heat transfer on plate was analyzed. A semi-theoretical model was also proposed for predicting the bubble departure diameter during pool boiling on wires. The results obtained here are intended to become a powerful aid for further investigation in the present discipline and development of two-phase systems for space applications.

1. Introduction

Two-phase gas–liquid systems have wide applications both on Earth and in space. On Earth, they occur in a variety of process equipments, such as petroleum production facilities, condensers and re-boilers, power systems and core cooling of nuclear power plants during emergency operation. The potential space applications include active thermal control system, power cycle, storage and transfer of cryogenic fluids, and so on. Reliable design of such systems requires a thorough understanding of the mechanism of two-phase flow, such as the phase distributions (flow patterns), pressure drops and heat transfer coefficients at different gas and liquid flow rates.

With the aid of numerous meticulous experiments, our present knowledge on two-phase gas–liquid systems has been built. It is, however, far from complete due to the complicate influence of gravity which is a dominant factor in normal gravity. Gravity strongly affects many phenomena of two-phase gas–liquid systems by creating forces in the systems that drive motions, shape boundaries, and compress fluids. Furthermore, the presence of gravity can mask effects that ever present but comparatively small. Depending on the flow orientation and the phase velocities, gravity can significantly alter the flow patterns, and hence the pressure drops and heat transfer rates associated the flow. Advances in the understanding of two-phase flow and heat transfer have been greatly hindered by masking effect of gravity on the flow. Therefore, the microgravity researches will be conductive to revealing of the mechanism underlying the phenomena, and then developing of more mechanistic models for the two-phase flow and heat transfer both on Earth and in space.

Research on two-phase gas–liquid flow and heat transfer in microgravity has a history of more than 50 years with a short pause in the 1970s and has been advanced with the development of various microgravity facilities and with increased experimental opportunities, especially in the last two decades. On the progress in this field, many comprehensive reviews and monographs are available now. Among many others, Hewitt (1996), McQuillen et al. (1998), Straub (2001), Di Marco (2003), Kim (2003), Ohta (2003a, b), and Gabriel (2007) summarized the experimental and theoretical works all over the world.

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Since the middle of 1990s, a series of microgravity research projects on two-phase gas–liquid flow and pool boiling heat transfer in microgravity have been conducted in the National Microgravity Laboratory/CAS (NMLC). These activities cover two parts, namely two-phase gas–liquid flows in pipelines, and heat transfer and bubble behaviors in pool boiling. In the following sections, the results obtained in these researches will be presented. In the end, some future projects for microgravity two-phase flow and boiling in China will also be introduced.

2. Two-phase gas–liquid flows in pipelines in microgravity

2.1. Microgravity flow pattern transition models

Because the influence of buoyancy is removed or weakened strongly, two-phase flows in microgravity are believed inherently simpler than those in normal gravity. For example, although other flow patterns appearing essentially in the transition zones are classified by some researchers, annular, slug, and bubble flows are usually considered as the major two-phase flow patterns in straight pipes in microgravity. Thus, there are two major transitions need to be modeled in microgravity.

For predicting the slug-to-annular flow transition in microgravity, the void fraction matched model proposed by Dukler et al. (1988) and modified by Colin et al. (1991) and Bousman (1995) is commonly used for the case of turbulent liquid and gas phases (Zhao, 2000). As shown in Fig. 1, it is possible that there will be 0, 1, or 2 solutions in this model according to the different values of the phase distribution parameter C_0 in the drift-flux model and the material parameter $\zeta = (\rho_G/\rho_L)(v_G/v_L)^{1/5}$ (here ρ and v denote the density and viscosity, respectively, while the subscripts G and L denote the gas and liquid phase, respectively). The solutions will alter if different correlations for interfacial friction, such as those proposed by Wallis (1969) and Chen et al. (1991), are used. Furthermore, the suggestion of Dukler (1989) that the slug-to-annular flow transition will take place at the solution of smaller void fraction is not a feasible criterion. For example, such a solution may locate in bubble flow regime for the case of $\zeta = 0.001$, which approximates to the experimental condition of Dukler et al. (1988).

A semi-theoretical Weber number model was developed firstly by Zhao and Hu (2000), and later modified by Zhao et al. (2001a), which was based on the balance between the impulsive force due to the gas inertia and the surface tension force near the slug-to-annular flow transition in microgravity. As shown in Fig. 2, the model can provide an improvement of the accuracy in comparison with others (Bousman, 1995; Reinarts, 1995; Carron and Best, 1996; Jayawardena et al., 1997; Lowe and Rezkallah, 1999). It was also proved to be accurate over a rather wide range of working fluids, tube diameters, and experimental methods including both flight experiments and ground simulated tests such as capillary gas–liquid experiments and equi-density, or neutral buoyancy, immiscible liquid–liquid experiments on the ground.

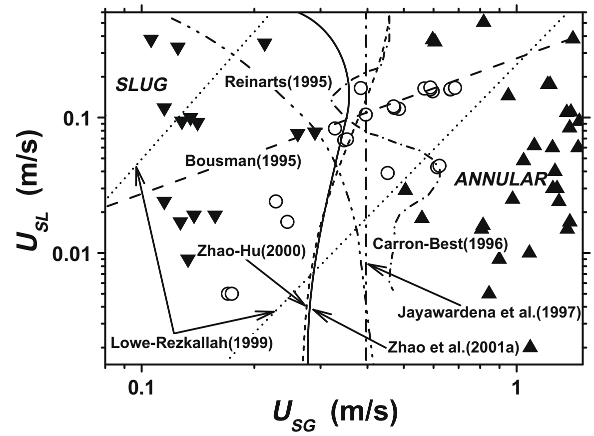

Fig. 2. Comparisons of the semi-theoretical Weber number model with the experimental data of Reinarts (1993) and other commonly used models. Symbols ▲,▼,○ denote slug, annular, and transitional flows, respectively. Re-drawing after Zhao et al. (2001a).

For predicting the bubble-to-slug flow transition in microgravity, the drift-flux model (Dukler et al., 1988; Colin et al., 1996) was commonly used in the literature. The empirical model proposed by Jayawardena et al. (1997) can also be re-written in the same form. It was, however, found that there exists an obvious difference between bubble flows in mini-scale channels in normal gravity and those in normal channels in microgravity. It may arise from the difference of the relative bubble initial size in the two cases. A Monte Carlo method was then used to simulate the influence of the initial bubble size d_b on the bubble-to-slug flow transition based on the bubble coalescence mechanism (Zhao, 2005). It was found that the dimensionless rate of collision is a universal function of the dimensionless bubble diameter d_b/D (where D denotes the pipe diameter), and that the bubble initial size can affect the bubble-to-slug flow transition when its dimensionless value locates in the range from 0.03 to 0.4. Assuming the transition void fraction α_{cr} depends only on the dimensionless collision rate, the correlation for the critical void fraction, $\alpha_{cr} = 0.60–2.32d_b/D$, was obtained,

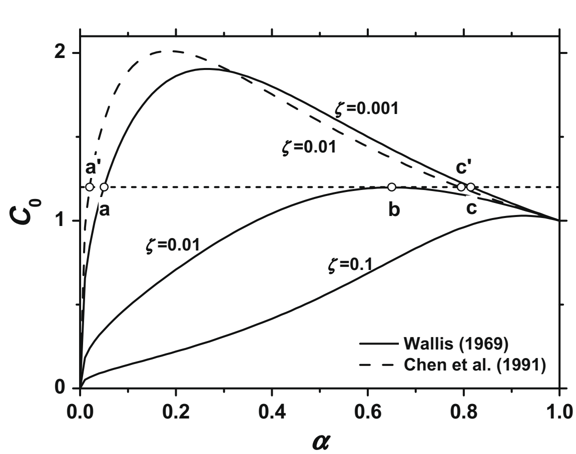

Fig. 1. Characteristics of the solution of the void fraction matched model for the slug-to-annular flow transition in microgravity. Re-drawing after Zhao (2000).

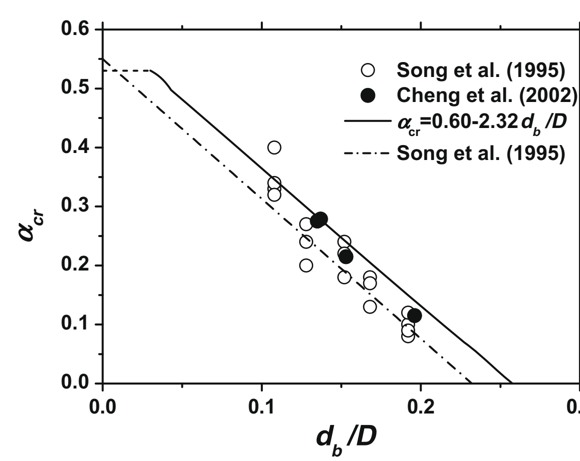

Fig. 3. The influence of bubble initial size on the transition void fraction for the bubble-to-slug flow transition. Re-drawing after Zhao (2005).