Experimental investigation on the condensation heat transfer in low wall subcooling

Ji-Hwan Hwang[a], Hyun-Jae Kim[b], Jung Jin Bang[c], Dong-Wook Jerng[a*]
[a]*School of Energy Systems Engineering, Chung-Ang University, 84 Heukseok-ro, Dongjak-gu, Seoul, 06974, Republic of Korea*
[b]*Taesung S&E, 27, Seongsui-ro 7-gil, Seoul, 04780, Republic of Korea*
[c]*FNC Technology Co., Ltd., Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi- do, 16954, Korea*
[*]*Corresponding author: dwjerng@cau.ac.kr*

1. Introduction

Condensation heat transfer in presence of noncondensable gases plays an important role in passive safety systems such as Passive Containment Cooling System (PCCS). To precisely estimate the performance of the passive safety systems, investigations on condensation heat transfer have been conducted [1-5], particularly for the effect of thermal-hydraulic conditions. However, unlike the effect of pressure and noncondensable gas content, the effect of wall subcooling on condensation heat transfer, particularly in the low subcooling region, has not been investigated a lot.

Experiments had conducted to analyze the effect of wall subcooling on condensation heat transfer; Dehbi [1] and Su et al. [4, 5] reported that the condensation heat transfer is inversely proportional to the wall subcooling when wall subcooling exceeds 25 K. For conditions in which wall subcooling is lower than 25 K, Su et al. reported the condensation heat transfer is inversely proportional to the wall subcooling, yet the influence of wall subcooling decreases. On the other hand, Liu [2] claimed that condensation heat transfer is proportional to the wall subcooling. The experiment of Kawakubo showed that the condensation heat transfer is proportional to the wall subcooling in low subcooling extent and became inversely proportional to the wall subcooling [3]. As the precedent research showed conflicting results, an experiment with a wide range of wall subcooling is needed.

Therefore, in this paper, we experimentally investigated the condensation heat transfer in various wall subcooling conditions. The experiment conditions include not only high-subcooling extent, but also low-subcooling range in which wall subcooling is lower than 15 K. The experiment result showed that the dependency of condensation heat transfer on wall subcooling changes at about wall subcooling 10-15 K.

2. Experiment Method

2.1 Experiment apparatus

The schematic of the experimental facility is shown in Fig. 1. The experimental facility comprised a 2.5 m high pressure vessel with a 0.447 m inner diameter. A stainless-steel condensing tube is vertically oriented in the middle of the pressure vessel. The condensing tube has an outer diameter of 0.0381 m, and a height of 0.75 m. The steam is supplied using a 20-kW boiler. The temperature of the coolant was controlled using a 6.5-kW chiller and 8-kW preheater. The flow rate of the coolant was controlled using a pump and measured with an electromagnetic flowmeter.

The bulk temperatures were measured using 1Φ K-type thermocouples. Wall surface and coolant temperatures were measured using 1/8-inch K-type thermocouples. The thermocouples used for wall temperature measurements were silver soldered on the surface. The bulk temperatures were measured in 3 elevations. The coolant temperatures were measured in 4 elevations, and the wall surface temperatures were measured in 3 elevations and 3 azimuths to precisely measure the wall subcooling.

The noncondensable gas concentration was obtained by assuming the steam-air mixture was in saturation condition $x_{nc} = 1 - P_{saturation} / P_{total}$.

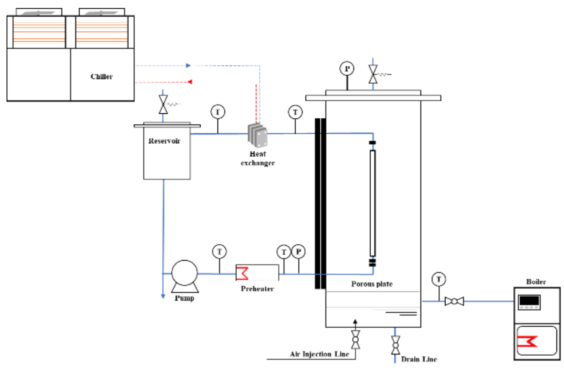

Fig. 1. Schematic diagram of the experimental apparatus.

2.2 Data acquisition and reduction

The heat transfer coefficient was calculated using the following equation:

$$h = \frac{\dot{m}c_p\left(T_{c,o} - T_{c,i}\right)}{2\pi rL\left(T_\infty - T_w\right)}. \tag{1}$$

$\dot{m}$, $T_{c,o}$, $T_{c,i}$, T_∞, and T_w represent the mass flow rate of coolant, the outlet temperature of the coolant, inlet temperature of the coolant, bulk temperature, and wall surface temperature.

The experiment starts with emptying the pressure vessel with a vacuum pump. Thereafter, the air was injected to reach a desired partial pressure. Steam was then injected at the bottom, which helps mixing of the atmosphere in the pressure vessel. The coolant was circulated, and the temperature of the coolant was controlled using a chiller and preheater. After bulk and coolant temperature reached steady-state, data were acquired for 10 minutes, once in a 5 second.

The uncertainty of the experiment was calculated by following the work of Moffat [6]. The average uncertainty of the condensation heat transfer coefficient was about 9 %.

3. Results and discussions

The results of condensation experiments are shown in Fig. 2. It can be found in Fig. 2 that the increase of air mass fraction reduces condensation heat transfer dramatically. In addition, the increase of pressure enhances condensation heat transfer, which is consistent with the precedent research [1-5].

In case of the effect of wall subcooling, the increase of wall subcooling deteriorated condensation heat transfer, in the subcooling range exceeding 10-15 K. It should be also noted that when wall subcooling exceeds 15 K, the condensation heat transfer was proportional to the -0.25-th power of wall subcooling ($h = f\left(Y_a, P\right)\Delta T^{-0.25}$), which was almost identical to that derived with Nusselt's film theory. This can be recognized that the experimental heat transfer coefficient is similar to that obtained from Dehbi's experiment [1]. The comparison with Dehbi's experiment also indicates that the test facility is well designed and built.

In the subcooling range under 10-15 K, the change of condensation heat transfer reduces significantly, i.e., the condensation heat transfer changed little with wall subcooling. Such results were identical to the result of Kawakubo [3] and Su et al. [4, 5], which reported that the change of heat transfer is reduced.

The effect of condensation heat transfer changed with air mass fraction. In high air mass fraction, the condensation heat transfer became proportional to the wall subcooling, while the condensation heat transfer remained with the inverse proportional relationship in low air mass fraction conditions. Moreover, with a higher air mass fraction, the effect of wall subcooling was reinforced; that is, the condensation heat transfer changed more according to the wall subcooling when compared with the lower air mass fraction case.

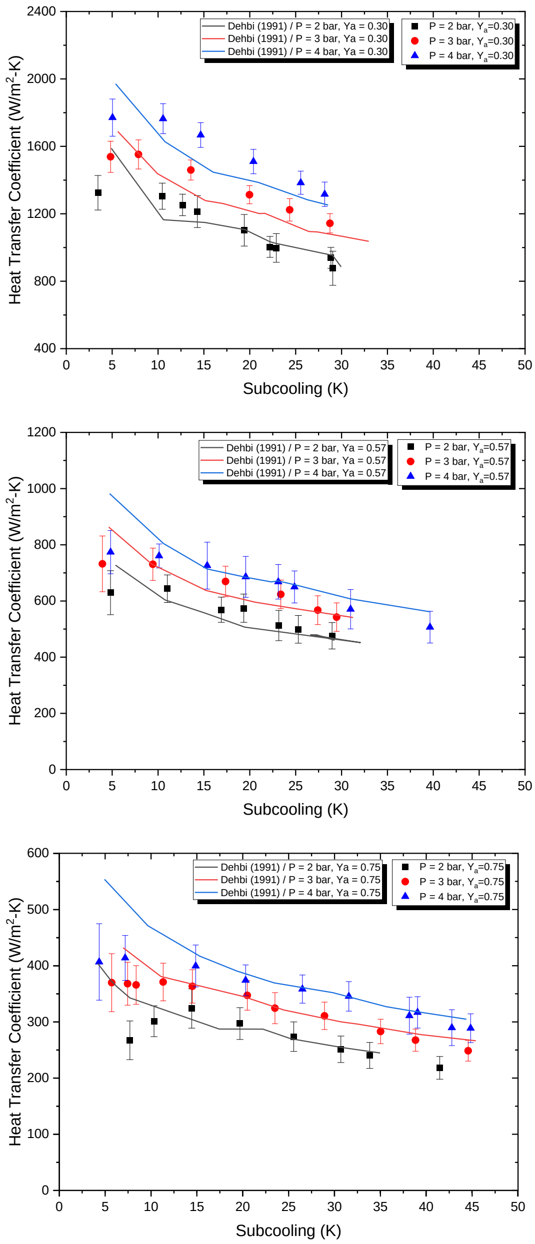

Fig. 2. The effect of wall subcooling on condensation heat transfer: (top) air mass fraction 0.3 case, (middle) air mass fraction 0.57 case, (bottom) air mass fraction 0.75 case.

4. Conclusions

In this paper, we experimentally studied the effect of wall subcooling on condensation heat transfer. The experiment was conducted with a 0.75 m high, 0.0381 m diameter condensing tube. According to the experiment, the condensation heat transfer was decreased with increasing wall subcooling, in high wall subcooling extent exceeding 15 K. In such region, the condensation heat transfer was proportional to the -0.25-th power of wall subcooling, which is similar to that derived from Nusselt's film theory. In the low wall subcooling range, in which wall subcooling is lower than 15 K, the dependency of condensation heat transfer to the wall subcooling decreased. In some high air mass fraction case, the condensation heat transfer even became inversely proportional to the wall subcooling. In addition, in the low subcooling range, the effect of wall subcooling on condensation heat transfer was higher in high air mass fraction which indicates the air mass fraction affects the wall subcooling effect.

REFERENCES

[1] A.A. Dehbi, The effects of noncondensable gases on steam condensation under turbulent natural convection conditions, Massachusetts Institute of Technology, 1991.

[2] H. Liu, N. Todreas, M. Driscoll, An experimental investigation of a passive cooling unit for nuclear plant containment, Nuclear Engineering and Design, 199(3) (2000) 243-255.

[3] M. Kawakubo, M. Aritomi, H. Kikura, T. Komeno, An experimental study on the cooling characteristics of passive containment cooling systems, Journal of nuclear science and technology, 46(4) (2009) 339-345.

[4] J. Su, Z. Sun, G. Fan, M. Ding, Experimental study of the effect of non-condensable gases on steam condensation over a vertical tube external surface, Nuclear Engineering and Design, 262 (2013) 201-208.

[5] J. Su, Z. Sun, M. Ding, G. Fan, Analysis of experiments for the effect of noncondensable gases on steam condensation over a vertical tube external surface under low wall subcooling, Nuclear Engineering and Design, 278 (2014) 644-650.

[6] R.J. Moffat, Describing the uncertainties in experimental results, Experimental thermal and fluid science, 1(1) (1988) 3-17.