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Experimental study on bubble dynamics and wall heat transfer arising from a single nucleation site at subcooled flow boiling conditions – Part 1: Experimental methods and data quality verification

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ABSTRACT

A novel experimental method and data acquisition/analysis strategy that ensures reliable measurements of various subcooled flow boiling parameters is discussed. In this study, all experiments were performed by keeping a single active nucleation site within the entire heated area in a square upward flow channel. This approach greatly facilitated the observation of bubble and wall heat transfer features in subcooled boiling flow.

Vapor bubbles originating from the nucleation site were observed with both micro- and macroscopic views from high-speed cameras while corresponding wall temperature was measured by an infrared camera. This allowed simultaneously capturing various bubbles characteristics with multiple scales (both space and time) as well as their impact on wall heat transfer. In addition, efforts were made to characterize the observed boiling behavior with high statistical accuracy by analyzing numerous images taken at each test condition.

This study proves that by taking the current strategy excellent repeatability and thus reliability can be achieved for a wide range of flow boiling parameters such as bubble size, bubble velocity, statistical distribution of bubble size and time-averaged wall heat transfer coefficients. Also, the major sources of uncertainty for each measurement are thoroughly investigated, from which the final uncertainties are determined. Overall, the present study suggests what we must concern to achieve truly reliable and useful data from any boiling experiments.

1. Introduction

Forced convective boiling has been extensively studied both theoretically and experimentally because of its practical importance in the performance and reliability of many engineering applications such as nuclear reactors and electronic devices. Consequently many empirical correlations and mechanistic models have been proposed to predict the involved phenomena, which have been widely utilized in CFD simulations of two-phase flow boiling systems (Anglart et al., 1997; Bae et al., 2010; Krepper and Rzehak, 2011; Podowski and Podowski, 2009; Yeoh et al., 2008). However, the prediction capability associated with boiling using CFD code still remains unsatisfactory. The main issue is that the level of confidence of the CFD prediction strongly relies on the validity of constituent closure models. Therefore, to improve the current situation, the existing closure models should be significantly improved based on the correct understanding of the boiling mechanism. To this end, 'reliable' experimental data that can be used for boiling model validation and development are of critical importance. However, producing such high-quality data from any boiling experiment is not a simple task, and this difficulty has often caused substantial scattering and/or inconsistency of the measurements such as bubble departure/lift-off size and bubble frequency among researchers (Chu et al., 2011; Prodanovic et al., 2002; Situ et al., 2005; Situ et al., 2008). The major issues and/or difficulties affecting measurement accuracy in boiling experiments can be summarized as follows:

(1) The difficulty of measuring and characterizing boiling process originates from the chaotic nature of the phenomenon. That is, the experimental results such as bubble departure size and frequency can be affected even by small changes of

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the test boundary conditions. Also, boiling can often be initiated unexpectedly due to small perturbations such as the random deposition of small impurities on the heater surface; and such incipience of boiling usually affects the overall heat transfer characteristics of the system significantly while increasing its phenomenological complexity.

(2) Another issue results from the inherently stochastic nature of the boiling parameters. For instance, the bubble departure size and frequency measured under a given boiling condition are always presented as a distribution rather than a single deterministic value. This implies that such distributions are important for the description of boiling phenomena and should be well-characterized in addition to the statistical average of the measured parameters. Also, the stochastic nature of boiling parameters usually requires the analysis of numerous samples in order to correctly represent the boiling characteristics at a given condition.

(3) As revealed in our previous study (Yoo et al., 2014), due to the local, fast, and random nature of the wall nucleation process, the observation view of nucleating bubbles and/or camera resolution can cause significant mis-measurement which leads to inaccurate experimental results of boiling parameters.

(4) Finally, gaining complete insight into the boiling heat transfer mechanism based on the limited number of parameters measured is always challenging because the boiling process generally accompanies a variety of thermal-hydraulic subprocesses which are tightly coupled to one another.

To the best of our knowledge, despite the extensive experimental works reported in literature, especially for forced convective boiling (Abdelmessih et al., 1972; Chu et al., 2011; Klausner et al., 1993; Li et al., 2013; Okawa et al., 2005; Unal, 1976), few works are free of those issues mentioned above. This is often due to the limitations of available experimental techniques and/or the significance of such issues in boiling experiments has yet to be well recognized by experimentalists. Of course, our understanding on the boiling phenomena has progressed substantially due to such previous experimental efforts; and a number of empirical correlations (Ivey, 1967; Kocamustafaogullari and Ishii, 1983) and mechanistic models (Klausner et al., 1993; Yeoh et al., 2008; Zeng et al., 1993) have been developed and validated based on them. However, in order to fill the gap that is still debatable regarding the convective boiling heat transfer mechanism and its modeling, a more precise experimental approach is required. In particular, the effort to overcome the shortcomings existing in earlier experimental works related to the measurement issues described in the list above can be a good start to reach the goal more efficiently.

In this context, we devised a subcooled flow boiling experiment in a square, vertical, upward flow channel. The main objective is to improve the fundamental insight into the subcooled flow boiling process through the intensive and extensive observation of boiling parameters with a multi-scale observation approach. For this, high-speed photography and infrared (IR) thermometry were simultaneously employed based on the experimental method established by Yoo et al. (2015). Using this method, we could capture both bubble dynamics and boiling heat transfer features with high fidelity in a single flow boiling facility. In addition, a special effort was made to better investigate the characteristics of thermal-hydraulic process within the subcooled flow boiling channel by addressing the anticipated issues of boiling measurement as follows: (i) To avoid the phenomenological complexity caused by the random presence of nucleation sites, the heater was specially designed to keep a single active nucleation site over the entire heated area during the experiments. (ii) To improve the reliability of experimental results, a large number of images were taken and analyzed for each test condition; and the discussion was made after properly characterizing the observed behaviors rather than discussing them after taking a few samples at a selected moment. The number of images (or amount of data) used to characterize the bubble behaviors was usually much more than those used in the statistical analysis of bubble characteristics reported in literature (Klausner et al., 1993; Maurus and Sattelmayer, 2006; Thorncroft et al., 1998). (iii) To investigate the various aspects of bubble behaviors within the test channel, the bubble behaviors were recorded using simultaneously three high-speed cameras at different resolutions (*i.e.*, multi-scale observation). (iv) To gain deeper insight into the complex flow boiling phenomena, various parameters such as bubble size, bubble velocity, bubble release frequency, bubble size distribution, and wall heat transfer coefficients were investigated together, and relevant relations among them were studied. (v) Lastly, the physical parameters of interest were observed within relatively large area of flow path rather than at a local position (*e.g.*, nucleation site) to investigate the axial development of such parameters as well.

This paper, the first in a series describing our work with subcooled flow boiling experiment, focuses on discussing the novel experimental methods which assure reliable measurement of various flow boiling parameters and thus allow better insight into the heat transfer mechanism induced by vapor bubbles. In the following sections, the experimental setup, optical measurement strategy, image acquisition/analysis method, and data quality achieved from the present work are described in detail.

2. Experimental facility and measurement strategy

2.1. Flow boiling loop

The flow boiling loop was designed to perform the subcooled flow boiling experiment in a vertical square test section at atmospheric pressure. The refrigerant HFE-301 (Novec™ 7000, 3M Inc.) was employed as working fluid (boiling point: 34°C at 1 atm). As shown in Fig. 1, the main components of the loop included a centrifugal pump, control valves, a heat exchanger, a test section, and a degassing tank. The working fluid was circulated through the loop by the centrifugal pump which delivered a constant volumetric flow; the flow rate was manually controlled for the experiments by means of a control valve installed downstream of the pump and upstream of the test section. The heat exchanger was used to control the fluid temperature to the test section. At the highest position of the loop (downstream of the test section), a degassing tank was installed to keep the system at atmospheric pressure and to function as a phase separator. Also, to ensure hydro-dynamically fully developed flow within the test section, the loop was designed to include an unheated section with the length of $l/D_h \approx 61$ before the fluid enters the test section (l is the unheated channel length prior to the test section and D_h is the hydraulic diameter of the square channel).

The test section was vertically aligned, and its flow area had a square geometry of $10 \times 10\,mm^2$. The walls of the test section were made of transparent acrylic on three sides with the transparent heater wall serving as the fourth side. The heater wall consisted of multiple transparent layers, in which a thin layer of indium-tin-oxide (ITO) film was used as a heating element to induce the boiling. This test section design allowed us to clearly observe the bubble motions from different directions simultaneously, as shown by the camera positions in Fig. 2. More details of the multi-layer heater wall design as well as the experimental strategy are discussed in Section 2.2. The total height of test section was 305 mm, and the heated length L_0 was 224 mm (see Fig. 2). The remaining part of the heater wall was painted with conductive silver paint