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Heat Transfer Characteristics of SiC-coated Heat Pipe for Passive Decay Heat Removal

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1. Introduction

After Fukushima accident, the performance of the established emergency core cooling system (ECCS) was evaluated and supplemented. However, this supplementation is limited to extension of diesel generator lifetime and addition of alternative batteries to nuclear power plants. The main concern with the Fukushima accident was the failure of active and passive core cooling systems. The main function of existing passive decay heat removal systems is feeding additional coolant to the reactor core. Thus, an established ECCS cannot operate properly because of impossible depressurization under the station blackout (SBO) condition. Therefore, a new concept for passive decay heat removal system is required. In this study, an innovative hybrid control rod concept is considered for passive in-core decay heat removal that differs from the existing direct vessel injection core cooling system and passive auxiliary feedwater system (PAFS). A heat pipe is a passive heat transfer device that operates by convective heat transfer between hot interface (evaporator) and cold one (condenser section. The heat transfer between the evaporator and condenser sections occurs by phase change of the working fluid and capillary action induced by wick structures installed on the inner wall of the heat pipe [1]. In this study, a hybrid control rod is developed to take the roles of both neutron absorption and heat removal by combining the functions of a heat pipe and control rod. Figure 1 shows a schematic of the hybrid control rod's inner structure.

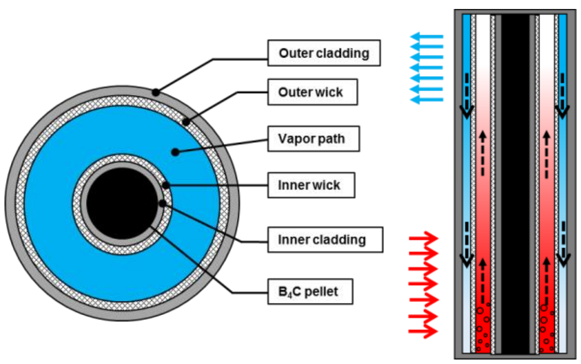


Fig. 1. Inner structure of hybrid control rod design.

Significant heat removal capacity must be ensured for heat pipes to be applied in passive decay heat removal systems. Previous studies on enhancing the heat removal capacity of heat pipes used nanofluids, self-rewetting fluids, various wick structures and condensers.

Many studies have examined the thermal performances of heat pipes using various nanofluids [2-5]. They concluded that the enhanced thermal performance of the heat pipe using nanofluids is due to nanoparticle deposition on the wick structures. Thus, the wick structure of heat pipes has been modified by nanoparticle deposition to enhance the heat removal capacity. However, previous studies used relatively small heat pipes and narrow ranges of heat loads. The environment of a nuclear reactor is very specific, and the decay heat produced by fission products after shutdown is relatively large. Thus, this study tested a large-scale heat pipe over a wide range of power.

2. Experimental

This section describes the geometry of the heat pipe and presents the experimental setup used to measure the heat transfer characteristics of the heat pipe.

2.1 Experimental Procedure

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.

Stainless steel 316L test sections having a sheath outer diameter of 3/4 in (17.4 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).

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 %.

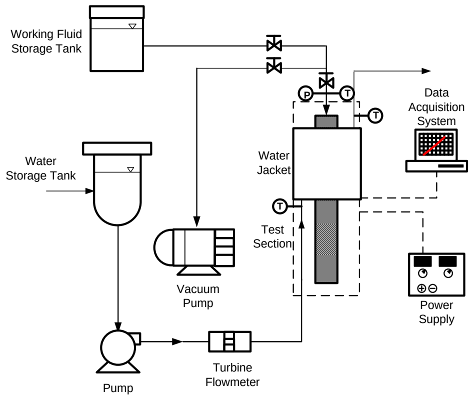


Fig. 2. Schematic diagram of heat pipe test facility.

Three K-type TCs were installed on the evaporator and adiabatic section of the test section (two for the evaporator and one for the adiabatic section), while two 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 0.3 kg/s.

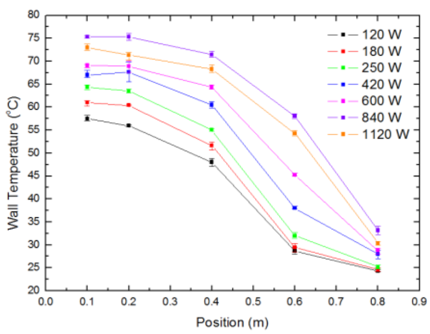
2.2 Coating of SiC Nanoparticles

Silicon carbide (SiC) nanoparticles were selected as the coating material of the heat pipe because of their high thermal conductivity (~490 W/mK). And SiC is compatible with the environment in a nuclear reactor because of its good resistance to high temperatures and radiation environment [6]. The SiC nanoparticles were coated onto the heat pipe by the boiling method. A heat pipe filled with 0.01 vol% SiC/water nanofluid was heated to boiling temperature at atmospheric pressure for 15 min.

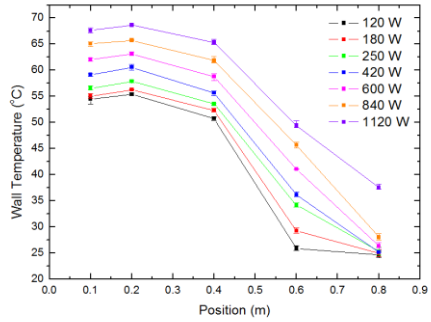
3. Results and Discussion

3.1 Temperature Distributions

Figure 3 compares the heat transfer rates of heat pipes with a bare wick and SiC-coated wick. As shown in Fig. 3, the temperature difference between the evaporator and condenser sections decreased as the heat input increases.



(a) Uncoated heat pipe



(b) SiC-coated heat pipe

Fig. 3. Temperature distributions of test sections according to heat loads.

The SiC-coated heat pipe showed smaller temperature differences than the uncoated heat pipe.

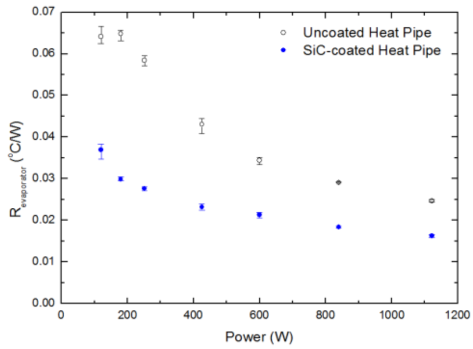
3.2 Thermal Resistances

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

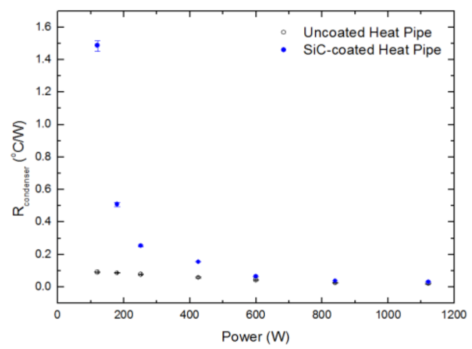
$$R_e = \frac{(\bar{T}_e - T_{sat})}{Q_e} \quad (1)$$

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

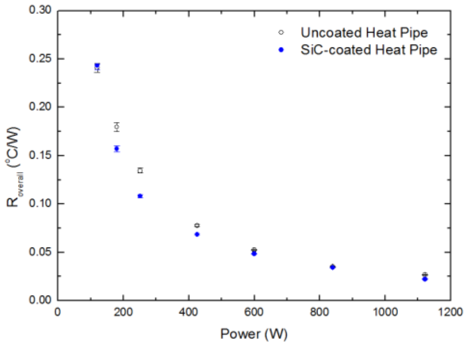
$$R_{overall} = \frac{(\bar{T}_e - \bar{T}_c)}{Q_e} \quad (3)$$



(a) Evaporator thermal resistance



(b) Condenser thermal resistance



(c) Overall thermal resistance

Fig. 4. Thermal resistances of test section according to heat loads.

As shown in Fig. 4, the SiC-coated heat pipe showed a lower thermal resistance at the evaporator section than the uncoated heat pipe because the nanoparticle coating layer formed small pores provides more nucleation sites. The SiC coating layer on the wick structure enhanced the wettability and liquid film on the condenser section, which increased the condensation thermal resistance of the coated heat pipe. The SiC coating reduced the overall thermal resistance of the heat pipe by a maximum of 19.4% compared to the uncoated heat pipe

3.3 Heat Transfer Coefficients

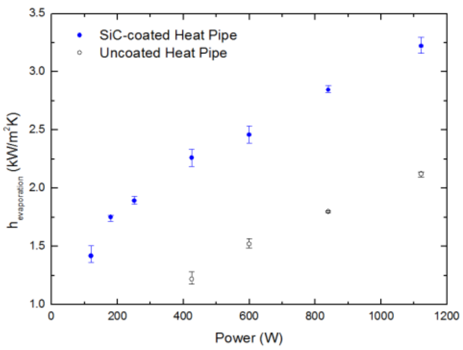
The evaporation, condensation, and overall heat transfer coefficients (h_e, h_c, and $h_{overall}$) were calculated by using the below equations:

$$h_e = \frac{q_e''}{(\bar{T}_e - T_{sat})} \qquad (4)$$

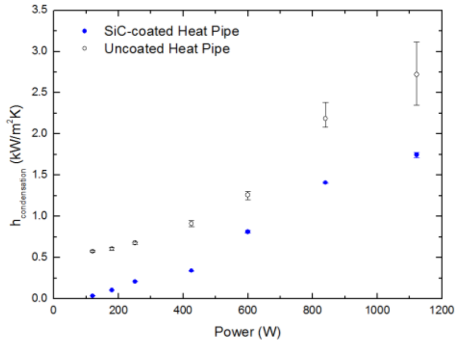
$$h_c = \frac{q_c''}{(T_{sat} - \bar{T}_c)} \qquad (5)$$

$$h_{overall} = \frac{q_e''}{(\bar{T}_e - \bar{T}_c)} \qquad (6)$$

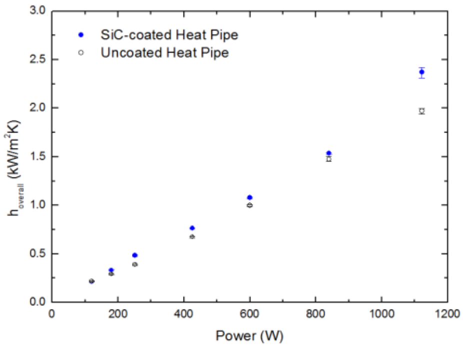
As shown in Fig. 5, the results were similar with observation in terms of thermal resistances.



(a) Boiling heat transfer coefficients



(b) Condensation heat transfer coefficients

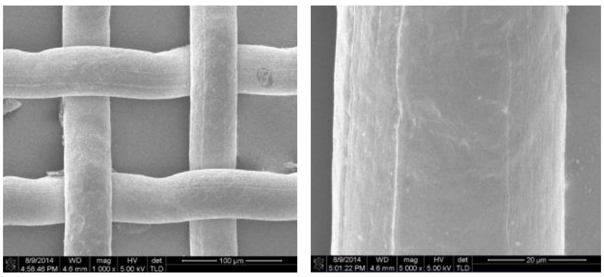


(c) Overall heat transfer coefficients

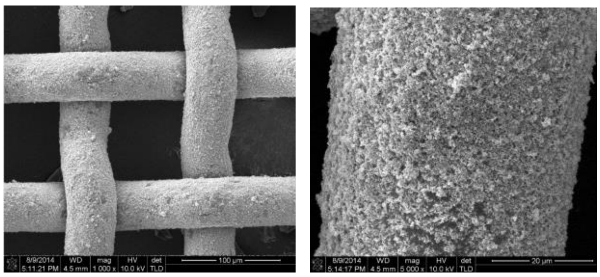
Fig. 5. Heat transfer coefficients of test section according to heat loads.

3.4 SEM Images

Figure 6 shows SEM images of the wick structures after the heat pipe experiments. The SiC nanoparticles were deposited on the screen wire mesh.



(a) Uncoated wick (×1000, 5000)



(b) SiC-coated wick (×1000, 5000)

Fig. 6. SEM images of wick structures.

The SiC coating layer formed a rough surface and provided many small pores which act as nucleation sites. Thus, the images support the argument that the enhanced boiling heat transfer and reduced evaporation thermal resistance of the SiC-coated heat pipe are due to the more nucleation sites and increased bubble departure frequency.

4. Conclusions

The concept of a hybrid heat pipe for an advanced in-core decay heat removal system was introduced for complete passive decay heat removal. A heat pipe was coated with SiC nanoparticles to enhance its heat removal capacity.

The following results were obtained:

(1) The evaporation thermal resistance of a SiC-coated heat pipe is reduced compared to that of an uncoated heat pipe because the SiC coating layer on the wick structure provides more nucleation sites.

(2) The condensation thermal resistance of a SiC-coated heat pipe is increased compared to that of an uncoated heat pipe because SiC deposition results in film-wise condensation.

(3) The SiC coating layer on the wick structure was observed using SEM images. The images support the reasons for the enhanced heat transfer of the SiC-coated heat pipe.

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