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Heat Removal Performance of Hybrid Control Rod for Passive In-Core Cooling System

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1. Introduction

Passive in-core cooling system (PINCs) based on hybrid control rod was suggested as a candidate of passive safety system for pressurized water reactor safety. The hybrid control rod is combination of the two-phase closed heat transfer device and control rod. The two-phase closed heat transfer device can be divided by thermosyphon heat pipe and capillary wicked heat pipe which uses gravitational force or capillary pumping pressure as a driving force of the convection of working fluid. If there is a temperature difference between reactor core and ultimate heat sink, the decay heat removal and reactor shutdown is possible at any accident conditions without external power sources [1].

To apply the hybrid control rod to the commercial nuclear power plants, its modelling about various parameters is the most important work. Also, its unique geometry is coexistence of neutron absorber material and working fluid in a cladding material having annular vapor path. Although thermosyphon heat pipe (THP) or wicked heat pipe (WHP) shows high heat transfer coefficients for limited space, the maximum heat removal capacity is restricted by several phenomena due to their unique heat transfer mechanism. Flooding is the main phenomena limiting the operation of THP because of countercurrent flow between vapor and liquid. There are many correlations [2-6] to predict the thermal performance and flooding limit of the THP. However, the correlations have not reflected geometry of the annular vapor path thermosyphon. Thus, validation of the existing correlations on the annular vapor path thermosyphon (ATHP) which has different wetted perimeter and heated diameter must be conducted.

The effect of inner structure, and fill ratio of the working fluid on the thermal performance of heat pipe has not been investigated. As a first step of the development of hybrid heat pipe, the ATHP which contains neutron absorber in the concentric thermosyphon (CTHP) was prepared and the thermal performance of the annular thermosyphon was experimentally studied.

2. Experiment

The annular vapor path thermosyphon (ATHP) is manufactured which contains neutron absorber material (boron carbide pellet) was manufactured. The prepared ATHP was tested in the heat pipe test facility.

2.1 Annular vapor path thermosyphon

Themosyphon is a type of two-phase closed heat transfer device which comprises working fluid and cladding. The working principle of the thermosyphon is as below: (1) working fluid evaporates at the hot interface and reaches to the condenser (2) the condensed liquid returns to evaporator section by gravitational force.

Outer diameter of 25.4 mm (22 mm inner diameter) and 1000 mm length stainless steel 316L test sections were prepared. Boron carbide (B_4C) pellets of 17 mm outer diameter and 215 mm height were located at the center of the test section to simulate the neutron absorber of established control rod in APR-1400 as shown in figure 1.

Water was used as working fluid and the fill ratio (ratio of working fluid volume to evaporator volume) varies from 100 to 167 % to observe the effect of the fill ratios on the thermal performance and maximum heat removal capacity of the thermosyphon.

Fig. 1. Composition of hybrid control rod.

2.2 Experimental setup and Procedures

Figure 2 shows the scheme of heat pipe test facility which comprises a working fluid tank, a test section, a water jacket, a pump, a vacuum pump, and two copper electrodes on the top and bottom of the evaporator section connected to the DC power supply.

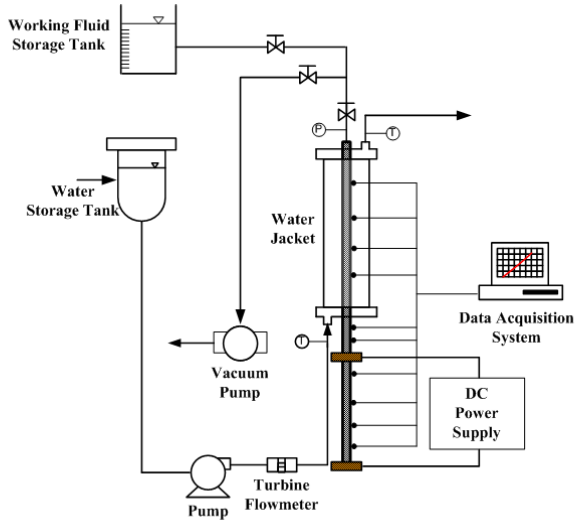

Fig. 2. Schematic diagram of heat pipe test facility.

After charging the certain amount of working fluid to the test section, the non-condensable gases are removed by vacuum pump. The working fluid-charged test section is heated by passing current to the test section (Joule heating). The pump circulates water to the water jacket for the purpose of condensation of evaporated working fluid. Twelve K-type TCs were installed on the evaporator and adiabatic section of the test section (six for the evaporator and six for the adiabatic section), while four T-type TCs were installed on the condenser. The internal pressure was measured by pressure transducer and the mass flow rate of the coolant was controlled to maintain constant temperature at condenser section.

3. Results and Discussion

3.1 Heat Transfer Characteristics

As shown in Fig. 3, the ATHP showed higher evaporation heat transfer coefficients (4200–6750 $W/m^2{\cdot}K$) compared with that of the concentric thermosyphon (3500–6500 $W/m^2{\cdot}K$), with the maximum enhancement of 20%. Also, the heat transfer coefficients increase higher than 400 W which means the onset of boiling. Moreover, the ATHP had similar condensation heat transfer coefficients to the concentric thermosyphon (100–1300 $W/m^2{\cdot}K$), because the differences of the liquid film thickness on the wick surfaces between annular thermosyphon and the concentric thermosyphon could be small in steady state operation.

The higher working fluid level at the annular thermosyphon results in the natural convection between adiabatic section and condenser section which makes the better heat transfer between those parts as shown in figure 4. So, the total wall temperature of the annular thermosyphon will be flattened and lowered compared to the concentric thermosyphon.

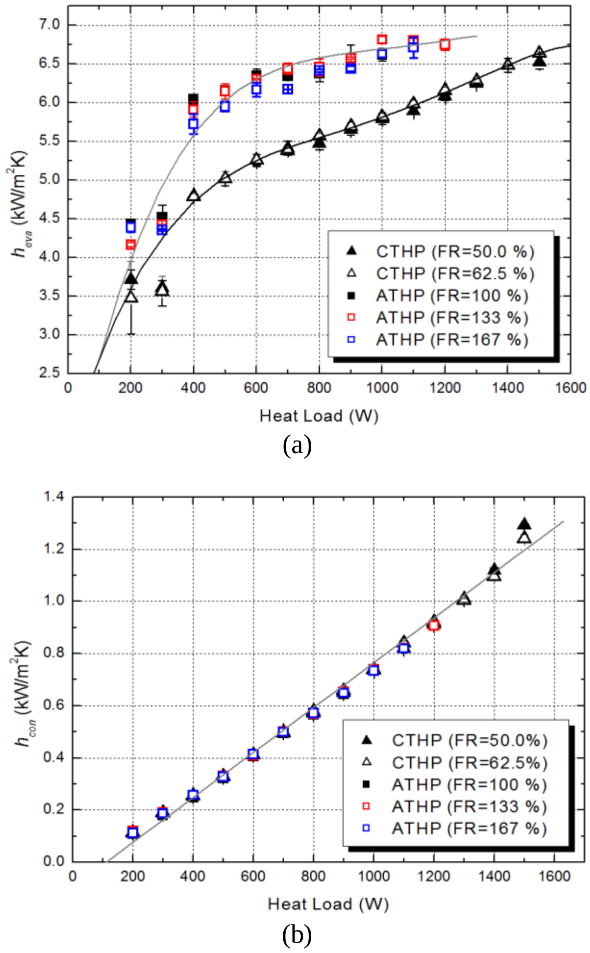

Fig. 3. Heat transfer coefficients according to heat loads: (a) evaporation heat transfer coefficients, (b) condensation heat transfer coefficients.

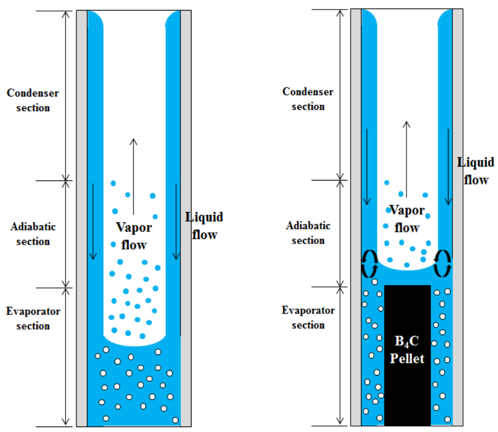

Fig. 4. Axial variation of the liquid-vapor interface of thermosyphons: (a) CTHP, (b) ATHP.

The equal evaporation heat transfer coefficients were observed despite different fill ratios. Thus, the effect of the fill ratio on the heat transfer characteristics can be ignored.

3.2 Flooding Limits

The flooding limit is the most common concern for long thermosyphon. This limit occurs due to countercurrent flow by high value of vapor-liquid interfacial shear. The vapor shear hold-up prevents the condensate from returning to the evaporator and leads to an flooding condition in the condenser section. Effect of fill ratio on the operation limit of the thermosyphon has not been considered in most correlations as shown in Faghri`s correlation [5], and Tien and Chung correlation [6].

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

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

The amount of working fluid is one of the important parameter for determination of the operation limit. Thus, the equal f;ppdomg limit is predicted at various fill ratios as shown in figure 5. The observed flooding limit was 30 - 50 % higher than predicted value (844 and 851 W) because heat transfer between B_4C pellet and working fluid, and effect of fill ratio were not considered. The 133 % charged annular thermosyphon showed the highest flooding limit. As the fill ratio increases the flooding limit was increased with maximum enhancement of 18 %.

The difference between wetted perimeter and heated perimeter of the ATHP was not contained in the existing correlations. Thus, there is the deviation between predicted values and experimentally measured values.

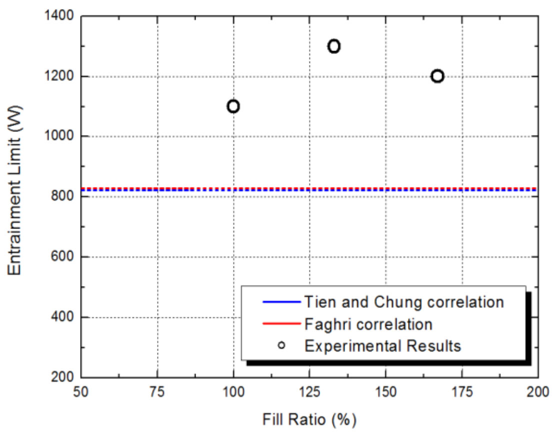

Fig. 5. Comparison of predicted entrainment limit and measured entrainment limit according to fill ratios.

3. Conclusions

The heat transfer characteristics and flooding limit of the annular vapor path thermosyphon was studied experimentally to model the performance of hybrid control rod. The following results were obtained:

(1) The annular vapor path thermosyphon showed better evaporation heat transfer due to the enhanced convection between adiabatic and condenser section.
(2) Effect of fill ratio on the heat transfer characteristics was negligible.
(3) Existing correlations about flooding limit of thermosyphon could not reflect the annular vapor path condition.
(4) Flooding limit of the annular vapor path thermosyphon was increased as fill ratio increases.
(5) Modelling on the flooding limit of ATHP will be conducted by observation of the limitation according to diameter of inner structure and internal pressure.

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