Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2015

Inside-pipe hydrophobic coating method promoting dropwise condensation in a passive cooling system

Joo Won Kang [a], Jun Young Kang [a], Kyoung Won Hwang [b], Hyun Sun Park [a*], Moo Hwan Kim [c], Kiyofumi Moriyama [a]
[a]*Division of Advanced Nuclear Engineering, POSTECH, 77 Chongam-Ro Nam-Gu Pohang, Republic of Korea*
[b]*Department of Mechanical Engineering, POSTECH, 77 Chrongam-Ro Nam- Gu Pohang, Republic of Korea*
[c]*Korea Institute of nuclear safety, 62 Gwahak-Ro, Yuseong-Gu, Daejeon, Republic of Korea*
[*]*Corresponding author: hejsunny@postech.ac.kr*

1. Introduction

After the tragic accident at Fukushima, the importance of the passive safety system has been significantly raised. Submerged by large tsunami, active cooling system was not operated to cool down decay heat. Likewise, station black out can lead to severe accident so that the necessity of cooling system without requesting any electric power was stressed out.

Passive Auxiliary Feedwater System(PAFS) is one of the passive cooling systems suggested by Korea Atomic Energy Research Institute(KAERI) [1]. It has hundreds of slightly inclined horizontal U-shaped pipes submerged in a large water pool. Under the accident circumstances, this system cools steam that comes from the steam generator into condensed water inside the pipes without any electric power. These pipes are made of stainless steel 304L, with the diameter of 50 mm, and the length of 8 m.

The main heat transfer phenomenon inside a pipe is the condensation phenomenon. There are two modes of condensation: one is filmwise condensation(FWC) and the other is dropwise condensation(DWC). On a surface wetted by a liquid well, FWC occurs to form liquid film. If a surface is not wetted by a liquid, DWC occurs to form droplets on the surface. In the heat transfer point of view, DWC has generally higher heat transfer coefficient than that of FWC, but the more general condensation mode on metal surfaces is FWC.

The final goal of this study is to increase cooling capacity of passive safety system like PAFS. Up to now, the attempts to increase condensation heat transfer were limited to make finned tube [2]. DWC which has higher heat transfer coefficient was only promoted on vertical plates or external pipes. By promoting DWC inside a pipe, condensation heat transfer will be fundamentally enhanced. In this paper, hydrophobic coating inside a pipe method will be presented for promoting DWC, and its condensation heat transfer performance will be evaluated by conducting condensation experiment on a vertical plate.

2. Hydrophobic coating method

To promote DWC, the condensation surface should not be wetted by the liquid. In this section, Teflon coating method inside a pipe will be introduced, and the validation of promoting DWC will be done by visualization with a transparent glass pipe.

2.1 Teflon coating inside a pipe method

To promote DWC, a condensation surface has to be hydrophobic. For this, amorphous Teflon resin, AF2400, was selected for simplicity of inside-a-pipe coating method. A sponge was attached at the end of a long stick, and Teflon was applied evenly inside a pipe by rubbing the stick. After an hour of drying, the Teflon coated pipe was cured at 100 °C for 3 hours in a convection oven as depicted in Fig. 1. After using this method, the contact angles on bare and Teflon coated surface were 80.5° and 120.8°, respectively.

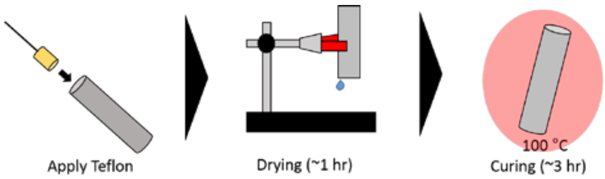

Fig. 1. Inside-a-pipe Teflon coating method

2.2 Condensation visualization inside a pipe

To validate that DWC is possibly promoted inside a pipe by this coating method, a transparent borosilicate glass pipe was used to visualize inside a pipe. Like the PAFS, glass pipes were in horizontal position. The diameter of the pipe was 50 mm and the length was 300 mm. Steam was supplied by adjustable 150 kW steam generator, and the pressure of the steam was 3 bar. For comparison, bare borosilicate pipe and Teflon coated pipe were used, and each pipe was submerged in a water pool of 15 °C. By visualizing condensation phenomenon inside the borosilicate pipe, FWC was showed in the bare pipe, while DWC was promoted in the Teflon coated pipe as in Fig. 2.

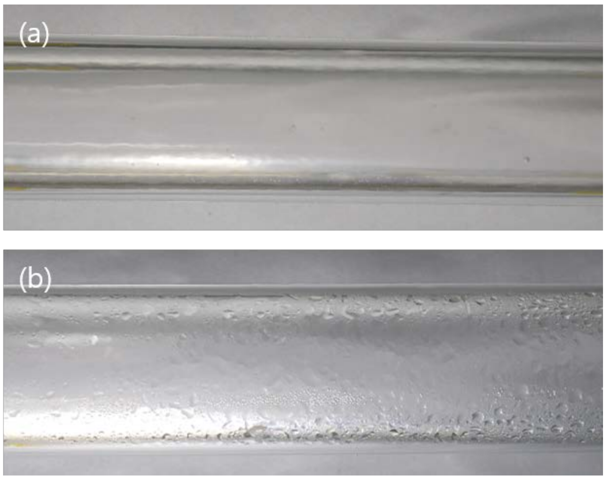

Fig. 2. Visualization inside horizontal borosilicate pipes. (a) FWC was showed inside a bare borosilicate pipe, (b) DWC was showed inside a Teflon coated pipe. Images were taken in top view.

3. Condensation heat transfer coefficient measurement experiment

Inside a Teflon coated pipe, droplets will form on its surface. In PAFS geometry, the pipes are horizontal and the droplets that form on top and side wall will roll down to the bottom by gravity. It is the almost same phenomenon with droplets on a vertical plate. In this section, condensation on vertical plate experiment was conducted to measure condensation heat transfer coefficient with the conceptually same coating method developed in previous section.

3.1 Experimental loop for condensation heat transfer coefficient measurement

The test loop was designed to measure condensation heat transfer coefficient on vertical plate as described in Fig. 3. Pure steam was supplied from PID controlled steam generator of maximum power of 4 kW, and goes into the steam chamber. The pressure of the steam chamber was about 145 kPa and maintained properly by a needle valve at drain. The temperature of bulk steam in steam chamber was measured by a calibrated K-type thermocouple. In the steam chamber, steam condensed on vertical plate specimen. Behind the specimen, the cooper block is attached, where coolant flows at the opposite end side. Tap water was used as coolant, whose temperature was around 15 °C. At the copper block, two calibrated K-type thermocouples were mounted at intervals of 7 mm to measure heat flux. Test specimens were made of stainless steel 304L, the same material of pipes in PAFS. The size of the specimen was 30X40 mm and 2 mm thick. Inside of the specimen, a calibrated K-type thermocouple was inserted.

To promote DWC, surface of the stainless steel specimen was coated with Teflon by conceptually same Teflon coating method as described in section 2.1. Teflon was applied on test specimen surface, and cured at 100 °C in a convection oven. For the comparison, condensation experiment on bare stainless steel specimen was also conducted. The measured contact angles of Teflon coated and bare stainless steel surface were 80.5° and 120.8° each.

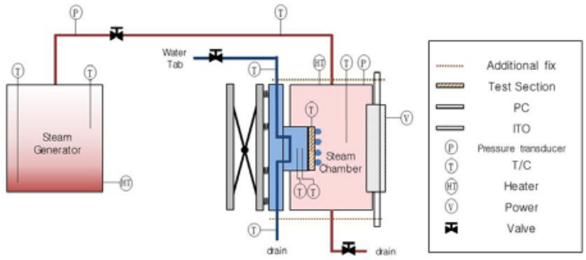

Fig. 3. Condensation on vertical plate experimental loop

3.2 Heat transfer coefficient calculation

For the calculation of condensation heat transfer coefficient, heat flux was calculated from the two thermocouples in copper block, and temperature of condensation surface was computed.

Heat flux is calculate by,

$$q'' = \frac{k_{copper}(T_1 - T_2)}{\Delta x_1} \tag{1}$$

, where q'', k_{copper}, T_1, T_2, and Δx_1 are heat flux, conductivity of copper, temperatures in copper block, and distance between the thermocouples measuring T_1 and T_2.

Temperature of condensation surface was computed from,

$$T_{surf} = \frac{q''\Delta x_2}{k_{sus}} + T_s \tag{2}$$

, where T_{surf}, Δx_2, k_{sus}, and T_s are temperature of condensation surface, distance between thermocouple and condensation surface, conductivity of stainless steel 306L, and temperature inside the specimen.

Finally, condensation heat transfer coefficient was figured out,

$$h = \frac{q''}{T_{bs} - T_{surf}} \tag{3}$$

, where h, and T_{bs} are heat transfer coefficient, and temperature of bulk steam.

The average uncertainty of measured heat transfer coefficients were 18.3%, and the maximum uncertainty was 25.2%

3.3 Experiment result

To check the repeatability, each experiment was repeated 3 times, and two specimen were used to make sure reproducibility. The average repeatability error was 8.3% and the maximum repeatability error was 11.0%.

As a result, the average heat transfer coefficient on Teflon coated surface was 53.3 kW/m^2/K, and that on stainless steel bare surface was 13.5 kW/m^2/K. heat transfer coefficient on Teflon coated surface was 2.94 times higher than that on stainless steel bare surface. Nusselt's condensation model on vertical plate predicted 12.1 kW/m^2/K [3].

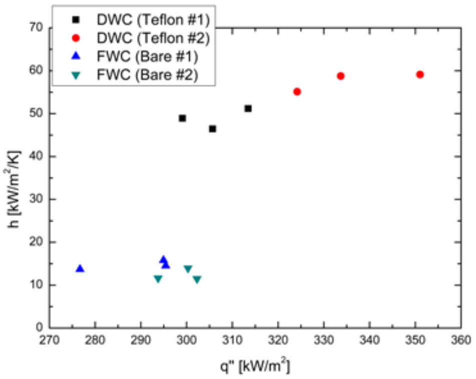

Fig. 4. Condensation on vertical plate experimental result

4. Conclusions

The inside-pipe hydrophobic coating method was developed using Teflon, and it was checked that DWC was promoted by this method with visualization results. Condensation heat transfer coefficients were measured experimentally on vertical stainless steel plates. At the saturation pressure of 145kPa, average heat transfer coefficient for DWC was 53.3 kW/m^2/K, and that for FWC was 13.5 kW/m^2/K. Based on this results, it can be concluded that this coating method will increase heat transfer coefficient inside a pipe at a passive safety system.

AKNOWLEDGEMENT

This work was also supported by National Research Foundation of Korea (NRF) grants funded by the Korean government (MSIP) (2014M2B2A9031122).

REFERENCES

[1] Kang, K. H., Kim, S., Bae, B. U., Cho, Y. J., Park, Y. S., & Yun, B. J., Separate and integral effect tests for validation of cooling and operational performance of the APR+ passive auxiliary feedwater system, Nuclear Engineering and Technology, (6), 597-610, 2012.

[2] Cavallini, A., Censi, G., Del Col, D., Doretti, L., Longo, G. A., Rossetto, L., & Zilio, C., Condensation inside and outside smooth and enhanced tubes—a review of recent research, International Journal of Refrigeration, 26(4), 373-392, 2003.

[3] Nusselt, W, "Die Oberflachenkondesation des Wasserdamffes the surface condensation of water." Zetrschr. Ver. Deutch. Ing. 60: 541-546, 1916.