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Pressurized Hybrid Heat Pipe for Passive IN-Core Cooling System (PINCs) in Advanced Nuclear Power Plants

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1. Introduction

Various safety systems were installed on the nuclear power plants to cope with design basis accidents and beyond design basis accidents. However, their defects were appeared from the Three-Mile Island (TMI) and Fukushima accidents. Hence, the various types of safety systems such as passive containment cooling system (PCCS), passive autocatalytic recombiner (PAR), and passive auxiliary feedwater system (PAFS) have been studied and installed in nuclear power plants with reconsideration about established safety features. As a one of methods for the decay heat removal during the accidents, the passive in-core cooling system (PINCs) using hybrid heat pipe was proposed and the efficiency of the system has been investigated [1]. Heat pipe has been widely used in thermal engineering fields because it has several advantages of high heat transfer rate per unit volume, a fully passive working principle, and easy manufacturability [2]. The hybrid heat pipe is a device combining the functions of existing control rod in commercial nuclear power plants and heat pipe. The hybrid heat pipe contains the neutron absorber material and working fluid. Thus, reactor shutdown at the initial phase of accidents and decay heat removal through the phase change and convection of the working fluid is possible simultaneously. The application of hybrid heat pipe for nuclear power plant can extend the limited heat removal capacity in an accident [1].

The hybrid heat pipe contains cylindrical boron carbide pellet which is a neutron absorber material in the evaporator section corresponding to the active core of the reactor pressure vessel. The boron carbide has low thermal conductivity and negligible heat generation during the reaction. Hence, the inclusion of the neutron absorber material causes a difference between wetted perimeter and heated perimeter, different cross-sectional area of vapor path among the evaporator, adiabatic, and condenser section. Although the thermal performance of annular vapor-path heat pipes has been studied, most studies have not considered geometries where the wetted perimeter is different from the heated perimeter [3–7]. The representative operating limit of the thermosyphon heat pipe is flooding limit that arises from the countercurrent flow of vapor and liquid. The effect of difference between wetted perimeter and heated perimeter on the flooding limit of the thermosyphons has not been studied; despite the effect of cross-sectional area of the vapor path on the heat transfer characteristics of thermosyphons have been studied. Additionally, the hybrid heat pipe must operate at the high temperature and high pressure environment because it will be inserted to the active core to remove the decay heat. However, the previously studied heat pipes operated below the atmospheric pressure. Therefore, the effect of the unique geometry for hybrid heat pipe and operating pressure on the heat transfer characteristics including the flooding limit of hybrid heat pipe was experimentally measured.

2. Experiment

A hybrid heat pipe was manufactured based on geometry of the control rods in the commercial pressurized water reactor, APR-1400. 1 in. stainless steel 316L test sections (25.4 mm outer diameter and 22 mm inner diameter) with length of 1000 mm were prepared. The test sections were charged with the 120 mL deionized water to fulfill the volume of evaporator and adiabatic section. The B_4C pellet which is a neutron absorber material was installed at the center of evaporator section (17.7 mm outer diameter and 285 mm length). Fig. 1 shows the scheme of prepared hybrid heat pipe.

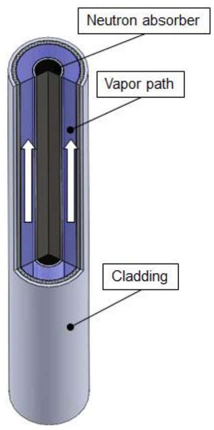

Fig. 1. Drawing for inner structure of the test section

Fig. 2 shows the heat pipe test facility. The test facility comprises 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, and a backpressure regulator which maintain the internal pressure of the test section at a certain pressure.

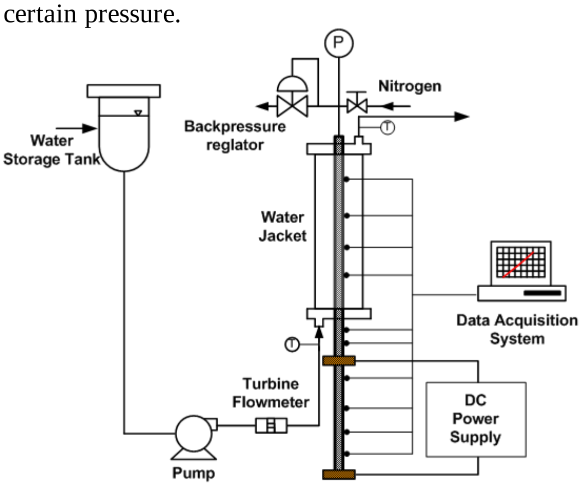

Fig. 2. Scheme of heat pipe experimental setup

Twelve K-type thermocouples (TCs) were installed on the evaporator and adiabatic sections of the test section (six on the evaporator and six on the adiabatic section), four T-type TCs were installed on the wall of the condenser section. The temperatures at the inlet and outlet of water jacket were also measured to quantify the heat removal rate through the water jacket.

3. Results and Discussion

Wall temperatures according to heat loads and time were recorded to measure the heat transfer characteristics of hybrid heat pipe for various operating conditions.

3.1. Heat Transfer Coefficients

Fig. 3 and 4 shows the evaporation and condensation heat transfer coefficients according to heat loads at various operating pressures.

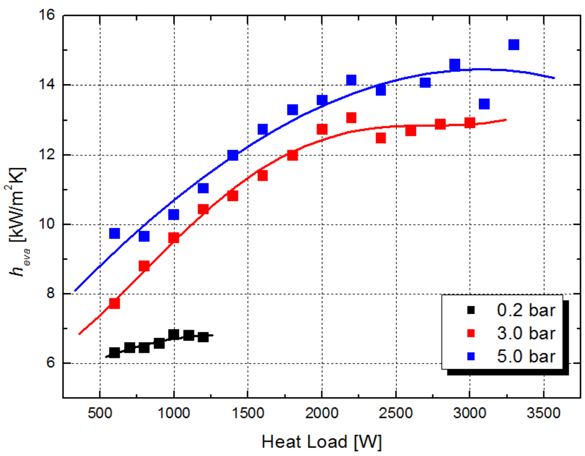

Fig. 3. Evaporation heat transfer coefficients according to operating pressures of the test sections

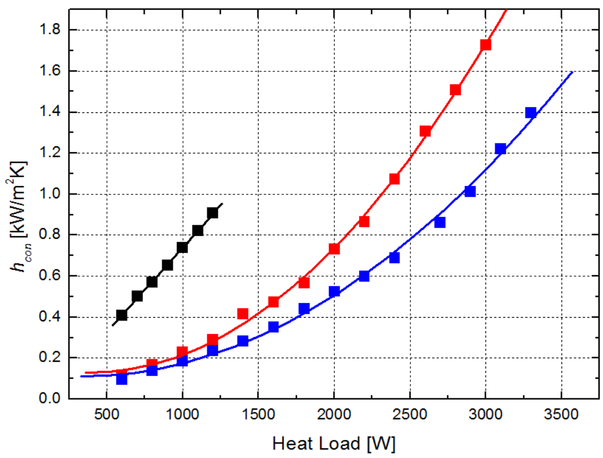

Fig. 4. Condensation heat transfer coefficients according to operating pressures of the test sections

The evaporation heat transfer coefficients of the test sections above the atmospheric pressure increases as the operating pressure increases because the nitrogen in the test section compresses the working fluid resulting in the convective pool boiling. The density difference between vapor and liquid is large below the atmospheric pressure. Hence, the some portion of the liquid phase working fluid rises to the condenser section due to the volume expansion during the phase change. As a result, the liquid inventory in the evaporator section will be decreased and the evaporation heat transfer will be lower than pressurized test sections. As the operating pressure increases, the condensation heat transfer coefficients were decreased because the nitrogen gas in the pressurized test sections (3.0 and 5.0 bar) impede the working fluid to reach the condenser section.

3.2. Operation Limits

The entrainment limit that arises from the countercurrent flow of vapor and liquid is the main operating limitation of the thermosyphon. Thus, the enhancement of the entrainment limit is important to obtain the significant heat removal capacity of the hybrid heat pipe. Fig. 5 shows the operating limit of the test sections according to operating pressures. As shown in the Fig. 5, the entrainment limit of the hybrid heat pipe increases as the operating pressure increases. The non-condensable gas is not contained in the test section operating at the sub-atmospheric pressure. Thus, the oscillation of the working fluid between evaporator section and condenser section due to the vapor pressure produced in the evaporator section and gravitational head of the liquid film is generated more explosively than the test sections operating at the high pressures. Eventually, the instability at the interface between vapor and liquid will be magnified and cause the low entrainment limit.

The pressurized heat pipes at 3.0 and 5.0 bar shows the 2.46 (3200 W, 214 kW/m^2) and 2.77 times (3600 W, 241 kW/m^2) enhanced entrainment limits compared to that of 0.2 bar operating heat pipe (1300 W, 87 kW/m^2) because the countercurrent flow is suppressed due to the pressurization using nitrogen.

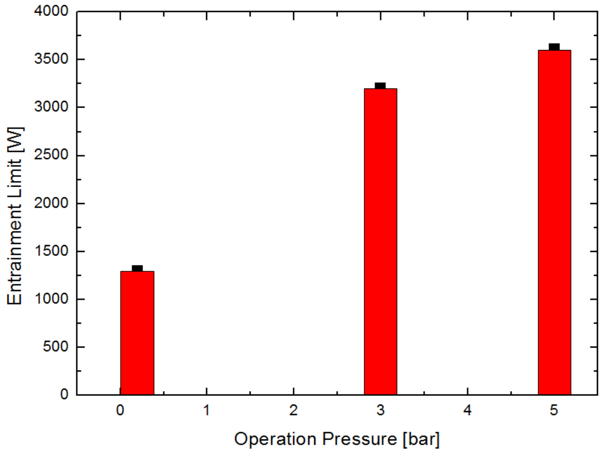

Fig. 5. Maximum heat removal capacities of hybrid heat pipes according to operating pressures

3.3. Comparison with Correlations

The entrainment limits measured by experiments in various operating pressures are compared with the predicted limits calculated from the existing correlations for concentric thermosyphons and annular vapor flow path thermosyphon. Imura et al. [8] suggested the correlation for the prediction of entrainment limit of concentric thermosyphon based on the experimental results. The correlation has been widely used in various studies to validate their experimental results. Faghri et al. [9] established the correlation about entrainment limit of the annular thermosyphon. The correlation modified the Kutateladze number to enhance the prediction ability of the correlation about the experimental data using water as working fluid.

$$Q_{Imura} = 0.64\left[\frac{\rho_l}{\rho_v}\right]^{0.13}\left[\frac{D_e}{4L_e}\right]h_{lv}[\sigma g \rho_v(\rho_l-\rho_v)]^{1/4} \quad (1)$$

$$Q_{Faghri} = Kh_{lv}A\rho_v^{1/2}[g\sigma(\rho_l-\rho_v)]^{1/4}\left[1+m\left(\frac{\rho_v}{\rho_l}\right)^{1/4}\right]^{-2} \quad (2)$$

The mentioned correlations are selected as the correlations to observe the analysis capability about the entrainment limits of the hybrid heat pipe. As shown in Fig. 6, the experimental results showed large deviation from the predicted limits. The difference between experimentally measured entrainment limits and predicted values attributed to the unique geometry of the hybrid heat pipe which has the hydraulic perimeter different with the heated perimeter due to the existence of the neutron absorber at the center of the evaporator section. The non-condensable gas effect was neglected in the correlations. The non-condensable gas charged in the test section influence to the formation of the liquid film and vapor flow velocity. Therefore, the thermal-hydraulics phenomena in the pressurized hybrid heat pipes will be different with those in the concentric or annular thermosyphon operating at the sub-atmospheric pressures. Thus, new model to predict the maximum heat removal capacity of the hybrid heat pipe at the high pressure must be established.

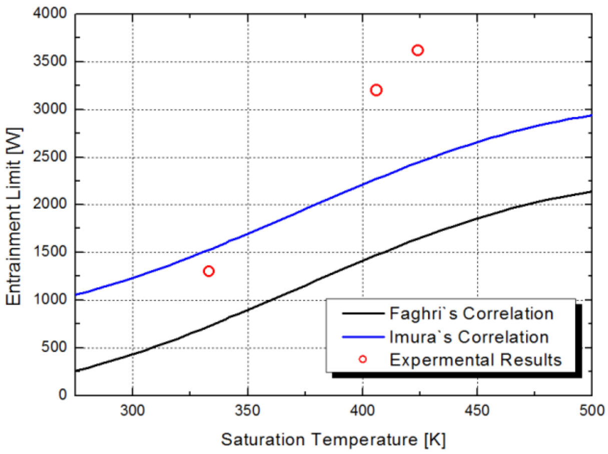

Fig. 6. Comparison of experimentally measured entrainment limits and calculated limits by existing correlations

4. Conclusion

Hybrid heat pipe as a new conceptual decay heat removal device was proposed. For the development of hybrid heat pipe operating at high temperature and high pressure conditions, the pressurized hybrid heat pipe was prepared and the thermal performances including operation limits of hybrid heat pipe were experimentally measured. Followings were obtained:

(1) As operating pressure of the heat pipe increases, the evaporation heat transfer coefficient increases due to heat transfer with convective pool boiling mode.

(2) Non-condensable gas charged in the test section for the pressurization lowered the condensation heat transfer by impeding the vapor flow to the condenser.

(3) Entrainment limit of the hybrid heat pipe increases as the operating pressure increases because the pressurization of the test section suppressed the countercurrent flow.

(4) The deviations between experimentally measured flooding limits for hybrid heat pipes and the values from correlation for annular thermosyphon were observed

(5) The deviations were caused by the difference in hydraulic perimeter and heated perimeter of the hybrid heat pipe and the presence of the non-condensable gas.

(6) New correlation considering the effect of hydraulic diameter and heated diameter and non-condensable gas effect will be modelled further.

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