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Preliminary Test of a small heat pipe for hybrid control rod in-core passive decay heat removal system

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1. Introduction

Decay heat removal is one of topics in nuclear power plants. In nuclear field, heat pipe design is not a new idea. Many researches have presented the conceptual design of heat removal systems using heat pipe to apply nuclear safety systems. For example, some groups suggested the concept of passive cooling system by using heat pipe for emergency core cooling system. Especially, J et al. referred to the potential of heat pipe technology in nuclear seawater desalination [1,2]. But those researches had the limitation such as high cost and large space for operation. In this work, the research focused on the combination of the heat pipe and control rod in nuclear system at the first time. This paper introduces “Hybrid control rod” combining its original function and heat removal ability.

The high temperature operation and high resistance of radiation should be considered to adopt the hybrid heat pipe at the in-core condition. Other design consideration is to make extra inlet parts because it has a high risk of inlet boundary failure [3]. It means that the introduction of heat pipe system is difficult to present nuclear power plants. The other concepts are presented to out-core cooling design but it has low performance compared with in-core heat removal system. Hybrid heat pipe for in-core heat removal system suggests the solution of these problems. It has many benefits as follows it is 1) not necessary to modify the core design, 2) it is possible to add the hybrid heat pips in present nuclear power plants, and additional 3) it is expected to enhance safety because of in-core cooling.

Ultimate objective of this research is to develop the passive emergency decay heat removal system using hybrid heat pipes targeting design bases accidents such as station black-out (SBO) and small break loss of coolant accident (SBLOCA). The purpose of this work is to confirm the performance and heat transfer behavior of hybrid heat pipe.

The hybrid heat pipe has special condition for operation. Therefore, it is hard to analyze their behavior in core. Table I shows the characteristics of hybrid heat pipe and consideration for manufacturing the heat pipe.

Table I: Characteristics of Hybrid Heat Pipe

Resistance	High resistance of radiation and high temperature.
Combination of two functions	control rod and heat removal function
Capillary force	Large particle size. (> 100 μm) High porosity (> 50 %) for capillary force and fluid path.
Manufacturing methods	High temperature and vacuum condition or Ar atmosphere sintering. Special sintering time depends on particle size and materials.

2. Experimental Setup and Procedure

The heat pipe has two layers of stainless steel (SS) mesh as the wick structure and distilled water as the working fluid which was tested horizontally at different heat loads. It has 3 cm long evaporation region that heated by direct heating using the copper electrode. The 6 cm long adiabatic region was insulated by the glass wool and 6 cm long condensation region was cooled with a constant temperature which used the once through cooling. Six thermocouples were used for measuring the temperature (T1-T6). A thermocouple was attached to the evaporation region at the side wall of heat pipe (T1). Another thermocouple was attached to the adiabatic region at the side wall of heat pipe (T2). Two other thermocouples measured the condensation region at the side wall of heat pipe (T3 and T4). The others thermocouple checked the inlet and outlet water temperatures in the condensation region (T5 and T6). Each location of thermocouples is shown in Fig. 1. Three bare tubes having 6.65 mm OD and 4.65 mm ID, was SS with vacuum state before distilled water was filled in the tube (tube a). A SS screen mesh was inserted and then distilled water was filled in the tube (heat pipe a). The other inserted SS screen mesh tube was sintered in the furnace at 900 °C, 5h and distilled water was filled in the tube (heat pipe b).

The main parameters were fluid charge, heat load, and wick condition (sintered or non-sintered screen mesh). Wick used 100 mesh SS screen was filled in two layers in heat pipe. The fluid charge was rated based on the void volume in the wick structure [4]. However, the water level had slightly different from instrumental error within ±5 %. Before the insertion of working fluid, vacuum condition maintained at 9 kPa due to the removal of air. The inlet temperature and mass flow rate of coolant were fixed by chiller; 15℃ and 1.3ml/s, respectively. The heat load range was 10W-45W and checked the surface temperature of each region in steady state condition.

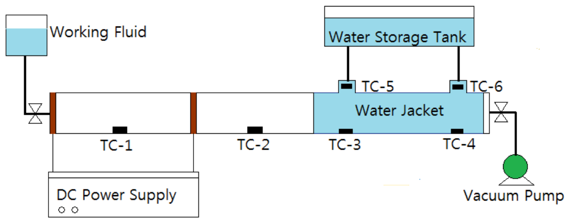

Fig 1. Schematic diagram for the experimental apparatus

3. Results and Discussion

The heat transfer of bare tube (tube a) filled with water (1.6 ml) was poor because the working fluid cannot transport the heat horizontally. At Q = 20 W, the temperature of bare tube and screen mesh in evaporation region rapidly increased due to sustained convection phenomenon of working fluid in tube. The vapor released from the evaporation region transported the heat to the condensation region. Condensed water could not move to the evaporation region and so water was maintained at condensation region. 80% working fluid (1.6 ml) in SS screen mesh heat pipe (heat pipe a) showed the similar results with bare tube due to bad performance of wick, which was attached loosely. However, sintered SS screen mesh heat pipe had decrease of the evaporator surface temperature because convection of working fluid worked in the tube. Vapor occurred at evaporation region and transported the heat to condensation region. After that, working fluid moved to the evaporation region through the sintered screen mesh.

Table II is the initial condition of experiment and a W et al. [4] work for confirming the test result. The experiment al result is shown in Fig 2.

Table II: Initial Conditions

Initial Condition	Test	W et al [4]
Water level	80 % in wick	80 % in wick
Condenser	15 °C, 1.3 ml/s	15 °C, 25 ml/s
Wick size	100 mesh	100 mesh
Porosity	0.62	0.65
Vacuum	60 mmHg (9kPa)	-
E : A : C	3 : 6 : 6	3 : 9 : 3
Inner diameter	4.65 mm	5 mm
Outer diameter	6.65 mm	6 mm
Total length	15cm	15cm

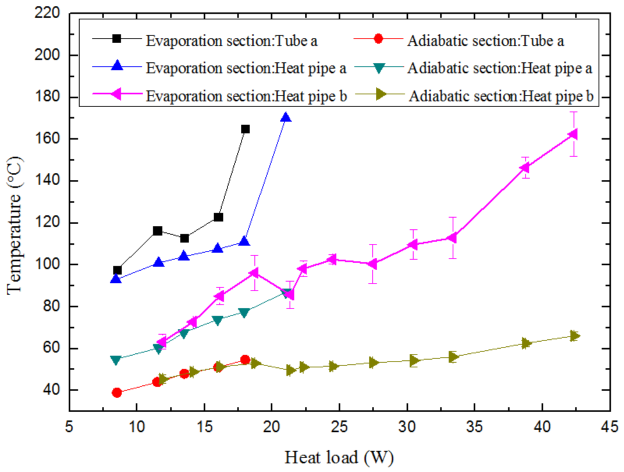

Fig 2. Experimental results (Tube. a, Heat pipe. a, and Heat pipe. b)

Thermal resistance R can be presented by

$$R\left({}^{\circ}C/W\right)=\frac{T_e-T_c}{Q} \tag{1}$$

The heat transfer coefficient, h of heat pipe can be given by

$$h\left(W/m^2\,{}^{\circ}C\right)=\frac{Q}{A(T_e-T_c)} \tag{2}$$

Where, T_e is the average temperature at the evaporator (°C), T_c is the average temperature at the condenser (°C), Q is the heat input (W), and A is the heat transfer surface area at the evaporator (m^2). From the experimental results and equations 1 and 2, thermal resistance and heat transfer coefficient can be found. These results compared to the W et al heat pipe experimental results. Table III is the summary of heat transfer coefficient of test and W et al.

Table III: Heat Transfer Coefficient of Experimental Results and Reference Data.

Q (W)	h_{System} (W/m^2°C)	h [4] (W/m^2°C)
10	10,300	-
15	8,600	-
18	12,600	-
20	10,700	15,900
25	11,700	15,700
30	12,500	14,700
35	11,400	15,200
40	9,600	14,000
45	9,900	14,000

Initial conditions of W et al. are geometrically similar with our conditions. The heat load of reference was from 20 to 45 W and it needed to modify the test data for matching with reference. The temperature and heat load graph is shown in Fig 3. A tendency of temperature from the experimental data had large temperature gap between evaporation and adiabatic region compared to the reference data. But the difference of temperature was less than 13 %. Heat flux was calculated for confirming the heat pipe performance. From the results, heat flux of experimental data was larger than reference but heat transfer coefficient and heat transport ability was lower than reference values. Therefore, the gaps between evaporation and adiabatic region were bigger than reference data. In other words, slightly small ability of heat transportation made more large temperature gaps. It needs to consider the heat transfer coefficient and thermal resistance for enhancement of hybrid heat pipe. Heat flux of experimental and reference data is shown in Fig. 4.

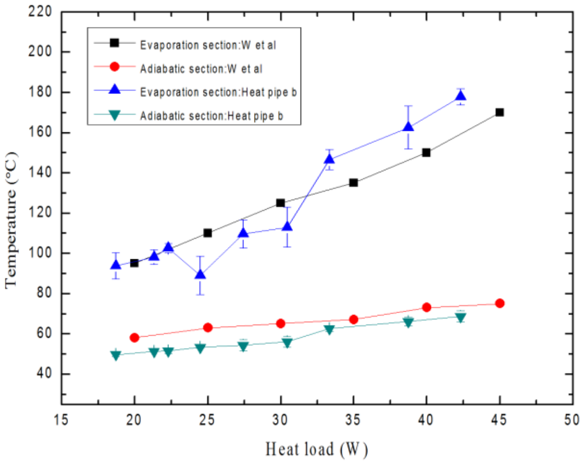

Fig 3. Temperatures load at the evaporation and adiabatic regions according to heat load.

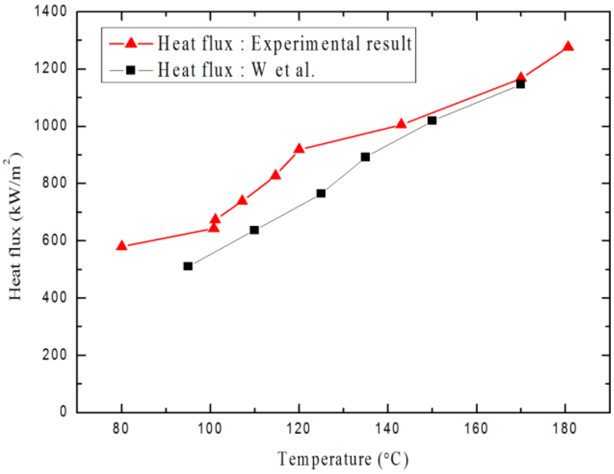

Fig 4. Heat flux of experimental and reference data

3. Summary and Future works

The main purpose of the research is analysis of heat transfer behavior of hybrid heat pipe and the performance of heat transfer. The results about three cases; horizontal tube a, heat pipe a, and heat pipe b are obtained. Among the three cases, sintered SS screen mesh heat pipe shows a good performance but the others had bad results. The results of heat transfer coefficient are small values compared to the reference data. The reasons of difference of heat transfer coefficient are initial condition and material of wick structure. Considering the adiabatic region, the difference between results is smaller than 35 %. Therefore, meshed heat pipe has relevant performance and it shows the possibility of hybrid heat pipe. Next plans are enhancement of the heat transfer coefficient and thermal resistance to optimize heat pipe by modifying the wick material and initial condition.

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