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Regulation of gas-liquid stratified flow boiling dynamic instabilities in horizontal tube: Effects of heat load distribution and wall thermal capacity

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ABSTRACT

In this work, an experimental investigation on the regulation of gas-liquid stratified flow boiling dynamic instabilities was carried out in a 1530 mm long horizontal arranged copper tube with an inner diameter of 12 mm. Two different thermal boundary conditions, namely (i) heat load distribution, (ii) wall thermal capacity were investigated. Three different heat load distributions (uniform heating, power decrease and power increase) and three kinds of tube with different thickness of graphite casing tubes (bare, 6 mm and 12 mm) were analyzed, respectively. The results showed that the oscillation intensity of gas-liquid stratified flow boiling dynamic instabilities was highly related to occurrence of the onset of nucleating boiling (ONB). In comparison with the based cases, the power increase heat load condition especially that with lower inlet subcooling degree and the case with thicker graphite casing tube had delayed the occurrence of ONB. And finally a suppression of dynamic instabilities was obtained. On the contrary, an early occurrence of ONB and an enhancement of gas-liquid stratified flow boiling instability were obtained for the other two cases.

1. Introduction

Two-phase flow instabilities occur frequently in various thermal energy conversion systems such as steam generators, conventional and nuclear power plants, refrigeration equipments, solar thermal systems, and heat exchangers, etc. [1–6]. The harms of undesirable flow instabilities in system control and operation, local heat transfer, mechanical vibrations have already been widely recognized. It has been a widespread consensus to regulate and control the two-phase flow instabilities on the basis of deepening the understanding of the mechanisms of two-phase flow instabilities. The mechanism of two-phase flow instabilities has been systematically studied in the past decades after a literature review [1–3]. The mechanism of dynamic instability involved propagation or transport disturbances, such as inertia, propagation time, compressibility, etc. [2].

The research work on two-phase flow instabilities in the past few decades has been focused on the high heat and mass flow rate in vertical tube since its popularization in industry such as the traditional power plant and nuclear power plants etc. With the development of energy saving and renewable energy, however, two-phase flow in horizontal tube, especially the one with low heat and mass flow rate, is also getting more and more attentions [7–10]. The main difference of the two-phase flow between horizontal and vertical tube is the effect of gravity. As the flow rate decreases, the two-phase flow in horizontal tube trends to stratify. Therefore it is of great importance to understand the differences of dynamic instabilities between horizontal flow and vertical flow, albeit there is no difference on oscillation mechanisms.

Presently, some research work on the effects of parameters on flow boiling instabilities in horizontal tubes has been carried out [11–15]. These studies, however, did not clarify the flow pattern, especially the gas-liquid stratified flow, according to the experimental test ranges and results. And the objectives were not dedicated to the instability of gas-liquid stratified flow. In gas-liquid stratified flow, Yin et al. [16] presented the flow pattern development from bubble flow to annular flow for water boiling in horizontal tubes. And a flow pattern map based flow boiling heat transfer characteristics including the gas-liquid stratified flow were studied by Kattan et al. [17–19], Ursenbacher et al. [20], Wojtan et al. [21–24]. Although these studies have concerned with the gas-liquid stratified flow boiling heat transfer, the two-phase

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flow instabilities were omitted. Recently, Ibarra et al. [25] and Morgan et al. [26]investigated the effects of Rayleigh-Taylor instability in liquid-liquid stratified flow using a novel simultaneous two-line technique combining planar laser-induced fluorescence (PLIF) with particle image/tracking velocimetry (PIV/PVT) to elucidate phase and velocity information. Moreover, Zhang et al. [27] investigated the thermal performance of gas-liquid stratified flow boiling in a natural circulation thermosyphon loop based on the applications in parabolic trough systems. And the instabilities of flow pattern and backflow were investigated based on the conditions of gas-liquid stratified flow [28–30]. The effects of inlet subcooling and heat flux on dynamic instabilities of gas-liquid stratified flow in horizontal tube were also investigated [31] recently. The results show that the inlet subcooling degree and heat flux has a significant effect on the gas-liquid stratified two-phase flow instabilities which was in consistent with the main conclusions for the two-phase flow instabilities in horizontal tubes.

Although most of the present studies were concentrated on the characteristics of two-phase flow instabilities, some preliminary research work on the modification of the two-phase flow instabilities were also carried out. Karsli et al. [32] and Windmann et al. [33] investigated the effect of internal surface modification on flow instabilities in forced convection boiling in a horizontal tube. And a stronger oscillation was obtained for tube with enhanced surface in comparison to bare tube. In addition, Guo et al. [34] firstly pointed out that moving compressible volume from the inlet of the steam generator upstream could dramatically suppress the occurrence of pressure drop oscillation. And non-uniform heat flux distribution along the flow direction would seriously decrease the initial boundaries of pressure drop oscillation (PDO), especially when higher heat flux was applied to the higher mass quality region. And a similar results for the effects of the compressible volume on two-phase flow instabilities in a closed natural circulation loop was also reported by Cheng et al. [35]. Chiapero et al. [36] reported that a higher heat flux at the beginning would result in a steeper negative slope of the two phase flow in horizontal tube. Moreover, the effects wall thermal capacity on two-phase flow instability were investigated by Stenning and Veziroglu [37], Liu et al. [38], Umekawa et al. [39], and Zhang et al. [40]. Liu et al. [38] reported that the wall thermal capacity and the characteristics of convective transition boiling heat transfer were the source of dynamic of thermal oscillation. A higher axial temperature difference would intensify the oscillation. Umekawa et al. [39] investigated the critical heat flux (CHF) under dynamic instabilities condition in three different diameter tubes with different heat capacity. And the results showed that the reduction of the CHF ratio of the large heat capacity tube was smaller than that of the small heat capacity tubes. Stenning and Veziroglu [37] and Zhang et al. [40] confirmed that an increase of wall thermal inertia would suppress the compressible flow boiling oscillations since the wall thermal inertia controls the exact heat exchange rate between the external heat load and internal heat absorption, respectively. Kuo and Peles [41] and Kandlikar et al. [42] investigated the effects of fabricated nucleation sites on stabilization of two-phase flow instabilities in micro-channels, respectively. It is worth pointing out that although these studies do not involve the gas-liquid stratified flow, they still have important referential significance for the regulation of gas-liquid stratified flow boiling instabilities. And a further work on the stratified flow boiling condition should be carried out.

In the present study, an extended work is devoted to regulate the dynamic instabilities of gas-liquid stratified flow as presented in Ref. [31]. The effects of heat load distribution and wall thermal capacity were analyzed, respectively. And the regulation mechanisms were also discussed based on the development of gas-liquid stratified flow boiling.

2. Experimental methodology

2.1. Experimental setup

Fig. 1 shows the schematic diagram of the experimental test rig of two-phase flow boiling in horizontal tube. The system mainly consisted of three parts: preheater, evaporator (test section) and condenser. The working process of the system was as follow: The working fluid (water) was firstly preheated to a setting temperature in the preheater and then flowed into the evaporator through the pump. The working fluid at a setting inlet temperature was heated to gas-liquid stratified flow under an appropriate heating load in the evaporator. Then the outlet steam was condensed in the coiled condenser and stored in a tank. The evaporator was made of a 1530 mm long cooper tube with a diameter of 12 mm. The evaporator was uniformed coiled with three equal parts of nickel-chromium electric heating wires. And the heating power of the three equal heating sections could be controlled by the voltage (U) and current (I) separately. The length of each heating section was 430 mm and with an 80 mm long space for sensor installation. Two T type thermocouples were placed (up and down, denoted by subscripts 1 and 2, respectively) between the heating sections and the two ends of the evaporator (cross sections A–D). Meanwhile, a T type armor thermocouple was inserted into centerline of the tube at the two ends of the evaporator to monitor the inlet and outlet fluid temperature, respectively. A glass window was placed at the inlet ant outlet of the evaporator to monitor the flow pattern. In addition, there was one T type thermocouple was placed at the two ends of the preheater and condenser to monitor the fluid temperature. Two pressure sensors (±0.2%) and one differential pressure transducer (±0.3%) were installed at the two ends of the evaporator to measure the inlet and outlet pressure and pressure differential of the evaporator, respectively. A mass flowmeter (*G*, DMF-1-3-B,) with an accuracy of ±0.2% was installed before the preheater. Thermocouples in this test rig were calibrated to an accuracy of ±0.1 °C.

The maximum uncertainties of the voltage, current, diameter, length, pressure and mass flow rate is 1.0%, 1.0%, 0.1%, 0.1%, 2.11% and 4.0%, respectively. The uncertainty of heat loss was estimated to be 4.25%. The maximum uncertainty of the heat flux was estimated to be 4.5%. The uncertainty of the wall superheat was estimated to be 5.0% [31].

2.2. Description of the regulation methods

In this work, the effects of heat load distribution and wall thermal capacity was considered on the regulation of dynamic instabilities of gas-liquid stratified flow. Based on the instability boundary of the system which was determined by our previous work [31], the values of heat flux and inlet subcooling degree were all selected to be in the unstable region in this work.

2.2.1. Heat load distribution

As mentioned above, the heat load at each heating section can be controlled separately. Fig. 2 shows the details of the three kinds of heat load distribution along the evaporator. An average heat flux of 6.17 kW/m^2 and an average mass flow rate of 24.57 kg/m^{2}s were selected in this experiment. Based on the uniform heating condition (baseline, case 1), two other heat load conditions (case 2: power decrease, case 3: power increase) were adopted. In order to keep a constant dryness fraction at the outlet, the total heat load for the three cases was kept consistent. In the meantime, two types of instability oscillation (pressure drop oscillation, PDO and density wave oscillation, DWO) were obtained by gradually decreasing the