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Multi-scale full-field measurements and near-wall modeling of turbulent subcooled boiling flow using innovative experimental techniques

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HIGHLIGHTS

- Near wall full-field velocity components under subcooled boiling were measured.
- Simultaneous shadowgraphy, infrared thermometry wall temperature and particle-tracking velocimetry techniques were combined.
- Near wall velocity modifications under subcooling boiling were observed.

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ABSTRACT

Multi-phase flows are one of the challenges on which the CFD simulation community has been working extensively with a relatively low success. The phenomena associated behind the momentum and heat transfer mechanisms associated to multi-phase flows are highly complex requiring resolving simultaneously for multiple scales on time and space. Part of the reasons behind the low predictive capability of CFD when studying multi-phase flows, is the scarcity of CFD-grade experimental data for validation. The complexity of the phenomena and its sensitivity to small sources of perturbations makes its measurements a difficult task. Non-intrusive and innovative measuring techniques are required to accurately measure multi-phase flow parameters while at the same time satisfying the high resolution required to validate CFD simulations. In this context, this work explores the feasible implementation of innovative measuring techniques that can provide whole-field and multi-scale measurements of two-phase flow turbulence, heat transfer, and boiling parameters. To this end, three visualization techniques are simultaneously implemented to study subcooled boiling flow through a vertical rectangular channel with a single heated wall. These techniques are listed next and are used as follow: (1) High-speed infrared thermometry (IR-T) is used to study the impact of the boiling level on the heat transfer coefficients at the heated wall, (2) Particle Tracking Velocimetry (PTV) is used to analyze the influence that boiling parameters have on the liquid phase turbulence statistics, (3) High-speed shadowgraphy with LED illumination is used to obtain the gas phase dynamics. To account for the accuracy and to complement these innovative techniques, redundant and simultaneous measurements are performed by means of thermocouples, flow and power meters, differential and absolute pressure transducers, etc. The present experiments are intended to improve the understanding of subcooled boiling flow and to provide reliable and accurate subcooled boiling flow experimental information for verification and validation of two-phase flow computational models.

1. Introduction

Turbulent subcooled boiling flow has been used extensively in industry because it is one of the most efficient heat transfer modes. The continuous mixing and stirring of liquid produced during the life cycle of the subcooled boiling bubbles due to nucleation, growth, detachment, coalescence and collapsing are enhancing mechanisms of heat and momentum transfer. The understanding of two-phase flow parameters and their impact on the liquid turbulence plays a key role on the behavior prediction, safety analysis and design of the high energy systems found in industry.

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In particular, the nuclear industry relies on the accurate prediction of local two-phase flow parameters. For example, the nucleation sites location and the amount of void within coolant/moderator sub-channels affect not only the reactor's reactivity, but also promote the crud formation which has been shown to contribute to the generation of heat transfer non-uniformities along the fuel rods and ultimately fuel rod structural failures. Although multiple experimental efforts has been directed toward the understanding of subcooled boiling flow, the complexity of the phenomenon and its high dependence on the experimental conditions has produced large discrepancies among experimental results, even at similar conditions.

Therefore there is a need of innovative experimental techniques that can fulfill the demanding statistical requirements to describe the stochastic nature of subcooled flow boiling. This work 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. Emphasis is given to achieve measurements with the required temporal and spatial resolutions for both: average and fluctuating quantities. There are multiple studies on subcooled boiling flow, but for sake of brevity, only those relevant to this study are classified in the following groups: (1) studies that focus on measuring average turbulence quantities and (2) studies that focus on the measurement of bubbles dynamics parameters. Most of the studies that focus on measuring average turbulence quantities rely on point measurement probes and generally focus on the study of the liquid turbulence and local void properties. One of the early attempts to measure local fields of subcooled boiling parameters of the liquid phase was performed by Roy et al. (1993). They measured turbulent velocity and temperature fields in the all-liquid region adjacent to a subcooled flow boiling layer. Significant changes in the turbulent structure of the all-liquid region were observed due to boiling. Improving their measurement techniques, Roy et al. (1997) were able to measure liquid turbulence statistics of the liquid refrigerant R-113 even within the boiling layer region adjacent to the heated wall. They found that the near-wall liquid velocity field was significantly different from that in single-phase liquid flow at a similar Reynolds number. Lee et al. (2002) performed measurements of subcooled boiling flow of water in a vertical concentric annulus. Using a two-conductivity probe they measured the local void fraction and vapor velocity and with a Pitot tube they measured the liquid velocity. Situ et al. (2004) measured the flow structure of subcooled boiling flow in an annulus. They used a double-sensor conductivity probe method to measure local void fraction, interfacial area concentration and interfacial velocities. Using the experimental information from the previous studies, different two-phase flow models were developed and used to calculate convective subcooled boiling flow (Končar et al., 2004, 2005; Končar and Matkovic, 2012; Končar and Tiselj, 2010; Ramstorfer et al., 2008) with some success. These models share the characteristics of being based on time-average analysis of information from point measurements probes. However, due to the complex nature of the turbulence found in subcooled boiling, this approach seems to be limited. A full-field measurement approach is needed to provide spatial and temporal information. Visualization techniques such as Particle Image Velocimetry (PIV) and Particle Tacking Velocimetry (PTV) can be used to overcome some of the limitations associated with point measurements techniques. Using visualization techniques in conjunction with PTV, several adiabatic two-phase flow experimental studies were performed (Dominguez-Ontiveros et al., 2006; Hassan et al., 2005; Koyasu et al., 2009; Ortiz-Villafuerte and Hassan, 2006) to investigate the influence of void fraction on liquid turbulence parameters. These studies elucidate the phenomenological events important for the modeling of two-phase flows. However, there appears to be a scarcity of subcooled boiling experimental studies that can capture instantaneous whole-field measurements with a fast time response. As an answer to the need of high quality and reliable experimental information of subcooled boiling flow, Estrada-Perez (2004) performed PTV experiments in a square vertical channel with a single heated wall. 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 toward the development of a two-phase wall law and for CFD simulation verification and validation Končar and Matkovic (2012). When studying the bubble dynamics in subcooled flow boiling, most of the studies rely on visualization techniques. A summary of such works is presented next. Abdelmessih et al. (1972) used high speed photography to investigate the effect of fluid velocity on the growth and collapse of vapor bubbles in slightly subcooled distilled water in an open loop.

The measurements included the description of typical parameters describing the lifetime of a bubble: bubble nucleation frequency, growth, and collapse. Similarly Ünal (1976) with high speed film photography measured maximum bubble diameters at different subcooling levels and flow rates. Their results fitted previously proposed correlations for the bubbles diameters. Klausner et al. (1993) used high speed digital photography to measure bubble departure diameters. Also, a theoretical analysis was performed to predict that the expected bubbles departure diameter is strongly influenced by the flow velocity and the wall superheat. Bibeau and Salcudean (1994) performed bubble dynamics measurements using high speed photography. They concluded that bubbles generated near the onset of nucleate boiling conditions slide for longer distances compared to those at different conditions. The maximum bubble diameter and condensation time are shown to be influenced by the location relative to the onset of significant void. Thorncroft et al. (1998) performed a visualization study of vapor bubble growth and departure in vertical upflow and downflow forced convection boiling. They observed significant differences on the boiling bubbles behavior depending on the liquid flow direction. They observed that the vapor bubble sliding process was an important enhancing mechanism of the heat transferred from the heater wall to the liquid. Chen et al. (2011) studied the effects of channel size on subcooled boiling. They found an increase of both, heat transfer and bubble nucleation frequency when the channel dimensions were reduced. They also observed bubbles merging on the nucleation site due to increases on heat flux. Ahmadi et al. (2012) observed that at high liquid subcooling close to the onset of nucleate boiling conditions, all nucleated bubbles departed for the heater wall and condensed. For lower subcooling levels, bubbles reattached to the wall after lift-off, consequently the bubble lifetime was increased. Chu et al. (2011) measured the bubble lift-off diameters and bubble nucleation frequency in terms of heat flux, mass flux, and degree of subcooling. From this data they suggested a correlation for the bubble nucleation frequency and bubble lift-off diameters. Euh et al. (2010) focused on measurements of bubble departure frequency as a function of pressure, heat flux, flow rate and subcooling level. They developed an automatic image processing technique to obtain the bubble departure frequency. Their measured data was compared with bubble frequency models available in existing literature and an improved version was proposed. Zhou et al. (2013) analyzed the behavior of single bubbles in a narrow vertical rectangular channel. They showed that at high subcooled conditions nucleated bubbles stick to the wall and slide slowly. From their analysis they suggested that thermophoresis contributes largely to promote the bubble detachment from the wall and that this contribution increases at conditions with high liquid temperature gradients.