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Effects of Vapor Path Structures on Critical Heat Flux and Boiling Heat Transfer in Pool Boiling

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1. Introduction

The demand for the thermal management in terms of safety and economics has been extensively increased because of the power density of the devices. Boiling is an effective heat transfer mode because it delivers a latent heat. However, there is a phase change limit, which is called as critical heat flux (CHF). Most of industry areas which have used the boiling heat transfer determine the safety margin of the power systems based on the CHF point. If the power density of the systems exceed the CHF region, the systems will be damaged because vapor films, which have much lower heat transfer capabilities, will cover the heating surface. Therefore, numerous studies related to the CHF prediction models have been extensively studied over the last 60 years, in terms of its physical mechanisms. Hydrodynamic instability, macrolayer dryout, hot/dry spot, and bubble interaction theories have been proposed as the CHF triggering and prediction models. One theory widely used to predict the CHF mechanism is hydrodynamic instability theory proposed by Zuber [1] and modified hydrodynamic theories have been proposed and developed to analyze the CHF enhancement mechanisms.

The hydrodynamic instability model illustrated that critical vapor velocity determined the CHF region and the Kelvin–Helmholtz (KH) instability wavelength was a criteria for determining the critical vapor velocity. Zuber [1] assumed that the critical Rayleigh–Taylor (RT) wavelength is related to the KH instability wavelength and further approximation was conducted to derive the CHF model. Lienhard and Dhir [2] proposed the hydrodynamic instability CHF model that the KH instability wavelength is equal to the most dangerous RT instability wavelength and they further investigated to develop the CHF prediction models based on the heater size conditions. Further study was also conducted by reducing the characteristic length of the heating surfaces and provided the CHF correlation based on the hydrodynamic instability [3]. Lu et al. [4-5] proposed a modified hydrodynamic theory that the KH instability wavelength was assumed to be the heater size and the area of the vapor column was used as a fitting factor. For the aspect of the KH instability wavelength in hydrodynamics, previous studies assumed that the KH instability wavelength is related to the RT instability wavelength or the heater size effects.

For the effect of the RT instability wavelength, Liter and Kaviany [6] proposed a modulation wavelength which could bring the change of the RT instability and the KH instability wavelengths in porous heating surfaces. Experimental results were supported to the change of the RT instability wavelength when the heater modification was performed [7-10]. Based on the experimental results, additional experimental correlation based on the change of the RT instability wavelength was proposed [10]. Recently, there was a revisiting study to find the relationship between the RT instability wavelength and the CHF values with different system pressures and heater sizes [11]. The paper concluded that the RT instability should consider the effect of heater characteristics to predict the CHF values more accurately. The CHF studies related to the hydrodynamic instabilities have been focused on finding the change of the RT instability wavelength and making a relation between the RT instability and KH instability wavelengths, but the effect of the critical height for the vapor path which can represent the KH instability wavelength has not been reported. Therefore, the effect of the critical height of the vapor path was examined using various types of intended vapor path with different heights of the structures.

2. Experimental Setup

Transparent material of polycarbonate was used as the boiling vessel to visualize the boiling occurrence during the experiment. There are four cartridge heaters to maintain the desired temperature of the working fluid during the experiment. In the experiment, FC-72 refrigerant was used as the working fluid, which boiling point is 56 °C at atmospheric pressure. The saturation state of the working fluid was monitored two thermocouples. An indium tin oxide (ITO) material on a Si substrate with the thickness of 750 nm was used as a heating layer (32 mm × 32 mm) and the power was supplied by a DC power supply which a maximum capacity of voltage and current was 150 V and 35 A, respectively.

To investigate the effects of the structural grids on heat transfer performance, several types of the structural grids were proposed, based on the RT instability wavelength. The critical and the most dangerous RT instability wavelength of the FC-72 were calculated as 4.91 and 8.51 mm, respectively. The length of the heating surface was five times higher than the critical wavelength, which heating surface can be assumed to be infinite. Therefore, the heights of the 10, 5, 3, and 1 mm were designed to show the effect of the structural grids on the CHF and BHT performance in the infinite heating surface. For the vapor path area, the diameters of the structural grids were 4.3, 2.15, and 1 mm with having 9, 49, and 225 holes, respectively. The diameters were based on the ratio of the RT instability wavelength. The area of the vapor path was 130.7, 177.9 176.7 mm^2 for the diameter of the 4.3, 2.15, and 1 mm, respectively.

The experimental procedure is as follows. The saturation state of the working fluid was maintained through the cartridge heaters and reflux condensers. The applied voltage was controlled to achieve the desired heat flux and the heat flux was increased up to the CHF. The IR thermometry and the HSV were used during the experiment to capture the heater surface temperature and the boiling occurrence. The steady state of each heat flux region was confirmed by the fluctuation of the average heating surface temperature profile.

3. Results and Discussion

Three types of different vapor path with different heights were examined in the plate pool boiling facility. CHF and BHT performance using the different vapor paths were presented through the IR thermometry and HSV results. The hydrodynamic instability CHF model, proposed by Zuber [1], attributed the critical vapor velocity phenomenon.

$$q''_{CHF} = \frac{\pi}{24}\rho_g^{1/2} h_{lg} \sqrt[4]{g\sigma(\rho_l-\rho_g)}\sqrt{\frac{\rho_l}{\rho_l+\rho_g}} \qquad (1)$$

where ρ_l and ρ_g are the liquid and vapor densities, respectively, h_{lg} is the latent heat of the working fluid, and σ is the surface tension of the working fluid. Based on the hydrodynamic instability model, the prediction CHF value of the FC-72 refrigerant was 148 kW/m^2. In the experiment, the CHF value was obtained as 135 kW/m^2 for the heating surface without the intended vapor path structures. The obtained CHF value was similar to the hydrodynamic instability CHF prediction value. This means that the reliability of the pool boiling experiment was proved as the point of hydrodynamic instability theory.

Figure 1 shows the boiling curves for different heights of the vapor path with the different path diameters. For the various vapor hole diameters at the height of the 10 mm, the CHF and BHT performance for all vapor path conditions showed similar trend. In addition, different CHF and BHT performances were not observed in the height of the 5 mm and 3 mm. For the height of the 1 mm, different heat transfer performance was observed. The CHF values for the 9, 49, and 225 holes were 98.9, 103, and 84.0 kW/m^2, respectively. In addition, BHT performance of the vapor path at the 1 mm height showed different results in the different vapor path area, which hole diameters were different. The most efficient boiling performance at the nucleate boiling region was observed in the 9 holes vapor path. The pitch and diameter of the 9 holes vapor path was based on the RT instability wavelength at the plain heating surface conditions, while the 49 and 225 holes vapor path were designed by the change of the RT instability. The results indicated that the boiling performance can be influenced by the vapor path characteristics. Table I lists the CHF results for the various experimental conditions.

Table I. CHF results under various experimental conditions

	CHF (kW/m2)			
Plain	135			
Heights (mm)	1	3	5	10
9 holes	98.9	134	129	135
49 holes	103	134	132	135
225 holes	84.0	133	132	135

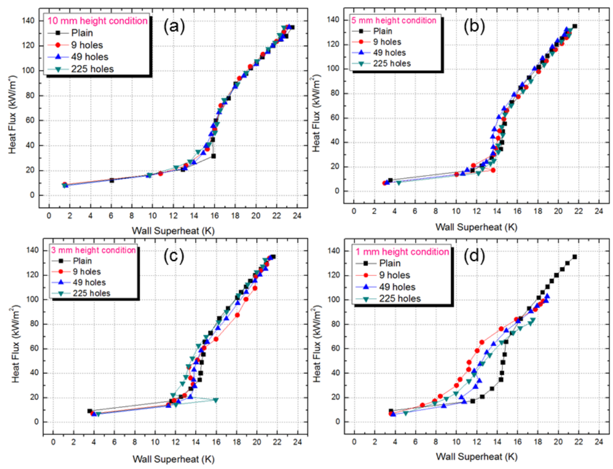

Figure 1. Boiling curves of different height of the structural grids: (a) 10 mm, (b) 5 mm, (c) 3 mm, (d) 1 mm

Figure 2 shows the boiling observations using the HSV with 1000 fps. For the plain, 10 mm, 5 mm, and 3 mm height of structural grids, the boiling occurrence was observed at 100 kW/m^2, while the HSV results for the 1 mm height was captured with different heat fluxes because the CHF phenomenon was observed near the 100 kW/m^2. As shown in Fig. 2, the bubble dynamics were similar to the same vapor path area, but the different CHF performance was observed when the critical height of the vapor path was created. The results indicated that the CHF and BHT performance were changed when the height of the intended vapor path was less than 3 mm. Based on the experiment using the IR thermometry and the HSV, we confirmed that there was an effect for the heights of the intended vapor path on the CHF and the BHT performance at the same heating surface condition.

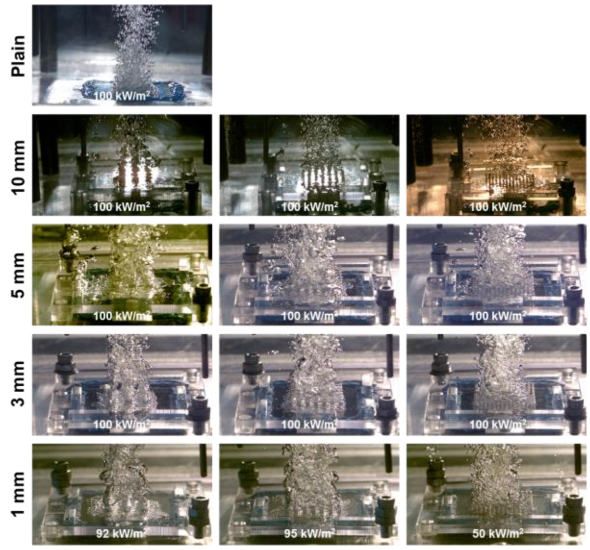

Figure 2. High speed video observations with different vapor path under various heights of the structures

The CHF prediction models based on the hydrodynamic instability illustrated that the KH instability wavelength is related to the RT instability wavelength [1,2]. The RT instability wavelength was based on the interfacial stability theory, which did not consider the effect of the surface characteristics. This means that the RT instability wavelength and the KH instability wavelength did not consider the surface effects. However, there have been studies to show the CHF enhancement based on the change of the RT instability wavelength [6, 10, 12]. The papers showed that the change of the RT instability wavelength due to the change of the heating surfaces may increase the CHF enhancement. However, the study related to the effect of the intended vapor path to show the change of the CHF and BHT was not reported. In the present work, we showed that the critical height of the structure which can represent the KH instability wavelength was found. It can support the theory of the hydrodynamic instability for the CHF prediction. In the CHF prediction model developed by Zuber [1], he approximated a numerical constant of $3/\sqrt{2\pi}$ as one when the critical wavelength was related to the KH instability wavelength. When the value of the numerical constant is included in the KH instability wavelength, the modified KH instability wavelength can be calculated as 3.42 mm. This means that the critical height could be ranged around 3 mm. In the present work, the change of the CHF and the BHT was found in the height of 1 mm. Therefore, the relation between the critical KH instability wavelength and the change of the CHF was found through the intended vapor path with various heights of the structures.

Based on the experimental results, we showed that the critical height of the vapor path can influence the CHF and the BHT performance at the same heating condition. This means that the prediction of the RT instability and KH instability wavelengths should be performed based on the heating surface conditions. In the aspect of the heating surface modification, the CHF enhancement study based on the RT instability wavelength have been performed. Seo and Bang [12] performed an experiment related to the CHF enhancement study of the surface patterned surfaces, which patterns were based on the change of the RT instability wavelength. The change of the RT instability was observed through the HSV and CHF enhancement was followed by the regulated patterning surfaces. In addition, further study was performed to find the relation between the RT instability wavelength and the CHF with various heater conditions and system pressures [11]. The paper showed that the RT instability was changed when the heater diameters and the system pressures were different. The change of the RT instability wavelength with the CHF values was followed the modified hydrodynamic approach. They concluded that the RT instability wavelength should consider heater surface characteristics because the surface could bring the change of the balancing pressure on the wavy interface. Therefore, the CHF prediction model could be improved when the surface effects of heating surfaces and the critical height of the vapor path designed by the RT instability wavelength are considered.

4. Conclusions

The effect of the vapor path with various heights of the structures was considered in the plate pool boiling facility to find the hydrodynamic instability mechanisms. The critical height of the intended vapor path was found when the height was less than 3 mm. The modified KH instability wavelength by considering numerical constant of the Zuber's prediction model predicted the critical height of the vapor path as the similar value of the experimental results. The results indicated that the hydrodynamic instability model is valid in the present study.

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REFERENCES

[1] N. Zuber, Hydrodynamic Aspects of Boiling Heat Transfer, Ph.D. Thesis, Univ. of Califronia, (1959).
[2] J. H. Lienhard, V. K. Dhir, On the prediction of the minimum pool boiling heat flux, *J. Heat Transfer*, 102 (3) (1980) 457-460.
[3] W. R. Lee, W. S. Han, J. Y. Lee, Effect of Flow instability on Pool Boiling and CHF of Thin Flat Plate Heater PCB, *8th International Conference on Multiphase Flow*, 2013.
[4] M. Lu, R. Chen, V. Srinivasan, V. P. Carey, A. Majumdar, Critical heat flux of pool boiling on Si nanowire array-coated surfaces, *Int. J. Heat Mass Transfer*, 54 (25) (2011) 5359-5367.
[5] M. Lu, C. Hung, C. Huang, Y. Chen, A modified hydrodynamic model for pool boiling CHF considering the effects of heater size and nucleation site density, *Int. J. Therm. Sci.*, 91 (2015) 133-141.
[6] C. S. Liter, M. Kaviany, Pool-boiling CHF Enhancement by Modulated Porous-layer Coating: Theory and Experiment, *Int. J. Heat Mass Transfer*, 44 (22) (2001) 4287-4311.
[7] S. D. Park, S. W. Lee, S. Kang, I. C. Bang, J. H. Kim, H. S. Shin, D. W. Lee, D. W. Lee, Effects of Nanofluids Containing Graphene/Graphene-oxide Nanosheets on Critical Heat Flux, *Appl. Phys. Lett*., 97 (2010) 023103.
[8] S. W. Lee, S. D. Park, I. C. Bang, Critical heat flux for CuO nanofluid fabricated by pulsed laser ablation differentiating deposition characteristics, *Int. J. Heat Mass Transfer*, 55 (23-24) (2012) 6908-6915.
[9] H. Seo, J. H. Chu, S. Kwon, I. C. Bang, Pool boiling CHF of reduced graphene oxide, graphene, and SiC-coated surfaces under highly wettable FC-72, *Int. J. Heat Mass Transfer*, 82 (2015) 490-502.
[10] S. D. Park, I. C. Bang, Experimental Study of a Universal CHF Enhancement Mechanism in Nanofluids Using Hydrodynamic Instability, *Int. J. Heat Mass Transfer*, 70 (2014) 844-850.
[11] H. Seo, I. C. Bang, Revisiting the Rayleigh–Taylor instability and critical heat flux with R-123 for different heater sizes and pressures, *Int. J. Therm. Sci.*, 100 (2016) 324-332.
[12] H. Seo, I. C. Bang, Critical Heat Flux Enhancement Mechanism by Surface Modification based on Hydrodynamic Instability Model, *NURETH-16*, 2015.