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Heat flux partitioning analysis of pool boiling on micro structured surface using infrared visualization

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ABSTRACT

We study a heat flux partitioning analysis of nucleate pool boiling on microstructured surface through infrared visualization technique. A heat flux partitioning analysis of the nucleate pool boiling consists of three kinds of heat flux mechanisms; convective, quenching and evaporative heat flux. It is importance of understanding the dominance among those heat flux mechanisms to fundamental study of the nucleate boiling heat transfer, but it is not clearly figured out. In this study, directly measuring the boiling parameters; bubble departure size, bubble releasing frequency, nucleation site density and bubble growth time through the infrared visualization technique, a nucleate boiling heat flux portioning analysis on pool boiling has been carried out. The experimental results indicate that sum of the three heat flux partitions from the measured boiling parameters shows good agreement with the experimentally given total heat flux. In addition, the quenching heat flux and evaporative heat flux becomes dominant at high heat flux regime by numerous bubble generation and fast bubble growth. On the microstructured surface, the increased heating surface area by the roughness ratio intactly contributes the heat transfer performance enhancement, and the area increase effect have to be reflected on the heat flux partitioning calculation. Although there are still many arguments of the heat flux portioning model analysis on pool boiling heat transfer from literatures and the methodological limitation due to the chaotic boiling phenomena, this study gives good inspiration and understanding of the boiling heat transfer mechanism and the importance of each heat transfer mechanism.

1. Introduction

Thermal management through two-phase heat transfer has received significant interest in thermal engineering (e.g., microchip cooling and management of the thermal load of nuclear power plants) due to the large latent heat associated with the phase change [1–4]. Nucleate boiling, as a key phenomenon of the liquid–vapor phase change, has been studied by numerous researches with the aim of improving the thermal management of the various systems. In general, evaluations of boiling performance mainly focus on two physical parameters: boiling heat transfer (BHT) and critical heat flux (CHF). These parameters evaluate the thermal system efficiency and integrity, respectively. For example, in nuclear power plants, BHT performance determine the efficiency of the energy conversion, and CHF to the safety margin and integrity of the nuclear hydraulic system. Because of the importance of BHT and CHF in the various thermal management systems, numerous studies of both understanding of fundamental boiling phenomena and performance-enhancing studies have been conducted.

At initial stage of the nucleate boiling study, the nucleate boiling heat transfer has been usually dominated in empirically, by relatively simple models based on hypotheses which are not clearly figured out. For example, the most widely popular Rohsenow's correlation assumed that the nucleate boiling heat transfer can be analyzed with a single-phase convection physical process. [5] Therefore, the Rohsenow's prediction correlates with the Reynolds and Prandtl number of the liquid phase and the environmental conditions (surface features, sub-cooled condition etc). Since then, numerous studies have been reported for each fitting empirical factor to reflect a wide range of physical conditions; pressure and subcooled etc. [6–9] Not only the single-phase convective

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Nomenclature

I	electric current [A]
R	electrical resistance [Ω]
A	area [m^2]
q''	heat flux [W/m^2]
V	voltage [V]
a	constant [–]
$\dot{q}$	heat generation [W/m^3]
J	electric current density [A/m^2]
d	micro-pillar diameter [m]
g	micro-pillars gap [m]
h	micro-pillar height [m]
h_c	convective heat transfer coefficient [kW/m^{2}K]
N''	nucleation site density [#/m^2]
D_b	bubble size [m]
k	thermal conductivity [W/mK]
ρ	density [kg/m^3]
c_p	heat capacity [J/K]
f	bubble frequency [#/s]
L	latent heat [J/kg]
r	roughness ratio [–]
K	influencing area factor [–]

Subscript

cir	circuit
heat	heater
ref	reference
c	convective
q	quenching
e	evaporative
l	liquid
v	vapor
str	structure

assumption but also a substantial number of such simplifying efforts have been carried out to model and evaluate the momentum and energy transport during the nucleate boiling. For examples, micro convection model (Forster and Grief [10]), vapor–liquid exchange model (Forster and grief [10]) and Natural convection analogy model (Zuber [11]) has been suggested and discussed. While the above models so far all describe some of the important element of the transport during the nucleate boiling, idealization incorporated into the models limit their accuracy and/or range of applicability. Basically, the above models have been developed in crude idealizations, reflecting isolated single bubble or single phase convection assumptions. In addition, to develop more detail model of nucleate boiling heat transfer including some basic features of the complex boiling process; number density of active sites, bubble frequency and departure bubble size, more careful experimental study is required.

From 80–90s, a more detail mechanistic model of nucleate boiling heat transfer that is reflecting on bubble dynamics has been developed. Accounting for the boiling parameters (bubble size, bubble frequency, and nucleation site density), semi-empirical model boiling heat transfer, called heat flux partitioning model, was presented. [12,13] The heat flux partitioning model suggests that the total boiling heat flux from the wall to the environmental liquid is partitioned into three components, namely the convective heat flux, the quenching heat flux, and the evaporative heat flux. The convective heat flux indicated that the heat transfer to the liquid phase outside the zone of influence of the bubbles by convection. The quenching heat flux accounts for the heat expanded in reformation of the thermal boundary layer following bubble departure. And, the evaporative heat flux explains the latent heat consuming by liquid–vapor phase change during the boiling process. The portion of each heat transfer contribution has not been clearly understood yet, but there were several approach to figure out the predominance of the heat transfer mechanisms.

In order to analyze the heat flux partitioning model quantitatively, several boiling parameters depending on heat flux or wall temperature have to be obtained. Basically, the bubble dynamics on the heating surface shows quite complex and chaotic behaviors, especially in high heat flux regime, so it is difficult to obtain the boiling parameters through experiment. Furthermore, these parameters vary with not only wall thermal conditions such as a wall super heat and a heat flux but also heating surface physical conditions; geometry and wettability. Although there were many reports of the bubble parameters, the prediction of each approach and model shows remarkable inconsistency and fluctuation with the experimental observation owing to the complexities of the bubble dynamics. Recently, through the high resoled and infrared visualization technique, the boiling parameters; bubble size, bubble frequency and nucleation site density has been directly measured. [14] Gerardi et al. reported the validity of the above heat flux partitioning model with experimentally measured boiling parameters and also the predominance of the quenching heat flux of all nucleate boiling regimes. From boiling incipience to critical heat flux, the quenching heat flux become dominant, compared with the other heat flux partitions. Yet, there are many arguments of the importance on each heat transfer mechanism on the nucleate boiling heat transfer, as mentioned above.

Recently, as nano- and micro- technology develops remarkably, various approaches for enhanced nucleate boiling heat transfer performance have been reported. Using nanoparticle deposition (nanofluids) or artificial nano/microscaled structures formations on boiling surface, a boiling performance (BHT & CHF) were enhanced. Kim et al., Bang et al. and You et al., carried out the pool boiling experiments with various nanofluids, and they not only increase but also decrease the boiling heat transfer change. [15–17] According to the literatures, nanoparticle deposition on the boiling surface usually decrease cavities for nucleation site, and it also affect the other boiling parameters. As a results, the boiling performance increases or decreases via those boiling parameter changes. In addition, Chen et al., Li et al. and Jo et al. conducted pool boiling performance evaluation on nanoscale wire or rods surface [18–20], and reported noticeable enhancement in not only boiling heat transfer but also critical heat flux. In detail, the nanostructures produced remarkable changes of the boiling parameters. Generally, while the bubble size becomes smaller, bubble departure frequency and nucleation site density increase on the nanoscaled structures. Not only nanoscaled structures but also designed microscaled structure by MEMS (MicroElectroMechanical Systems) affect the bubble dynamics and boiling parameters. [21] Although there were several reports about the bubble dynamics on the structured surface, the understanding of the boiling parameter changes on structured surface are still under debating.

In this study, a heat flux partitioning model has been carried out on a few designed microstructures surfaces, measuring all boiling parameter through infrared visualization. First, heat flux partitioning model on bare smooth surface has been evaluated and validated by comparison to the experimentally measured heat flux. The total heat flux from heat flux partitioning model shows good agreement with the experimentally measured heat flux, and both the evaporative heat flux and quenching heat flux becomes