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Rainbow schlieren-based investigation of heat transfer mechanisms during isolated nucleate pool boiling phenomenon: Effect of superheat levels

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ABSTRACT

Experimental investigation of various heat transfer mechanisms associated with isolated nucleate pool boiling have been presented. Measurements have been made in a complete non-intrusive manner using rainbow schlieren deflectometry technique. Boiling experiments have been performed for two levels of superheat with the bulk fluid maintained under saturated conditions. The rainbow schlieren images have first been subjected to qualitative interpretation wherein various sub-processes associated with the boiling phenomenon, such as development of thermal boundary layer on the substrate surface, inception of single bubble, growth of the vapor bubble till it departs, and scavenging of the superheat layer following the bubble departure have been discussed. Contributions of individual sub-processes towards the overall heat transfer rates achieved for a given superheat level have been determined through quantitative analysis of the images. Schlieren observations revealed the effect of varying superheat levels on parameters such as bubble diameter and departure time. Detailed heat transfer analysis revealed the dominance of evaporative heating in contributing towards the overall heat transfer rates. On the other hand, the contribution of natural convection from the heated substrate was found to be relatively small. In quantitative terms, the evaporative heating was seen to have an individual contribution as high as ≈66% to the overall heat transfer and ≈88% to the growth of the vapor bubble in the case of superheat level of 7 °C.

1. Introduction

Boiling heat transfer is one of most efficient modes of thermal energy transfer in which the vapor that is formed at the heater surface is periodically removed, thereby enhancing the heat transfer rates. Over the past two decades, wide applications of boiling heat transfer, ranging from day to day appliances to huge thermo-nuclear power plants, has motivated the researchers to study this phenomenon from a fundamental point of view. Some of the earliest work in boiling by Nukiyama [1] involved the classification of different regimes of boiling phenomenon namely, nucleate, transition and film boiling. Of these three regimes, importance of nucleate pool boiling heat transfer can be attributed to its ability to dissipate a significantly large amount of thermal energy from the heated surface without any significant change in the surface temperature. Hence, nucleate boiling can be used as a potential cooling method for applications wherein the dissipation of high heat fluxes is required and the conventional ways of heat transfer enhancement show severe limitations.

Nucleate boiling is a complex heat transfer mode in which the vapor bubble(s) generated at the point(s) of nucleation leave the surface of the heater periodically, resulting in the periodic breakdown of the boundary layer. The study of boiling heat transfer is limited by the range of time scales and length scales of the constituting fundamental processes, which include micro-layer phase transfer [2–7], fluctuations in the temperature of the heater surface [8], and shape, size and density of the nucleation site [9–11]. The conventional method of studying the boiling phenomenon involves the use of high speed cameras to understand the bubble dynamics. Bubble dynamics parameters like contact angle, bubble departure diameter and its departure frequency, etc. have been extensively studied over the past two decades [12–15]. As part of recent advances in the field, the works of Gerardi et al. [16] and Golobic et al. [17] made use of high speed thermal imaging cameras to study the transient heat transfer processes associated with single vapor bubble-based nucleate boiling phenomenon. The bubble dynamics studies of vapor bubbles generated from the heater

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Nomenclature

D	diameter
f	focal length (m)
h	heat transfer coefficient (W/m^2 K)
H	hue (radians)
Ja	Jacob number
k	thermal conductivity (W/m K)
L	length of the test cavity (m)
l_0	capillary length of water
n	refractive index
t	time
ΔT	temperature difference (°C)
T	temperature of fluid (°C)
W	width of the test cavity (m)
Δy	light ray displacement (m)
x, y, z	coordinate axes
r	radial position

Greek symbols

θ	angle of deflection (radians)
λ	wavelength (nm)
δ	deflection (mm)
σ	surface tension of water

Subscripts

avg	average
amb, 0	ambient conditions
$bulk$, b	bulk fluid
Cycle	bubble inception to departure
d	de-collimating lens
Eq	spherical equivalent
v, g	vapor phase
l, f	liquid phase
NC	natural convection
S, s	surface
sat	saturated

surface have enabled the development of numerical models, which use the experimentally obtained bubble dynamic parameters like contact angle, bubble frequency, etc. [18–21]. In this context, a range of empirical correlations [22–25] as well as heat transfer models proposed by various researchers have proved to be of significant importance. Some notable heat transfer models include those proposed by Yu et al. [26,27], Podowski et al. [28,29] and Marcel et al. [30].

Recent developments in the field of refractive index-based non-intrusive optical diagnostics coupled with the technological advancements in terms of increased data processing speeds of computers for digital image processing have helped in significantly improving both temporal and spatial resolutions of such laser and/or white light-based measurements systems. The inherent advantages of the refractive index-based whole field measurement techniques lie in the fact that these techniques not only serve as a qualitative tool for direct visualization of heat transfer processes but also provide the whole field quantitative data; for instance, fringe patterns in interferometry [31–34], color re-distribution in rainbow schlieren deflectometry representing the thermal gradients [35–38] and intensity variations in shadowgraph [39]. Some of earliest efforts which involve the use of non-intrusive optical diagnostic tools in the context of nucleate boiling can be seen in the works of Mayinger [40–43]. Digital holographic interferometry, which is one of the variants of conventional interferometric technique, has been employed by Mayinger and his co-workers in order to map the whole field temperature field around an upward moving condensing vapor bubble injected into a fluid maintained under sub-cooled bulk conditions. Similar holographic techniques have also been used to study flow boiling in order to map the temperature field at the heater surface and around the vapor bubble by Lucic et al. [44,45] and Manickam et al. [46]. In the context of pool boiling phenomena, Yabuki et al. [47,48] also employed the digital holographic interferometer in order to quantify the temperature field during the bubble generation on a custom made MEMS sensor for single bubble generation.

In the context of nucleate pool boiling phenomenon, it has been widely accepted in the research community that the microlayer, which is a thin film of superheated fluid trapped between the vapor bubble and the heater surface just beneath the vapor bubble, plays an important role for the effective dissipation of thermal energy from the heated substrate and bubble generation. Thus, efforts have intensified in recent years to characterize the microlayer and to develop a fundamental understanding of the heat transfer phenomena associated with this narrow region in the vicinity of the heated substrate surface. In this regard, the inherent advantages of refractive index-based imaging techniques, for instance, high spatial and temporal resolutions, measurements being inertia-free and completely non-intrusive, may possibly be utilized to characterize the phenomenon of microlayer-based heat transfer during the process of bubble formation, and on the whole, in the context of nucleate pool boiling. Motivated by these factors, over the years, researchers have employed the concept of classical interferometric techniques in which the incident coherent light beam interferes with the reflected light from the bubble interface creating alternate bands of bright and dark fringe patterns in order to quantify the thickness of microlayer and its time evolution during the process [49–51].

Some of the more recent literature involving various optical techniques to study variety of parameters includes the use of optical coherence tomography (OCT) by Meissner et al. [52,53] for direct three-dimensional reconstruction of the vapor bubble interface and digital holography based reconstruction of velocity field by Bloch et al. [54,55]. Recent study by Duan et al. [56] employed particle image velocimetry (PIV) for the determination of the velocity field around a vapor bubble during pool boiling, the results of which can be used as a benchmarking results for the development of numerical models. An intrinsic need for both qualitative as well as quantitative understanding the fundamental micro-convection processes associated with boiling heat transfer has also been emphasized in one of the recent review articles by Prosperitti [57]. This reported work mainly focuses on understanding both the fluid dynamics and thermodynamic processes associated with the formation of vapor bubbles. Although significant strides have been made in order to understand the various fundamental processes and their relative contribution towards the overall heat transfer rates that can be achieved during nucleate pool boiling process using intrusive techniques, increased complexities, such as strong temperature gradients around the vapor bubbles have limited the number of studies involving the applications optical techniques. The maximum possible spatial resolutions provided by high speed cameras for any given recording speed has also been one of the major limitations which has limited the number of such studies.