Applied Thermal Engineering 70 (2014) 172–182

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Bubble dynamics in nucleate pool boiling on micro-pin-finned surfaces in microgravity

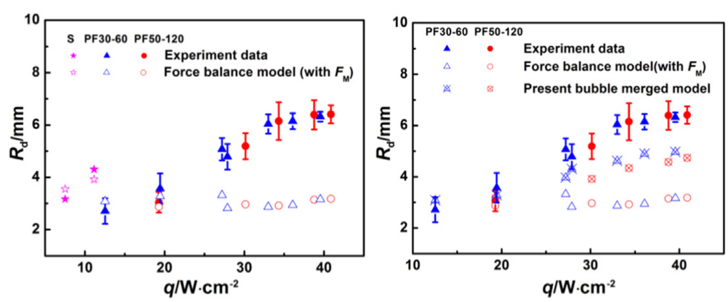
Yonghai Zhang [a], Jinjia Wei [a,*], Yanfang Xue [a], Xin Kong [a], Jianfu Zhao [b]

[a] *State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China*
[b] *Key Laboratory of Microgravity (National Microgravity Laboratory)/CAS, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China*

HIGHLIGHTS

- We performed micro-pin-finned surface in pool boiling in microgravity.
- Bubble behaviors on micro-pin-finned surface in microgravity were analyzed.
- A new bubble departure radius prediction model on micro-pin-fins in μg was developed.
- Both bubble force balance and bubble coalescence are considered in the model.
- The predictions agree much better with the experimental data than force balance model.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 October 2013
Accepted 29 April 2014
Available online 9 May 2014

Keywords:
Pool boiling
Bubble dynamic
Micro-pin-fins
Microgravity
Bubble departure radius
Model

ABSTRACT

Bubble dynamics is an important phenomenon, which basically affects the nucleate boiling heat transfer coefficient. Nucleate boiling heat transfer of gas-saturated FC-72 on micro-pin-finned surface was experimentally investigated in microgravity environment by utilizing the drop tower facility in Beijing. The dimensions of the silicon chips were 10 mm × 10 mm × 0.5 mm (length × width × thickness) on which two kinds of micro-pin-fins with the dimensions of 30 × 30 × 60 μm^3, 50 × 50 × 120 μm^3 (width × thickness × height, named PF30-60, PF50-120) were fabricated by the dry etching technique. The experimental data were presented for the bubble departure radius on micro-pin-finned surface. Experimental results showed that the bubble detachment radius increases with increasing heat flux, but the traditional force balance model failed to predict the bubble detachment radius on micro-pin-finned surfaces especially at high heat fluxes. Therefore, a new modified model for predicting bubble departure radius on micro-pin-finned surface in microgravity was developed. In this model, both bubble force balance and bubble coalescence are considered as two main factors influencing the size of bubble departure radius, and the predictions agree much better with the experimental data at moderate and high heat fluxes than the force balance model.

1. Introduction

Nucleate pool boiling heat transfer is widely used in desalination, chemical, petrochemical, refrigeration and power plants owing to the very high heat transfer coefficient, compared with those of other heat transfer methods. Previous studies showed that

* Corresponding author. Tel.: +86 029 82664462.
E-mail address: jjwei@mail.xjtu.edu.cn (J. Wei).

http://dx.doi.org/10.1016/j.applthermaleng.2014.04.074
1359-4311/

micro-pin-finned surface enhances boiling heat transfer in both normal gravity and microgravity [1–4]. It can be seen from the experimental research that the bubble departure radius is very important for determining the boiling heat transfer efficiency during nucleate pool boiling. In microgravity, bubble growth and departure radius directly influence the occurrence of steady nucleate boiling period.

A large number of studies on bubble growth rate and departure radius have been reported in the literature. Many famous correlations were developed for predicting the bubble radius under nucleate pool boiling condition for different applications. The earliest known relation for the bubble departure radius was given by Fritz [5], which the bubble departure is governed by buoyancy forces and surface tension forces. The relation between bubble frequency and diameter during nucleate pool boiling was studied by Mcfadden and Grassmann [6]. From a dimensional analysis coupled with available experimental data a new relationship was developed. Cole and co-workers [7–9] have conducted a series of studies on bubble growth and departure at subatmospheric pressures, the bubble departure diameter was correlated with the Jakob number in their theory. Gorenflo et al. [10] correlated bubble departure diameter at high heat fluxes when inertia becomes important. A new model was proposed for the prediction of vapor bubble departure diameters in saturated pool boiling by Zeng et al. [11]. They considered that the vapor bubble growth rate is a necessary input to the model, and its reliable estimation was required to predict accurately departure diameters. A characteristic length scale and a time scale were proposed to describe the dynamic growth and departure process of bubbles by Yang et al. [12]. A correlation between bubble departure diameter and bubble growth time was established, and a prediction formula for bubble departure diameter was suggested by considering the analog between nucleate boiling and forced convection. As illustrated above, most of correlations are applied in gravity condition. Even after extensive research spanning more than half a century, there is no generalized correlation for bubble diameter at departure due to the complexity of the boiling phenomena.

For boiling heat transfer in microgravity, there are still some correlations to predict the bubble radius. The effect of gravity on the bubble dynamics for saturated pool boiling of water and 60% sucrose have experimentally studied by Siegel and co-workers [13,14]. Meanwhile, bubble departure radii were measured. The experimental data were compared with the predicted bubble departure radii obtained through Fritz [5] and Zuber [15] model. As concluded, the experimental results were in good agreement with Fritz's correlation [5] for saturated pool boiling of water in microgravity ($<10^{-1}g_0$, $g_0 = 9.81$ m s^{-2}), indicating that bubble detachment mainly depends on buoyancy and surface tension forces. While $10^{-1}g_0 < \mu g < 1g_0$, the experimental results were in good agreement with Zuber's correlation [15], indicating that there are other dynamic forces, except for buoyancy and surface tension forces, pull the bubble to detach from the heater. For 60% sucrose, the results were very different from those of the saturated pool boiling of water. The bubble departure radius is almost constant though with changing gravitational acceleration. By using a force balance model, the bubble departure radius on smooth surface was estimated and compared with that from experimental measurements on literature in microgravity, conducted by Karri [16], and the results were in good agreement with the experimental micro-g data of Siegel and Keshock [13].

Dynamic force and static force balances were applied by Lee [17] to analyze bubble departure process on a flat plate and on a thin wire. The results showed that the dominating forces are the pressure force, surface tension force and buoyancy force exist in cases when the contact angle was larger than 39.5°. In case the contact angle was smaller than the above value, buoyancy force was not essential to the departure process. The value of bubble departure radius in microgravity approaches to a constant, or have no solution for asymptotic growth period. As for the thin wire, if the bubble departure radius was much larger than the wire radius, the dominating factors were the drag force and the pressure force. In case a valid solution exists, the bubble departure radius in microgravity approaches to a constant.

In all models mentioned above, the Marangoni effect was ignored. Recently, considering Marangoni effect, a mechanistic model of bubble departure was presented by Zhao et al. [18] to reveal the mechanism for pool boiling on wires in microgravity. The predictions were in qualitative consistency with the experimental observations. However, the usage of the boiling heat transfer model is limited due to the complexity of boiling heat transfer, difficulties in determination of parameters and calculation of bubble departure radius. At present, the most common used method is for analyzing the bubble force balance, before establishing a departure criterion and calculating the departure radius. As the above model requires no heating surface microstructure to be considered, the model is not suitable for cases involving micro-pin-fins. In this paper, we develop a model for calculating bubble departure radius on micro-pin-finned surface in microgravity.

2. Experimental apparatus and test procedure

2.1. Experimental apparatus

The pool boiling test facility system designed for conducting drop-tower experiments is shown schematically in Fig. 1. The 100 mm × 100 mm × 100 mm boiling chamber made of polycarbonate for visualizing boiling phenomena, is filled with about 1 L air-dissolved FC-72, the test liquid, at saturation temperature (T_{sat}) of 56 °C and under atmospheric pressure. A rubber bag attached to the test vessel is used to maintain a near-atmospheric pressure. By this way, subcooling (ΔT_{sub}) and pressure (P_s) conditions can vary during the experiments. The bubble behavior is videoed by using a 25 Hz CCD camera installed in front of the test vessel at a direction angle towards to the heater surface for visual observation. Simultaneously, a high speed digital camera (VITcam

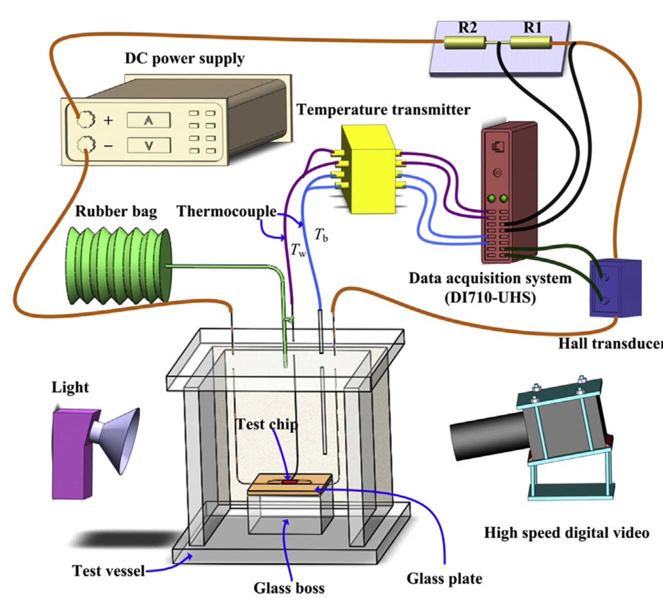


Fig. 1. Schematic diagram of the experimental apparatus.