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Thermal Performance and Operation Limit of Heat Pipe Containing Neutron Absorber

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1. Introduction

Recently, passive safety systems are under development to ensure the core cooling in accidents involving impossible depressurization such as station blackout (SBO). Hydraulic control rod drive mechanisms, passive auxiliary feedwater system (PAFS), Passive autocatalystic recombiner (PAR), and so on are types of passive safety systems to enhance the safety of nuclear power plants. However, the systems associated with the emergency core cooling focus on the feeding additional coolant to steam generator or reactor pressure vessel. These working principles have the failure possibility in the accidents with multiple events. So, if the core is cooled using the passive in-core safety systems (PINCs), the present problems can be solved. Heat pipe is a passive device which transfers heat from evaporator section to condenser section by phase change of working fluid in both of the sections. The condensed working fluid will be return to the evaporator section using gravitational force and capillary force which is induced by inner-lining wick structure. Heat pipe is used in various engineering fields due to its advantages in terms of easy fabrication, high heat transfer rate, and passive heat transfer [1]. Also, the various concepts associated with safety system and heat transfer using the heat pipe were developed in nuclear engineering field [2 – 7]. Thus, our group suggested the hybrid control rod which combines the functions of existing control rod and heat pipe. If there is significant temperature difference between active core and condenser, the hybrid control rod can shutdown the nuclear fission reaction and remove the decay heat from the core to ultimate heat sink. The unique characteristic of the hybrid control rod is the presence of neutron absorber inside the heat pipe. Many previous researchers studied the effect of parameters on the thermal performance of heat pipe. However, the effect of neutron absorber on the thermal performance of heat pipe has not been investigated. Thus, the annular heat pipe which contains B_4C pellet in the normal heat pipe was prepared and the thermal performance of the annular heat pipe was studied in this study.

2. Experiment

In this section fabrication of hybrid control rod, experimental setup and procedures will be described.

2.1 Test section

The hybrid control rod is prepared based on information of established control rod in commercial pressurized water reactor, APR-1400. Stainless steel 316L test sections having a sheath outer diameter of 1 in (25.4 mm outer diameter and 22 mm inner diameter) and length of 1000 mm were prepared with a single-layer screen wire mesh. The test section was charged with the working fluid at a 100% fill ratio (volume ratio of working fluid to wick structure).

Fig. 1. Composition of hybrid control rod.

B_4C pellet which is neutron absorber was then inserted in the center of heat pipe. The B_4C pellet has 17 mm outer diameter and 350 mm length. To prevent the effect of the pellet on the liquid flow through the test section, it was manufactured as non-porous structure.

2.2 Experimental setup and Procedures

Figure 2 shows the heat pipe test facility. The test facility comprises a working fluid tank, a test section, a water jacket to condense the evaporated working fluid, a pump that circulates coolant from the water storage tank to the water jacket, a vacuum pump, and two copper electrodes on the top and bottom of the evaporator section that are connected to the power supply and heat the test section by passing the current.

The lengths of the active core and control rod drive mechanism in APR1400 were considered to determine the length ratios of the evaporator and condenser sections. Thus, the length ratio was fixed to 35 %:15 %:50 %.

Five K-type TCs were installed on the evaporator and adiabatic section of the test section (three for the evaporator and two for the adiabatic section), while four T-type TCs were installed on the condenser. The pressure in the test section was set to 12.5 kPa to remove non-condensable gas. And water was passed through the water jacket at a mass flow rate of 0.133 kg/s.

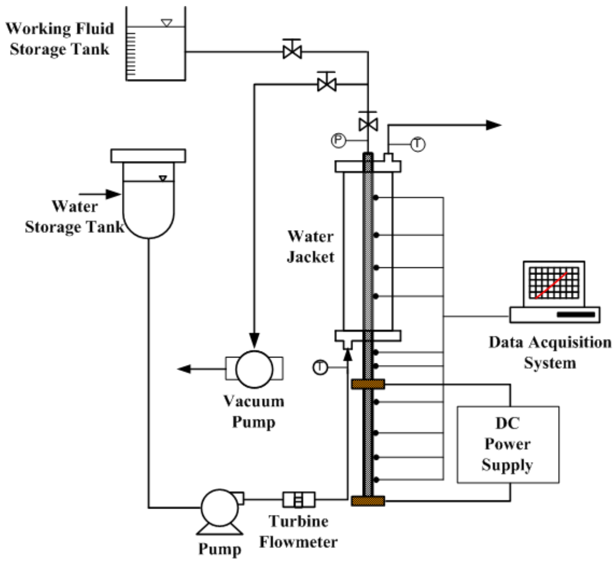

Fig. 2. Schematic diagram of heat pipe test facility.

3. Results and Discussion

3.1 Uncertainty Analysis

The uncertainties in the parameter measurements were analyzed. Table 3 presents the uncertainties in the instruments.

Table 1. Instrument uncertainties.

Parameters	Instruments	Uncertainties
Temperature	Thermocouple	1 ^{o}C
Pressure	Pressure gauge	0.4 %
Water flow rate	Turbine flowmeter	0.5 %
Voltage	Voltmeter	0.3 %
Current	Amperometry	0.08 %

The uncertainty in the heat input ($\Delta Q/Q$) was 0.31%. From this, the measurement uncertainties in the heat flux, heat transfer coefficient, and thermal resistance were measured. The uncertainty in the area was neglected because the length and diameter of the test section were fixed at constant values. The calculated maximum uncertainties in the input heat flux and condensation heat flux were 5.5% and 3.75%, respectively. Therefore, the maximum uncertainties in the heat transfer coefficient and thermal resistance were estimated to be 6.8% and 5.5%, respectively.

3.2 Temperature Distributions

The steady states for each test section were achieved to measure the heat transfer characteristics of each section. Figs. 3 – 4 show the temperature distributions of each test section according to heat loads at steady state condition.

As shown in figs. 3 – 4, the temperatures at evaporator section increases as heat load increases. The evaporized steam is reached to the condenser and then the condenser temperature increases. The temperatures at evaporator section of annular heat pipe were lower than those of normal heat pipe at same heat loads because the volume occupied by working fluid in the heat pipe is larger than normal heat pipe.

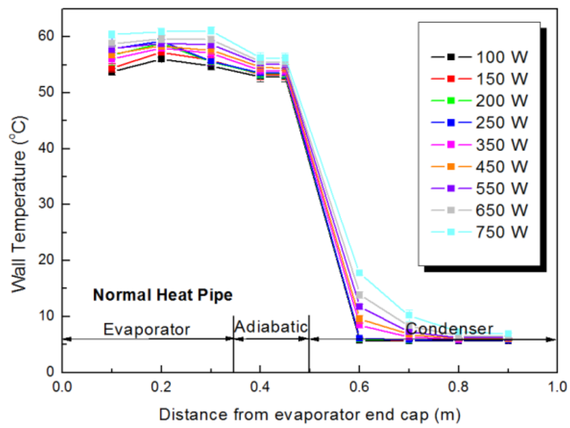

Fig. 3. Temperature distribution of normal heat pipe according to heat loads.

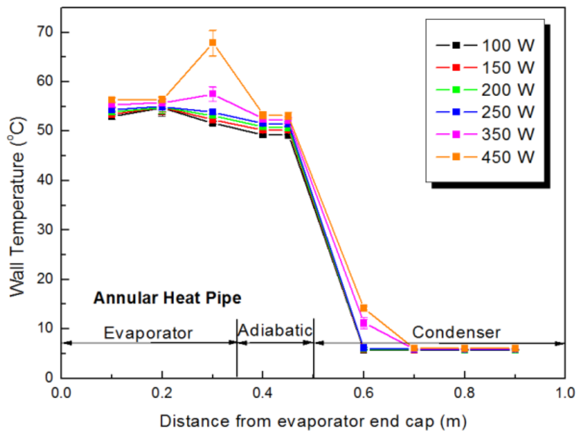

Fig. 4. Temperature distribution of annular heat pipe according to heat loads.

3.3 Thermal Resistances

The evaporation, condensation, and overall thermal resistances ($R_{evaporator}$, $R_{condenser}$, and $R_{overall}$) were calculated by the below equations:

$$R_e = \frac{(\overline{T}_e - T_{sat})}{Q_e} \quad (1)$$

$$R_c = \frac{(T_{sat} - \overline{T}_c)}{Q_c} \quad (2)$$

$$R_{overall} = \frac{(\overline{T}_e - \overline{T}_c)}{Q_e} \quad (3)$$

Thermal resistances of each test section were measured using the temperature distribution and saturation temperature. The saturation temperature was measured by recording internal pressure of the test section and the saturation temperature was validated with temperature of adiabatic section.

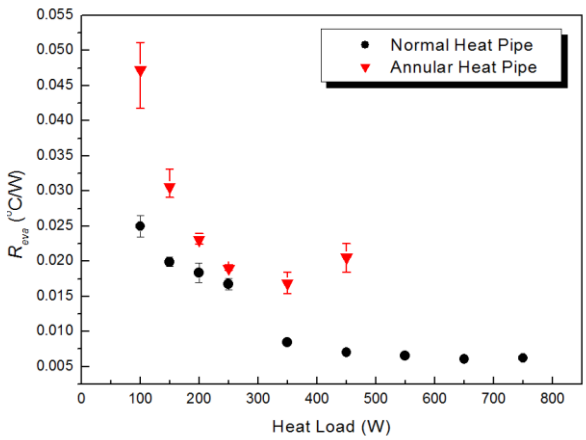

Fig. 5. Evaporator thermal resistances of each tests section according to heat loads.

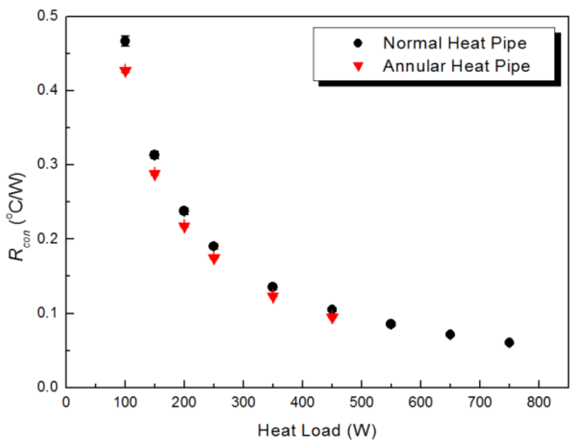

Fig. 6. Condenser thermal resistances of each tests section according to heat loads.

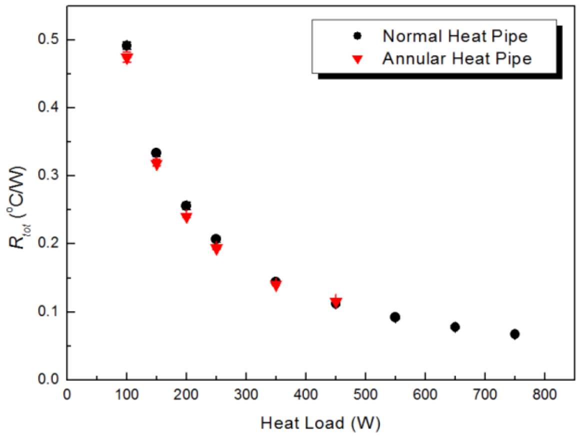

Fig. 7. Total thermal resistances of each tests section according to heat loads.

As shown in figure 5, the annular heat pipe shows higher evaporator thermal resistances because the larger volume of working fluid formed thicker liquid layer at the inner wall of test section.

The level of working fluid is located at adiabatic section in case of annular heat pipe. Thus, the evaporation of working fluid will be suppressed. This phenomena reduces the amount of evaporized vapor, finally, the liquid sublayer at condenser section will be decreased. As a result, the condenser thermal resistances of annular heat pipe were lower than those of normal heat pipe as shown in figure 6.

The liquid thickness at condenser section is thicker than evaporator section. So, the condenser thermal resistances are higher than evaporator thermal resistances for each test section and the thermal resistances at condenser section dominate the total resistance of heat pipe. Hence, the annular heat pipe shows higher total thermal resistances than normal heat pipe as shown in figure 7.

3.4 Operation Limits

To remove the significant decay heat from the core at accident conditions, the maximum heat removal capacity must be ensured. The heat pipes show five types of operation limits – viscous limit, sonic limit, entrainment limit, boiling limit, and capillary limit. Generally, capillary limit which is caused by limitation of mass flow rate through the wick structure against pressure losses inside the heat pipe is the lowest operation limit. When the heat load is reached to the capillary limit, the temperature at the end of evaporator section will be increased. However, figure 4 shows the temperature increase at the top of evaporator section at 450 W and the liquid level is enough to fill the gap between B_4C pellet and inner wall of the heat pipe. Thus, this phenomenon can be interpreted as boiling limit which is caused by the nucleation of bubble prevent the returning of liquid from condenser section to evaporator section.

After reaching the boiling limit, the evaporator thermal resistance was increased as shown in figure 5. However, the limitation was not observed for the normal heat pipe. Neutron absorber (B_4C pellet) reduced the cross section of vapor flow path resulting in higher vapor velocity. As a result, viscous pressure loss in vapor was increased and the lower maximum heat removal capacity was observed compared to normal heat pipe.

4. Conclusions

Hybrid control rod concept was developed as a passive safety system of nuclear power plant to ensure the safety of the reactor at accident condition. The hybrid control rod must contain the neutron absorber for the function as a control rod. So, the effect of neutron absorber on the thermal performance of heat pipe was experimentally investigated in this study.

Temperature distributions at evaporator section of annular heat pipe were lower than normal heat pipe due to the larger volume occupied by working fluid at the evaporator section. The evaporator thermal resistance of annular heat pipe was higher than normal heat pipe although the condenser and total thermal resistances are lower than those of normal heat pipe. And the maximum heat removal capacity of annular heat pipe was lower than normal heat pipe because the reduced vapor flow path resulted in the larger shear force at the vapor-liquid interface.

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