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An accurate wall temperature measurement using infrared thermometry with enhanced two-phase flow visualization in a convective boiling system

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ABSTRACT

This paper presents an experimental strategy to achieve the accurate wall temperature measurement using infrared (IR) thermometry with the enhanced flow visualization. Our particular interest is focused on the measurement of two-phase flow parameters in a convective boiling system which involves a large heated area. For the present application, the important issues such as the design of test section and material selection were discussed along with our decision-making process. Then, the IR-based temperature tracking algorithm was established based on the multi-layer heater wall design proposed. To apply this algorithm, however, the optical properties of materials must be identified first. Thus, the optical features of selected materials, e.g., soda-lime glass and indium-tin-oxide (ITO) were investigated and the measured values were validated through experiments.

The wall temperature tracking algorithm on the proposed heater wall design was validated both for steady-state and transient conditions. Also, such algorithm was proved to be applicable for the heat flux measurement. Finally, the feasibility of the present approach was demonstrated through a subcooled flow boiling experiment. The results showed that both the hydrodynamic motions of bubble and the corresponding wall temperature can be captured with high fidelity using the measurement strategy presented, from which the interrelation between the sliding vapor bubbles and the wall heat transfer were discussed.

1. Introduction

The heat transfer augmentation caused by boiling has been of great concern to researchers due to its potential to improve the cooling systems of many engineering applications. Often, the performance of engineering devices such as electronics and nuclear reactors has been limited by the amount of power that can be dissipated while using them because the operating temperature must be kept within specified limits to maintain the reliability. However, the traditional cooling systems employing the single-phase forced convection have limitations in addressing this issue, implying that alternative approach like boiling heat transfer needs to be introduced to make a breakthrough.

In order to realize the enhanced heat transfer of boiling in engineering applications, the physical mechanism should be understood well so that we can predict its performance with reasonable accuracy. In view of this, numerous experimental efforts have been made to obtain better insight into the boiling mechanism with various experimental techniques. Among such efforts, optical methods such as flow visualization and infrared (IR) thermometry are considered effective because they can provide direct observation of the thermal-hydraulic features related to boiling. Consequently, high-speed photography [4,16,22] and a laser-based flow visualization technique [6] have been utilized to study the hydrodynamics of liquid/vapor phases in a boiling system. For a wall heat transfer study, the thermal patterns under boiling conditions can be also visualized, for which liquid crystal thermography [2,14,19] and infrared (IR) thermometry [5,10,13,23,24] have been employed.

The above-mentioned optical techniques have an advantage over traditional methods relying on local probe sensors because the hydrodynamic and thermal features of interest can be captured

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non-intrusively with high spatial and temporal resolution. As a result, even the micro-physics of the two-phase flow such as wall boiling and local mass/momentum/energy transfer can be characterized without any disturbance of instrument. Also, using a measurement of macro-scale, the transitional changes between different flow regimes, e.g., single-phase/two-phase flow regions, bubbly/slug/annular flow regimes, can be captured over a large area.

In recent years, rapidly growing computing power and advances in high-speed imaging technology have led to aspirations among researchers to combine high-speed IR thermometry with the high-speed visualization techniques. So far, such attempts have been made primarily in pool boiling experiments [8,9,18] with a few flow boiling experiments in mini-/micro-channels [1]. All of these experiments were designed to observe the bubble dynamics and the wall temperature field simultaneously. This is obviously an appealing experimental approach because it can provide direct insight into the relation between hydrodynamic bubble motions and wall heat transfer. However, such efforts are rare in general convective boiling experiments, especially for technical applications involving a large heated area.

To achieve reliable data measurement from both high-speed flow visualization and IR thermometry, several sources of measurement error, especially optical issues, must be addressed correctly. Otherwise, the reliability of the parameters measured will decline substantially, despite the fancy-looking visual images obtained from such methods. Therefore, to implement both techniques in a single experimental facility, several issues must be taken into particular consideration. First, the materials composing the test section should be determined by considering their optical properties; and the experimental design should consider the feasibility both for flow visualization and IR thermometry. Also, since both techniques provide optical images from which quantifiable data can be acquired, optical distortions should be prevented. Additionally, to accurately estimate the target object's temperature from the thermal images taken by IR camera, proper calibration considering the optical property is required.

In this paper, we discuss the experimental strategy assuring both enhanced flow visualization and accurate wall temperature measurement using high-speed photography and IR thermometry. Our particular interest is focused on the improved observation of two-phase flow hydrodynamics as well as the wall temperature distribution in a convective boiling system which involves a large heated area. For this approach, the heater wall design is especially important because it directly affects the quality of IR temperature measurement and the flow visualization. In literature, about three different types of heater wall configurations have been utilized for the boiling study employing IR thermometry. Some of those are described here with brief descriptions of the wall temperature measurement strategies, after which the relevance of each approach for the present application is discussed.

(i) A heating channel coated with IR-opaque material

A heating channel lined with IR-opaque material of high emissivity has been primarily used in flow boiling experiments in mini- and micro-channels. Ref. [10] examined the wall heat transfer characteristics under flow boiling conditions in a mini-channel. They painted the outer wall of the test section with black lacquer (emissivity ≈ 0.94) to ensure high sensitivity of the IR temperature measurement. Then, the outer-wall temperature distribution was measured by IR camera, from which the inner wall temperature touching the fluid was evaluated by assuming quasi-steady conditions of the wall. The similar approach was also taken by Ref. [3] who performed a flow boiling experiment with water in a circular mini-channel. On the other hand, Ref. [1] attempted the high-speed photography along with IR thermometry in a rectangular micro-channel made of borosilicate glass. In order to visualize the boiling motions inside the channel while measuring the outer wall temperature using IR camera, they employed the transparent metallic deposit on the outer wall of the glass channel. Then, the local heat transfer characteristics at different flow boiling regimes were studied.

(ii) A thin metal foil heater

Recently, to observe the wall heat transfer characteristics during boiling, a thin metal foil on the order of micrometers thickness has been used as a heater by itself. This approach has been adopted to perform fundamental boiling studies with high spatial and temporal resolution at the local nucleation site. Ref. [9] performed an experiment under subcooled and saturated pool boiling conditions with water at atmospheric pressure. To create the boiling, they used a platinum heating foil of 6 μm thickness with a 2–3 μm thick layer of black paint on the back side. Then, a high-speed IR camera measured the two-dimensional wall temperature field during the growth of bubbles. Ref. [21] studied the nucleate boiling of FC-72 under variable gravitational conditions. The measurements were performed at a single artificial cavity created on a thin heating foil made of stainless steel 25 μm thick. Similarly to Ref. [9], Ref. [21] applied a coat of black paint to the back side of the heating foil for the IR thermometry. Ref. [18] investigated the effect of three-phase contact line motion on the local evaporative heat transfer within a micro-region. For the heater in this experiment, a stainless steel foil 20 μm thick was used, and the wall temperature was measured using IR camera while bubbles' motions were recorded by high-speed video camera.

(iii) A heating film deposited on an IR-transparent substrate

The heater wall temperature can be also measured using IR camera through an IR-transparent substrate onto which an IR-opaque heating film is deposited. Ref. [24] used an IR camera to visualize the dynamic thermal patterns on the heated wall in a pool boiling experiment. As a heating element, titanium films of 140–1000 nm thickness were deposited on 130 μm thick borosilicate glass. Then, the IR camera captured the thermal footprint created by the boiling motion through the glass substrate. In Ref. [8], a transparent and electrically conductive indium-tin-oxide (ITO) film was used as a heating element for their saturated pool boiling study. The IR-opaque ITO film was attached to a 0.4 mm thick sapphire substrate through which the bubble nucleation and the transient wall temperature were observed. Recently, in Ref. [7], an enhanced emissivity of chromium-based layer was applied on a 2 mm thick IR-transparent calcium fluoride (CaF_2) substrate, and a pure chromium heating layer was laid on top of that. Then, an IR camera detected the wall temperature through the CaF_2 substrate during the boiling process. In Ref. [15], a silicon wafer was employed as a substrate of the heater wall, and a polyimide tape coated with a thin black paint was attached to the substrate to improve the signal detected by IR camera for their wall heat transfer study.

(iv) Discussion on the previous experimental design approaches

The relevance of each approach described above for the present application can be discussed based on the specific measurement targets of the present study. The first approach (i) is inapplicable because the flow visualization is restricted by the opaque film on the outer wall of the test channel. Even in the case that the channel