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Nucleation dynamics and pool boiling characteristics of high pressure refrigerant using thermochromic liquid crystals

Ankur Miglani [a,1], Daniel Joo [b,1], Saptarshi Basu [a,1], Ranganathan Kumar [b,*,1]

[a] Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560 012, India
[b] Department of Mechanical, Material and Aerospace Engineering, University of Central Florida, Orlando, FL 32816, USA

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ABSTRACT

This paper reports an experimental investigation of oscillating temperature field beneath a single isolated nucleation site using a non-invasive TLC (thermochromic liquid crystal) based thermography technique. Empirical correlations are presented to demonstrate the influence of system pressure and wall heat flux on different ebullition characteristics in the nucleate pool boiling regime of refrigerant R-134a. TLC transient response and two-phase flow structure are captured using synchronized, high resolution imaging. It is observed that the area of influence of nucleation site exhibits a two-part distinct transient behavior during the bubble growth period and broadens to a maximum of 1.57 times the bubble diameter at the instant of bubble departure. This is accompanied by a sharp fall of 2.5 °C in the local excess temperature at the nucleation site, which results in momentary augmentation (~40%) in the local heat transfer coefficient at the nucleation origin. The enhanced heat transfer rate observed during the bubble peel-off event is primarily due to transient micro-convection in the wake of the retreating bubble. Further, the results indicate that a slight increase in system pressure from 813.6 to 882.5 kPa has no considerable effect on either the wall superheat or the overall heat transfer coefficient and ebullition frequency. In addition, correlations have been obtained for bubble Reynolds number, Jackob number and the dimensionless bubble generation frequency in terms of modified boiling number.

1. Introduction

The significance of nucleate boiling arises from its ability to scavenge heat efficiently at high rates. This two-phase heat extraction process is characterized by a dynamic coupling between energy transfer and bubble activity at the nucleation site which results in wall temperature distributions that vary significantly with both space and time. Various experimental investigations [1–3] have shown that depending on the extent of spatial overlap between these local temperature fields, some permanently active nucleation sites may show intermittent pauses while several other potential bubble sites may become momentarily active. Consequently, the wall temperature distribution is one of the key parameters in nucleate pool boiling. Other important parameters studied extensively in literature are the cavity structure and nucleation site density. For instance, Qi et al. [4] determined the statistical distributions of cavity half cone angles and cavity mouth diameters on brass and stainless steel surfaces using a vertical scanning interferometer. They found that the probability of finding vapor trapping cavities on these surfaces is very low and that the deep cavities are more efficient for nucleation site formation than shallow pits. Quantitative predictive models of nucleate boiling at high pressures, particularly for refrigerant fluids, are still at premature stages of development [5,6]. This is primarily due to the limited experimental data on wall temperature variations in the existing literature and the absence of a well-established theory that comprehensively explains the underlying physical mechanisms of heat transfer in boiling processes. In order to understand the statistical behavior of nucleation site activity and their non-linear interactions, it is imperative to determine the heater surface temperature at high spatial and temporal resolution. Since the ebullition activity is sensitive to cavity shape, cavity size distribution and wettability of the nucleating surface, a non-intrusive technique using encapsulated TLC is employed to accurately map the temperature field around the nucleation site. Liquid crystal based thermography uses cholesteric liquid crystals which reflect incident light preferentially over a narrow band of wavelengths depending on the imposed temperature. Its advantages are low response time of the order of 3 ms and the ability to capture global two-dimensional temperature fields at ebullition frequencies up to 500 Hz [7]. In contrast, even the most precise micro-thermocouples (TC) have a time constant which is one or two orders of magnitude higher than

* Corresponding author. Tel.: +1 407 823 4389; fax: +1 407 823 0208.
E-mail address: Ranganathan.Kumar@ucf.edu (R. Kumar).
[1] Equal contribution by all authors.

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Nomenclature

$\widetilde{A}$	non-dimensional area of influence
a	area of influence (mm)
Bo_m	modified boiling number
c_p	specific heat at constant pressure (kJ/kg K)
D	bubble diameter at departure (m)
f	ebullition frequency; bubble generation frequency (s^{-1})
G	average mass velocity of bubble (kg/m^2 s)
h	local heat transfer coefficient at the nucleation site (W/m^2 K); hue
h_{avg}	heat transfer coefficient averaged over the centerline of ROI (W/m^2 K)
h_{lv}	latent heat of vaporization (kJ/kg)
Ja	Jackob number
k	thermal conductivity (W/m K)
L	ROI length (mm)
N'	dimensionless ebullition frequency
Nu_{avg}	Nusselt number averaged over the centerline of ROI
Nu_o	overall Nusselt number
n	active nucleation site density (m^{-2})
p	pressure (kPa)
q	wall heat flux (kW/m^2)
Re_b	bubble Reynolds number
T_w	local wall surface temperature at the nucleation site
T_{wo}	overall wall surface temperature of ROI
T_{sat}	saturation temperature
ΔT	wall superheat; excess temperature; ($\Delta T = T_{wo} - T_{sat}$)
t	time
t_{cycle}	cycle time (ms)
t_d	departure time period (ms)
t_w	waiting time period (ms)
y_m	vertical distance to bubble top-most edge

Greek symbols

σ	standard deviation
β	bubble contact angle
α	thermal diffusivity (m^2/s)
ρ	density (kg/m^3)
η	surface tension (N/m^2)
ξ	dimensionless cycle time; ($\xi = t/t_{\text{cycle}}$)

Subscripts

b	bubble
l	liquid
o	overall
v	vapor

the TLC response, and are suitable for only point measurements. Furthermore, it is possible to obtain the full-field quantitative information about the spatial distribution of heat transfer coefficient [8] through true-color digital image processing of the recorded TLC response. TLC can be calibrated by using chromatic calibration method in which the dominant wavelength is determined as a function of temperature using the standard red, green and blue (RGB) color decomposition and chromaticity diagram. However, Akino et al. [9] formulated an efficient scalar descriptor of color by decomposing the tri-stimulus intensity count of color into RGB primaries. In addition, they found that a linear combination of RGB gave best results and that the hue of a TLC signal varied monotonically with its temperature.

Significant amount of work has been done in determining the geometry effects of a rectangular vertical duct in contrast with a circular tube [10–16]. Measurements of several local flow field characteristics such as void fraction, phasic velocities, interfacial velocity gradients and mean size of vapor bubbles were performed using R-134a as a model fluid in a vertical duct by Kirouac et al. [17] using multiple instruments such as gamma densitometer, hot-film anemometer and laser Doppler velocimeter. Their aim was to use this model fluid to simulate two-phase steam-water systems at high pressure/temperature. Buchholz et al. [18] reported pool-boiling experimental investigation on isopropanol at 104 kPa (reduced pressure $p/p_c = 0.022$, $T_{sat} = 82.9$ °C) using micro-thermocouples and miniature optical probe to measure local temperature fluctuations at the heater surface, surface wettability and void fraction.

Exploratory work on nucleate pool-boiling in refrigerant R-134a has been carried out by only a handful of research groups [19–22]. For instance, Barthau and Hahne [20] studied the angular variation of local heat flux on stainless steel tube in the reduced pressure range of 0.03–0.5 in R-134a. In another study, Gorenflo et al. [23] experimentally investigated the influence of thermo-physical properties on pool boiling heat transfer in both HFC-refrigerants/hydrocarbons using a twice sandblasted horizontal copper tube. They demonstrated that the topographical characteristics of heating surface, e.g. cavity size distribution of microstructure, local inter cavity distance and surface roughness parameter also influence the heat transfer coefficient in addition to the thermo-physical properties of the working fluid.

Based on the literature search, there appears to be a dearth of information on local surface temperature variations during a bubble ebullition cycle, in particular, for high pressure refrigerants. Thus, the current paper is a step forward to establish a methodology to generate surface temperature data synchronized with bubble activity and determine the influence of system pressure and wall heat flux on pool-boiling characteristics.

2. Experimental setup and procedure

2.1. Test loop

Experimental facility used to capture the bubble dynamics and TLC thermal response in nucleate pool boiling of pressurized R-134a is illustrated in Fig. 1. Refrigerant flow loop with inline test section and imaging system for flow visualization form two major sections of the experimental setup. The test chamber was fabricated from an aluminum block with top, bottom and side recesses machined to accommodate transparent quartz windows for visual access to the ebullition activity. Other auxiliaries consist of a positive displacement spur gear pump for generating high pressures in test section and pilot line operated positive feedback pressure regulator. The pressure regulator ensures that working pressure is maintained by by-passing a fraction of refrigerant fluid entering the test section. The test chamber contains an encapsulated TLC, pressure transducer, compression fittings for removable thermocouple (TC) arrangement and leak proof inserts for electrical connections to the heater foil. Ripple free DC current was fed to the heater element through narrow copper foils attached to its opposite side-edges.

The experimental arrangement of heating element configuration had three main design constraints: (1) TLC should not be directly exposed to the refrigerant pool, (2) the heater foil should