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MEMS sensor measurement of surface temperature response during subcooled flow boiling in a rectangular flow channel

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ABSTRACT

Subcooled flow boiling experiments have been conducted using water at atmospheric pressure in a rectangular flow channel. These experiments are conducted in support of a US DOE Nuclear HUB project, the Consortium for Advanced Simulation of Light Water Reactors (CASL). CASL aims at the development of an environment for predictive simulation of light water reactors, and subcooled flow boiling is investigated experimentally in order to develop and validate 3-D Interface Tracking Models (ITMs). In the present experiments, a MEMS sensor has been used to obtain wall temperature response during nucleation, growth and departure of a vapor bubble in subcooled water flowing upward through a vertical rectangular test section. High-speed video images and MEMS sensor data collected at 5000 fps and 50 kHz, respectively, revealed rapid microlayer evaporation, dryout and rewetting phenomena under a single vapor bubble following nucleation accompanied by rapid wall temperature changes of up to ~10 K.

1. Introduction

Subcooled flow boiling experiments have been conducted using water at atmospheric pressure in a rectangular flow channel. These experiments are conducted for a DOE Nuclear HUB project, the Consortium for Advanced Simulation of Light Water Reactors (CASL). The CASL project (www.ornl.gov/sci/nsed/docs/CASL Project Summary.pdf) aims at the development of an environment for predictive simulation of light water reactors, and subcooled flow boiling needs to be investigated in detail both experimentally and numerically in order to develop and validate 3-D Interface Tracking Models (ITMs) and CFD models which can predict subcooled flow boiling phenomena in fuel assemblies of Pressurized Water Reactors. The data needed for model validation include turbulent liquid flow characteristics, vapor bubble nucleation, growth and departure data, and wall temperature response during subcooled flow boiling.

In previous studies, subcooled flow boiling has been investigated experimentally. Euh et al. [1] measured the bubble departure frequency in water under vertical upflow in an annular channel over a pressure range of 167–346 kPa and liquid subcooling of 7.5–23.4 °C. Situ et al. [2,3] measured the bubble size, growth rate, and departure frequency at atmospheric pressure and inlet water temperature of 80.0–98.5 °C. Basu et al. [4] conducted subcooled flow boiling experiments using a flat plate copper surface and reported that the heat flux and wall superheat required for boiling inception are dependent on the liquid flow rate and subcooling, as well as the contact angle.

Thorncroft et al. [5] conducted an experiment investigating the bubble size, growth rate, and departure frequency for vertical upflow and downflow in a square duct and pool boiling of FC-87 as the working fluid. Their experiments provided a general understanding of the key differences between upflow, downflow, and pool boiling dynamics. Del Valle and Kenning [6] performed subcooled flow boiling experiments with water at atmospheric pressure on stainless steel. The bubble size and frequency, and the distribution of nucleation sites were measured at high inlet subcooling of 84 K at heat fluxes corresponding to 70–95% of the critical heat flux. Samaroo et al. [7] recently reported on the velocity profiles of water flowing past a heated rod in subcooled flow boiling in an annular flow channel.

Regarding the bubble nucleation phenomena, Kandlikar et al. [8] investigated bubble nucleation characteristics in subcooled

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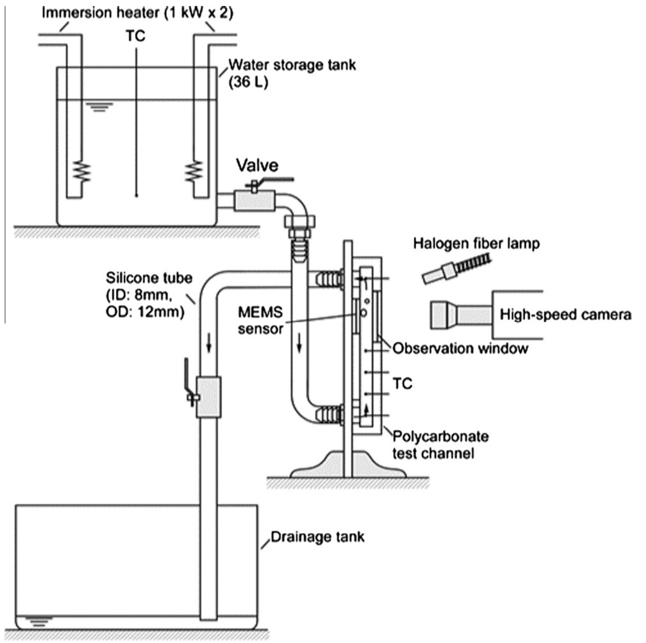

Fig. 1. Experimental apparatus.

flow boiling of water at atmospheric pressure using a microscope and high-speed camera. They reported that the model by Bergles and Rohsenow [9] could give the lower limit of wall superheat necessary for bubble nucleation. Basu et al. [4] proposed a correlation for the onset of bubble nucleation based on Hsu's theory [10] and available data that included the effects of surface wetting, system pressure, liquid subcooling and velocity. Basu et al. [4] also developed a correlation for the nucleation site density which depended on the wall superheat and static contact angle but not on the liquid subcooling and velocity.

Finally, there is still little data on the microlayer films below a nucleating bubble. Hollingsworth et al. [11] directly measured the liquid microlayer thickness between sliding cap-shaped bubbles in a static liquid FC-87 and the heated surface. Sliding was induced by pivoting the flow channel between 2° and 15° from horizontal. Bubbles were between 3 and 8 mm in length and their Reynolds numbers were between 819 and 2413. A fiber-optic microlayer thickness probe was utilized alongside stereoscopic high speed video. They obtained microlayer thicknesses between 22 and 55 μm. These measurements were used to correlate the microlayer thickness with the bubble size and motion. Their work resulted in a new correlation for the microlayer thickness based on a lubrication theory.

In the present experiments, a MEMS sensor has been developed and used to obtain wall temperature response during nucleation, growth and departure of a single vapor bubble in subcooled water at atmospheric pressure flowing upward through a vertical, rectangular test section. High-speed video images and MEMS sensor data were collected at sufficiently high sampling rates to investigate rapid microlayer evaporation, dryout and rewetting phenomena following the nucleation of a single vapor bubble accompanied by rapid wall temperature changes.

2. Experimental apparatus

The experimental apparatus used in this work is shown in Fig. 1. It consisted of a 36-L stainless steel water storage tank, a minichannel test section made of polycarbonate plates, and drain tank. The test section contained a MEMS sensor to measure the wall temperature response around a vapor bubble nucleation point.

Before each run, deionized water in the storage tank was degassed by boiling for at least 3 h using two 1 kW immersion heaters and setting the water temperature at a desired level of liquid subcooling. The top of both the storage tank and drain tank was open to the atmosphere so the water could be circulated through the test section by a gravity head difference between the water levels in the two tanks. The water flow rate was adjusted by two ball valves and measured immediately before each run by collecting the water flowing into the drain tank and measuring the time needed to fill a 500 mL container.

2.1. Rectangular test section

Fig. 2 shows a schematic diagram of the test section oriented vertically. Subcooled water flowed upward in the test section from the inlet at the bottom to the outlet at the top which was located 163 mm above the inlet. The distance from the inlet to the MEMS sensor was 120 mm. The flow channel was rectangular in shape and the cross section was 20 mm wide and 5.1 mm thick. Five thermocouples were installed inside the flow channel to measure the bulk liquid temperature. The liquid subcooling was calculated from the temperature obtained by the fourth thermocouple (TC4) closest to the MEMS sensor. The entrance region of the minichannel was heated by an aluminum block containing two embedded cartridge heaters, however, the cartridge heaters were not powered in the present experiments.

2.2. MEMS sensor

The MEMS sensor was fabricated to measure the temperature response of a heated surface. This type of a fast response temperature sensor was previously used by Yabuki and Nakabeppu [12] in pool boiling experiments. A photograph of the MEMS sensor used in this work is shown in Fig. 3. The sensor was fabricated on a 180 μm thick, 32 mm × 40 mm silicon wafer covered with a 2 μm thick SiO_2 layer on both sides. On the front surface (Fig. 3a), a total of six Resistance Temperature Detectors (RTDs) were fabricated by depositing 2 μm thick layers of nickel. Two and four RTDs were located upstream and downstream of the electrodes for bubble nucleation trigger, respectively. The bubble nucleation was induced by applying a DC voltage to the two electrodes which caused electrolysis of water at the electrode tip. The layout of the

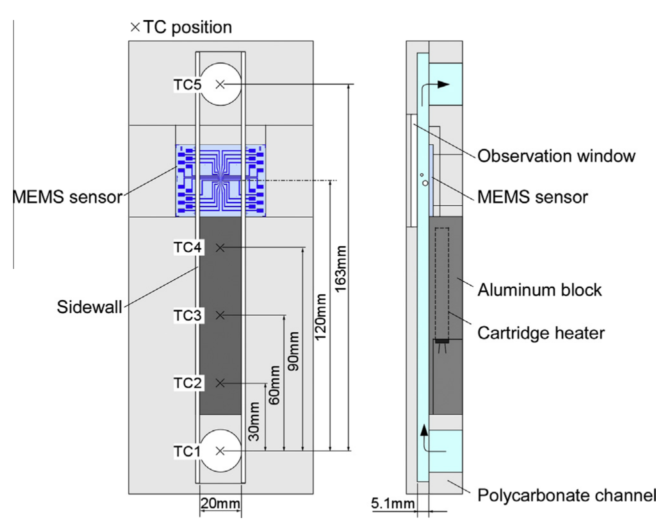

Fig. 2. Schematic diagram of the test section.