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Feasibility investigation of experimental visualization techniques to study subcooled boiling flow

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ABSTRACT

The purpose of this study is twofold: (1) to explore the feasible implementation of whole-field visualization techniques such as infrared thermometry, particle tracking velocimetry, and high speed shadowgraphy to study subcooled boiling flow through a vertical square channel with a single heated wall and (2) to provide subcooled boiling flow experimental measurements based on the methodology developed in this work. To fulfill the first objective, a series of sensitivity studies and uncertainty analyses was performed, from which recommendations for the proper implementation of these visualization techniques for the study of two-phase flows are given. The purpose of the second objective is to provide reliable information that can be used for the validation of CFD simulations and for the improvement and development of turbulence models under subcooled boiling conditions. Unique in the presented experimental results is the whole-field simultaneous measurement of turbulence characteristics for both the liquid and gas phases and for their interactions. These measurements were made under transitional conditions from a single phase flow region to a two phase boiling flow condition. The presented experimental results provide whole-field, multi-scale measurements that can help improve the accuracy of descriptions of the boiling phenomena.

Introduction

Understanding the influence of two-phase flow parameters on liquid turbulence plays a key role in developing numerical models to describe the complex behavior found in subcooled flow boiling. Model development depends upon the existence of experimental data that can provide detailed information about the liquid and vapor phases at multiple lengths and times scales. Furthermore, it is desirable to quantify the instantaneous and average influences of bubble characteristics on the neighboring liquid turbulence. Although multiple experimental efforts have been directed toward understanding subcooled boiling flow, the complexity of the phenomenon and its high dependence on the experimental conditions have made it difficult to implement whole-field and non-intrusive experimental techniques that can provide the multi-scales required. Therefore, innovative experimental techniques that can fulfill the multi-scale and statistical demands required for the description of the stochastic nature of subcooled boiling flow are needed. This study explores the scope and limitations of innovative measuring techniques to study subcooled boiling flow. Efforts for the simultaneous measurements of liquid and vapor parameters and their interactions are described, with an emphasis on fulfilling the temporal and spatial demands for both: average and fluctuating quantities. The presented measurements are accompanied with sensitivity studies to account for accuracy and repeatability.

Literature review

Multiple researchers have made efforts to study subcooled boiling flow experimentally with optical techniques (Abdelmessih et al., 1972; Klausner et al., 1993; Situ et al., 2004; Okawa et al., 2005; Chu et al., 2011). However, only a handful of works have attempted to measure liquid turbulence modifications due to boiling flow parameters (Roy et al., 1997; Lee et al., 2002; Yun et al., 2008, 2010). These experiments use point measurement techniques. Roy et al. (1997) utilized a two-component laser Doppler velocimetry system to measure both the liquid and boiling bubbles velocities. They also used a dual-sensor fiber optical probe and a constant temperature hot film anemometer to measure vapor bubble-related quantities and vapor/liquid temperatures. Lee et al. (2002) provided measurements of local void fractions and velocity profiles for both phases. Their measurements were based on a double-sensor conductivity probe for the local void fraction and

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vapor velocity and a Pitot tube method for the local liquid velocity. Situ et al. (2004) measured the flow structure of subcooled boiling flow in an annulus. They used a double-sensor conductivity probe to measure local void fraction, interfacial area concentration, and interfacial velocities. Yun et al. (2008) performed subcooled boiling experiments in a 3×3 rod bundle. They used a double-sensor conductivity probe for the vapor phase measurements and a Pitot tube for the local liquid velocity. Rather than presenting their results as local profiles, they presented interpolated 2D maps of liquid velocity, void fraction, interfacial area concentration, interfacial velocity, and bubble Sauter mean diameter for several conditions. Yun et al. (2010) performed subcooled boiling experiments through a concentric annulus. They used a double sensor optical fiber probe for the local measurement of void fraction, bubbles velocities, Sauter mean diameter, and the interfacial area concentration. In separate experiments using a specially designed Pitot probe and a K-type thermocouple, they also measured the local liquid velocity and temperature.

Although the above mentioned experiments delivered relevant information on the average two-phase flow parameter characteristics, they do not provide simultaneous measurements of the bubble and liquid characteristics. The techniques used in these experiments depend upon specialized measurements of either the gas or the liquid phase parameters, and the obtrusive nature of the probes and/or probe dimensions make measurements close to the wall a challenge.

To overcome some of the limitations inherent in point measurement techniques, full-field visualization techniques have been used on multiple two-phase flow studies (Hassan et al., 2005; Dominguez-Ontiveros et al., 2006; Ortiz-Villafuerte and Hassan, 2006; Koyasu et al., 2009). However, there appears to be a scarcity of subcooled boiling experimental studies that can capture instantaneous whole-field measurements. In response to the need for high quality, reliable experimental information on subcooled boiling flow, Estrada-Perez and Hassan (2010) performed whole-field particle tracking velocimetry (PTV) experiments in a square vertical channel with a single heated wall. They focussed on the liquid turbulence modification due to wall heating. Their results confirmed the behavior found in previous studies and provided new information due to the full-field nature of the technique. The new provided information has already been used towards the development of a two-phase wall law and for CFD simulation validation (Končar and Matkovič, 2012).

Although a large number of studies have been published, subcooled boiling flow is still not completely understood. Due to experimental and technical difficulties, most of these studies are often oriented to measure parameters of only one phase, i.e., either liquid or vapor parameters, with experimental approaches limited to either long-term averages such as average void fraction distribution and average velocity profiles or to instantaneous or fast-occurring events like bubble departure frequency and bubble growth rate. Furthermore, there have only been limited attempts to simultaneously capture the full-field wall heat transfer mechanisms and its interaction with the liquid and vapor dynamics (Theofanous et al., 2002a,b; Wang and Sefiane, 2012; Gerardi et al., 2010; Hetsroni et al., 2000; Barber et al., 2011; Golobic et al., 2012; Kim et al., 2012).

The present study is a continuation of the experimental endeavor started by Estrada-Perez and Hassan (2010) and has the objective of improving the measurement reliability when conducting simultaneous PTV, high speed shadowgraphy (HSS) and infrared thermometry (IR-T) for the study of subcooled flow boiling phenomena. Although these techniques have been previously validated under multiple experimental conditions (Kähler et al., 2012; Khan, 2012; Kim et al., 2012), no attempt has been made to use all these techniques simultaneously to study subcooled boiling flow. Therefore, issues related to the scope and limitations of these techniques have to be addressed before attempting meaningful subcooled boiling measurements. To this end, a series of sensitivity studies and uncertainty analyses were performed, from which recommendations for the proper implementation of visualization techniques for the study of two-phase flows are given. This work also provides subcooled boiling flow experimental measurements which are based on these recommendations.

This paper is organized as follows. Section 'Experimental setup' presents an overview of the experimental facility, instrumentation, and optical arrangements. Section 'Experiments' describes the experimental conditions and the unique features of the proposed measurements. Sections 'Experimental setup' and 'Experiments' are especially important because the experimental complexity and induced uncertainties are strongly defined by the experimental arrangement and the way in which the experiments are performed. Section 'Addressed issues' shows the measurement issues found and describes the sensitivity studies performed to quantify the influences of each of the addressed issues. Section 'Uncertainty analysis' defines the uncertainties and discusses how the issues found affect the measurements. Section 'Results' presents the experimental results of subcooled boiling flow experiments after addressing and correcting for the detected uncertainties, and finally, a brief conclusion as well as recommendations are given in Section 'Conclusions'.

Experimental setup

The experimental facility was designed for the visualization of subcooled boiling flow of refrigerant HFE-301 (3M™ Novec-7000™) at low system pressures. The facility consisted of a hydraulic loop and a visualization system. Experimental setup details are given in the following subsections.

Hydraulic loop

The hydraulic loop consisted of an external loop and a test section, both designed to withstand temperatures in excess of 200 °C and pressures up to 100 psi (0.7 MPa). The external loop provided thermal and hydraulic steady-state conditions. The system excess energy was removed with a small plate heat exchanger connected to a chilling system. This allowed us to control the inlet temperature to the test section. Liquid conditions such as volumetric flow rate, temperature, and density were measured by a Coriolis flow meter and controlled by adjusting valves in the test section. The test section was a rectangular channel made of transparent polycarbonate 30.5 mm long with a cross-sectional area of 10×10 mm. Energy for boiling was provided through a transparent indium tin oxide (ITO) heater with a length of 25.5 cm and a width of 9 mm and a maximum working temperature of about 150 °C. The heater was attached to the lateral interior face of the channel (see Fig. 1). The electric current to the heater was provided and adjusted by a DC power supply. To reduce ambient heat losses, the test section was covered with an insulation box. Three walls of the insulation box were made of transparent acrylic and the fourth wall was a sapphire window. The insulation box materials were selected to provide visual access for both the infrared camera and the high-speed cameras. The optical sapphire window provided almost 95% transparency to the infrared wavelengths of interest. An unheated length of about 61 cm was installed (i.e., $L/D_h \approx 61$) to ensure fully developed flow. To measure the heater wall temperature, a mid-wave infrared camera (3–5 μm) was used. To provide validation for the infrared camera measurements, K-type thermocouples were attached to the external face of the heater. The test section fluid inlet (T_{in}) and outlet (T_{out})