Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 27-28, 2011

Experimental study on pure steam condensation in a vertical tube

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1. Introduction

The System-integrated Modular Advanced ReacTor (SMART) is a small Korean nuclear reactor for electricity generation and seawater desalination. The Passive Residual Heat Removal System (PRHRS) removes the remaining nuclear core heat by natural convection in emergency situations. The present research has been performed to study the heat transfer characteristics for the PRHRS condensation heat exchanger. In this heat exchanger, steam condensation occurs in a vertical tube.

Nusselt[1] conducted a theoretical analysis of laminar film condensation on a flat plate using several assumptions. Shah[2] developed a correlation using the similarity between the mechanisms of heat transfer during film condensation and boiling without bubble nucleation. Recently, Lee and Kim[3] conducted condensation experiments on steam and a steam-gas mixture inside a 13 mm I.D. vertical tube. Kim et al.[4] developed a pure steam condensation model in a vertical tube using the assumption that liquid film undergoes Couette flow forced by the interfacial velocity at the liquid-vapor interface.

The objective of this paper is to investigate the effect of steam flow rate and pressure on condensation heat transfer characteristics in a vertical tube.

2. Experiments

2.1 Experimental facilities

A schematic diagram of the experimental loop is shown in Fig. 1. The experimental facilities consist of a steam generator, separator, sub-heater, test section, condenser, balance, and data acquisition system. Steam is generated in the steam generator. Residual liquid in steam is removed by the separator and sub-heater. Most of the steam is condensed in a test section, and the condenser is installed to remove residual steam in condensed water. Mass flow rate is measured by the balance. The test section is composed of a condenser tube and cooling jacket. Steam flows through the inside of the tube and coolant flows through the cooling jacket. The condenser tube's inner diameter is 13.88 mm, and its outer diameter is 21.34 mm, which is the same as the actual PRHRS condensation heat exchanger's size. The cooling jacket is square in shape, and the length of each side is 45 mm. The material of the test section is SUS 316L. A schematic diagram of the test section's cross section is shown in Fig. 2. Tube length is 1.5 m. At 20 different axial locations, K-type thermocouples are silver-soldered onto the outer surface of the condenser tube to measure its outer wall temperature. Cooling water temperatures are measured at 21 different axial locations with K-type thermocouples. One-fourth inch tubes are welded onto the outer surface of the condenser tube to measure the steam bulk temperature at 12 different axial locations. The experiments are conducted for the steam flow rates of 0.0032 and 0.008 kg/s at 2, 4, and 6 MPa.

2.2 Data reduction

This study focuses on the behavior of the condensation heat transfer coefficients. Local heat fluxes are calculated by the slope of the coolant temperature profile.

$$q''(z) = -\frac{\dot{m}_{cw} C_p}{\pi d_i} \frac{dT_{cw}(z)}{dz}$$

Inner wall temperature is calculated using local heat flux and outer wall temperature.

$$T_{w,i}(z) = q''(z) \cdot \frac{D_i \ln(D_o / D_i)}{2k_{sus}} + T_{w,o}(z)$$

Thus, local heat transfer coefficients are calculated by the following equation.

$$h(z) = \frac{q''(z)}{(T_b - T_{w,i})}$$

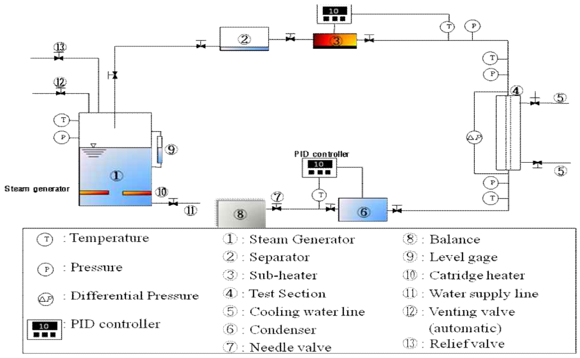

Fig. 1 Schematic diagram of test loop

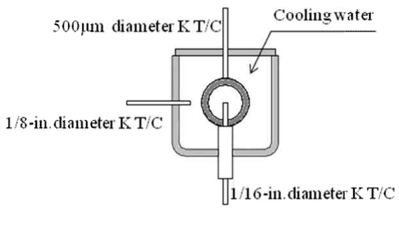

Fig. 2 Cross section of test section

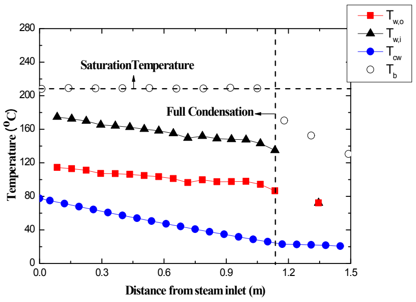

Fig. 3 Temperature distributions at 1.833 MPa, 0.0081 kg/s

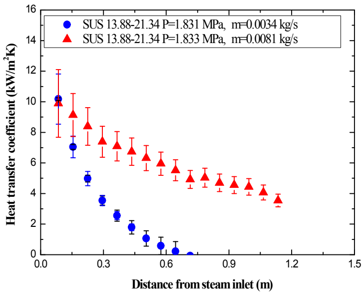

Fig. 4 Heat transfer coefficient variations according to steam mass flow rate changes

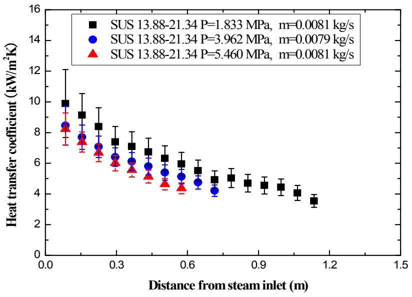

Fig. 5 Heat transfer coefficient variations according to steam pressure changes.

3. Results and Discussion

Fig. 3 shows the temperature distributions at pressure 1.833 MPa and steam mass flow rate 0.0081 kg/s. At two-phase flow region steam, bulk temperatures are maintained at saturation temperature. After the full condensation line, steam bulk temperatures dramatically decrease, because single phase heat transfer occurs. The dominant mechanism of steam condensation in a vertical tube is film-wise condensation. That is, condensate film flows as an annular film adjacent to the tube wall, and steam flows in the tube core region. In this situation, condensate film occupies major thermal resistance. When the liquid film is in the laminar state, the heat transfer coefficient can be defined as a function of thermal conductivity and thickness of the liquid film. Steam flow in a tube core can generate interfacial shear stress between the liquid film and vapor flow. Interfacial shear stress deforms the velocity profile of liquid film, and this velocity profile change affects the film thickness [4]. Fig. 4 shows the heat transfer coefficient variations according to steam flow rate changes from 0.0034 kg/s to 0.0081 kg/s at about 2 MPa. As steam mass flow rate increases, heat transfer coefficients increase. Steam mass flow rate is directly related to steam velocity. Increases in steam velocity cause increases in interfacial shear stress. Increases in interfacial shear stress cause a decrease of liquid film thickness and thermal resistance. Fig. 5 shows the heat transfer coefficient changes according to steam pressure changes from 2 MPa to 6 MPa at about 0.008 kg/s. The figure shows that as pressure increases, heat transfer coefficients decrease. As pressure increases, steam density increases. It brings about a decrease of steam velocity, and then of interfacial shear stress. This effect brings about an increase of liquid film thickness, and therefore of thermal resistance. As pressure increases, the thermal conductivity of saturated liquid decreases, and it causes a decrease of the thermal resistance of liquid film. Thus, it is estimated that the decrease of interfacial shear stress and thermal conductivity causes a decrease of condensation heat transfer coefficients.

4. Conclusion

Experimental research on pure steam condensation in a vertical tube was conducted. The heat transfer coefficients increase as steam mass flow rate increases or steam pressure decreases.

ACKNOWLEDGEMENTS

This study was supported by the Korea Atomic Energy Research Institute and the WCU (World Class University) Program through the National Research Foundation of Korea funded by the Ministry of Education, Science, and Technology (R31-30005).

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