Development of a novel infrared-based visualization technique to detect liquid-gas phase dynamics on boiling surfaces

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1. Introduction

Complex two-phase heat transfer phenomena such as nucleate boiling, critical heat flux, quenching and condensation govern the thermal performance of Light Water Reactors (LWRs) under normal operation and during transients/accidents. These phenomena are typically characterized by the presence of a liquid-vapor-solid contact line on the surface from/to which the heat is transferred. For example, in nucleate boiling, a significant fraction of the energy needed for bubble growth comes from evaporation of a liquid meniscus, or microlayer, underneath the bubble itself. As the liquid-vapor-solid line at the edge of the meniscus retreats, a circular dry patch in the middle of the bubble is exposed; the speed of the triple line retreat is a measure of the ability of the surface to transfer heat to the bubble. At very high heat fluxes, near the upper limit of the nucleate boiling regime, also known as Critical Heat Flux (CHF), the situation is characterized by larger dry areas on the surface, dispersed within an interconnected network of liquid menisci. In quenching heat transfer, which refers to the rapid cooling of a very hot object by immersion in a cooler liquid, the process is initially dominated by film boiling. In film boiling a continuous vapor film completely separates the liquid phase from the solid surface; however, as the temperature gets closer to the Leidenfrost point, intermittent and short-lived liquid-solid contacts occur at discrete locations on the surface, thus creating liquid-vapor-solid interfaces once again. Ultimately, if bubble nucleation ensues at such contact points, the vapor film is disrupted and the heat transfer regime transitions from film boiling to transition boiling. Finally, in dropwise condensation, the phase transition from vapor to liquid occurs via formation of discrete droplets on the surface, and the resulting liquid-vapor-solid triple line is where heat transfer is most intense.

To gain insight into and enable mechanistic modeling of all these two-phase heat transfer phenomena, there is clearly a need to detect the liquid-vapor-solid triple contact line and measure its physical characteristics (extension, speed, temperature). In this paper we demonstrate the application to boiling heat transfer of a recently-developed experimental technique, named DEPIcT [1].

2. Methods and Results

2.1 Description of the experimental technique

DEPIcT (DEtection of Phase by Infrared Thermometry) exploits temperature differences to detect the liquid-vapor-solid triple contact line. An IR camera is used to detect the phases present on a heated surface. The key feature of this technique is to use a heater material that is IR transparent (e.g. optical grade silicon wafer), and a fluid that has a very high IR absorptivity (e.g. water). The IR camera is placed below the heater, while the fluid lies on top (Fig. 1). Where the heater surface is wet, the IR camera measures the temperature of the hot water in contact with the heater. On the other hand, where vapor (whose IR absorptivity is very low) is in contact with the heater, the IR light comes from the cooler water beyond the vapor. The resulting IR image appears dark (cold) in dry spots and bright (hot) in wetted area. Using the contrast between the dark and bright areas, we can visualize the distribution of the liquid and gas phases in contact with the heater surface, and thus identify the liquid-vapor-solid contact line. In other words, we measure temperature beyond the surface to detect phases on the surface. This approach distinguishes DEPIcT from the now-established IR thermometry technique with IR-opaque heaters [2], where the temperature measured is the temperature of the surface, which makes it hard to identify phases on the surface conclusively.

2.2 Results

Using the proposed DEPIcT technique, we could detect the liquid-vapor-solid triple line in simple situations, but also in more complex situations such as bubble-bubble interaction in nucleate boiling and CHF. The obtained examples are shown in Figs. 2 and 3.

REFERENCES

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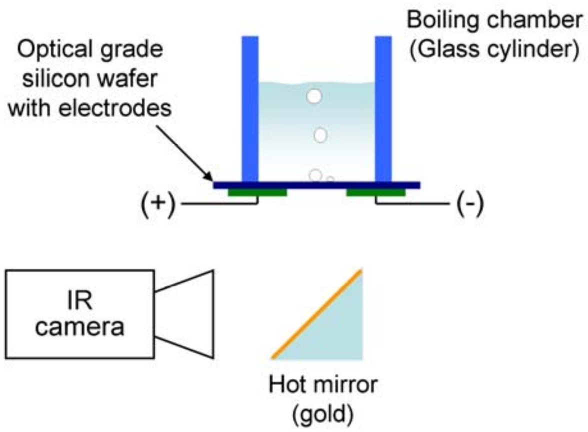


Fig. 1 Schematic of sessile droplet experimental setup

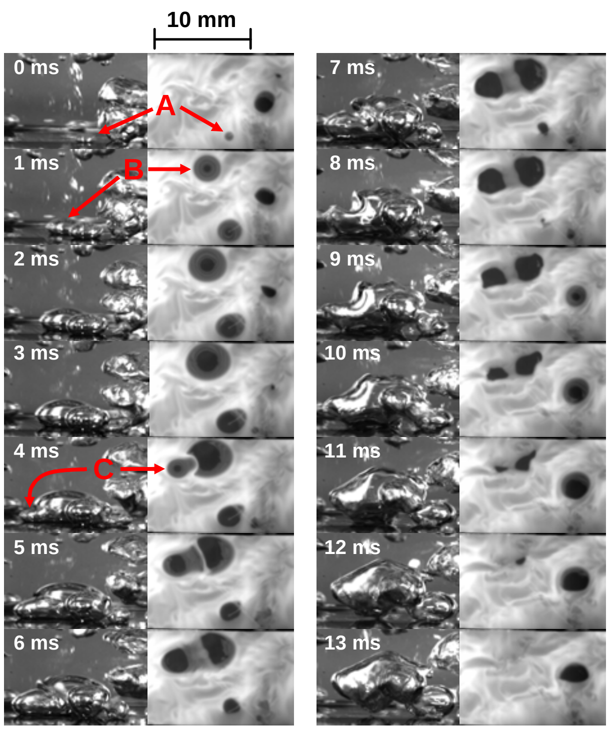
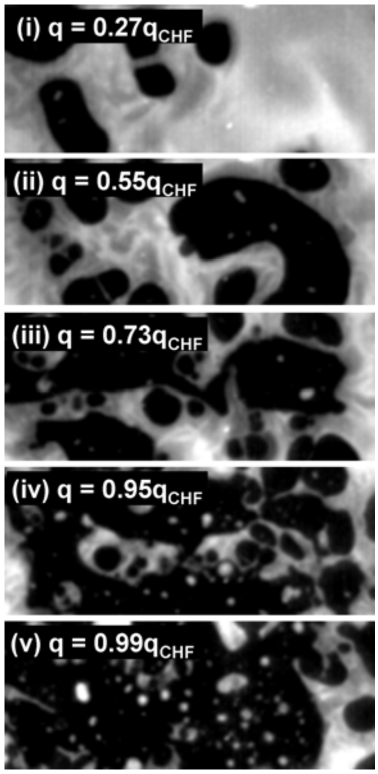
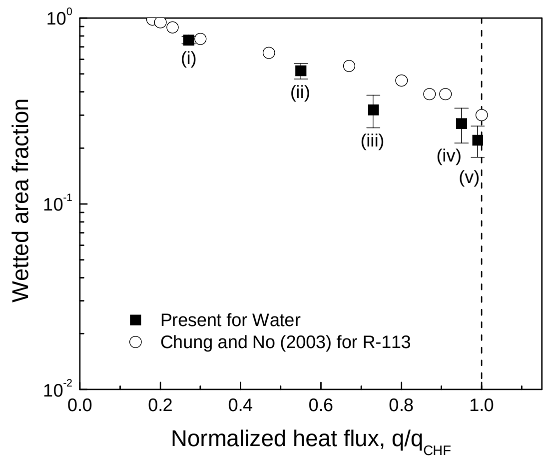


Fig. 2 Interactions of bubbles at boiling surface. A, B, and C indicate the bubbles tracked in the synchronized HSV images (lateral view) and IR images (from below the heater).



(a)



(b)

Fig. 3 Phase distribution and wetted area fraction at various heat fluxes (normalized to the CHF): (a) IR images of the heater surface; (b) average wetted area fraction.