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Visualization of the boiling phenomena and counter-current flow limit of annular heat pipe

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1. Introduction

After the invention of the heat pipe by Grover et al. [1] 50 years ago, much study has been done and many applications have been created in various fields including electric cooling devices, decay heat removal systems for nuclear power plants [2, 3]. Schampheleire et al. [4] investigated the gravity-assisted-orientation heat pipe using three different wicks: a screen-mesh wick, a sintered-powder wick, and outperforms the fiber wick. The metal-fiber wick showed the greatest potential as a wick material for high-performance heat pipes.

A heat pipe is a high-heat-capacity, fully passive heat-transfer device that uses the evaporation, condensation, capillary wick structure, and working fluid in the pipe. In general, the vapor flow from the evaporation section to the condensation section is caused by a difference in vapor pressure. At the same time, the liquid flow from the condensation section to the evaporation section is produced by net forces such as capillary force and gravitational force. The thermal resistance of conventional heat pipes increases over the capillary limit because of the insufficient supplement of the working fluid. Due to the shortage of the liquid supplement, thermosyphon is widely used for vertically oriented heat transport and high heat load conditions. Thermosyphons are two-phase heat transfer devices that have the highly efficient heat transport from evaporation to condensation section that makes an upward driving force for vapor. In the condenser section, the vapor condenses and releases the latent heat. Due to the gravitation force acting on the liquid in the tube, working fluid back to the evaporator section, normally this process operate at the vertical and inclination position. The use of two-phase closed thermosyphon (TPCT) for the cooling devices has the limitation due to the phase change of the working fluid assisted by gravity force [5,6]. Due to the complex phenomenon of two-phase flow, it is required to understand what happened in TPCT. The visualization of the thermosyphon and heat pipe is investigated for the decrease of thermal resistance and enhancement of operation limit. Weibel et al. [7] investigated capillary-fed boiling of water with porous sintered powder wick structure using high speed camera. At the high heat flux condition, dry-out phenomenon and a thin liquid film are observed at the porous wick structure. Wong and Kao [8] investigated the evaporation and boiling process of mesh wicked heat pipe using optical camera. At the high heat flux condition, the water filing became thin and partial dry-out was observed in the evaporator section.

Our group suggested the concept of a hybrid heat pipe with control rod as Passive IN-core Cooling System (PINCs) for decay heat removal for advanced nuclear power plant. The hybrid heat pipe is the combination of the heat pipe and control rod. It is necessary for PINCs to contain a neutron absorber (B_4C) to have the ability of reactivity control. It has annular vapor space and it might cause the heat transfer degradation to the thermal performance of the heat pipes. For clearly observed the operation phenomenon in annular heat pipe, comparison studies on the heat transfer performance of thermosyphon heat pipe and the capillary heat pipe is conducted containing neutron absorber. The present study investigates the effects of the filling ratios and liquid path for enhancement of heat transfer performance.

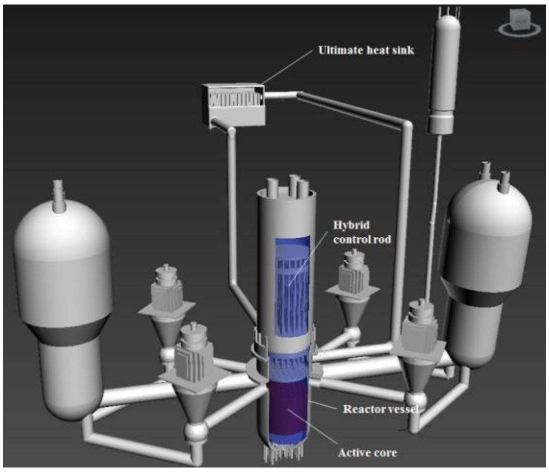


Fig 1. A design of Passive In-core Cooling system (PINCs)

2. Experimental Setup and Procedure

The experimental heat pipe is composed of one layer of stainless steel screen wire mesh as the wick structure, with distilled water as the working fluid. The thermal performance of the heat pipe was tested at a vertical orientation at various heat loads. The quartz tube had an outer diameter of 12 mm, an inner diameter of 10 mm, and a length of 650 mm. The test section had an evaporator region of 200 mm that was heated by direct-current copper electrodes. The condenser section was

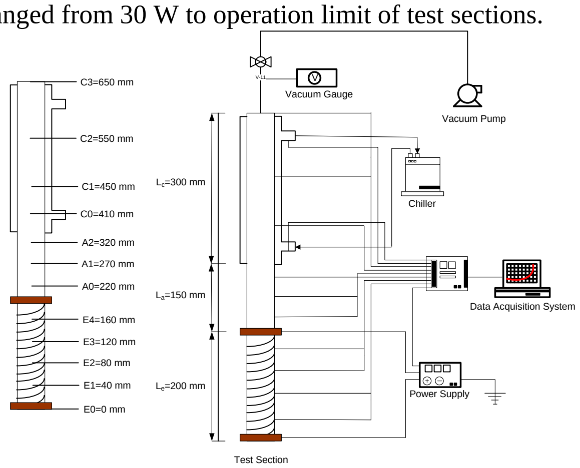
300 mm in length. Its role was to cool the working fluid and maintain a constant temperature. Thirteen thermocouples were installed to measure the wall temperature along the test section. Five thermocouples were attached to the outer wall of the evaporator region among the Nichrome wire. Four thermocouples measured the outer temperature of the condenser region. The others were attached to the adiabatic region as well. The uncertainty in the measurement of temperature is ±0.6℃. Thermocouple locations and a schematic view of the experimental system are shown in Fig. 2.

Before filling the system with the working fluid, all non-condensable gas was removed using a vacuum pump. The fluid charge was determined based on the evaporator volume. Distilled water was added to the evaporator section at an 11.2-100% fill ratio. Test scetion geometry and initial conditions are shown in Table.1

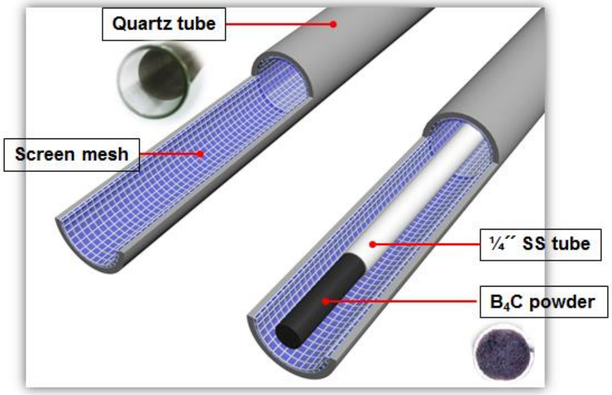
Table. 1 Test section geometry and initial conditions

	Mesh	B4C dia. (mm)	Filling ratio (%)	Working fluid (ml)
CHP1	250	Non	11.2	1.4
ACHP2	250	6.65	11.2	1.4
CHP3	250	Non	50.0	7.8
ACHP4	250	6.65	50.0	7.8
THP1	Non	Non	100.0	15.7
ATHP2	Non	6.65	50.0	7.8
THP3	Non	Non	50.0	7.8
ATHP4	Non	6.65	25.0	3.43

A pressure gage was placed at the top of the condenser section to measure the initial saturation pressure as well as the operating pressure of the steam in the heat pipe. The uncertainty of the water level owing to the instrumental error was less than ±5%. The inlet temperature of the coolant was maintained at a constant level with the use of a chiller. The heat load ranged from 30 W to operation limit of test sections.



(a) Experimental apparatus



(b) Test sections

Fig. 2 (a) Schematic diagram for the experimental apparatus (b) Test sections of the capillary heat pipe with neutron absorber.

3. Results and Discussion

2.1 Evaporation heat transfer

Fig. 3 shows the evaporator thermal resistance and correlation of thermosyphon according to the heat load. Imura's correlation (1982) had good accuracy according to the heat load.

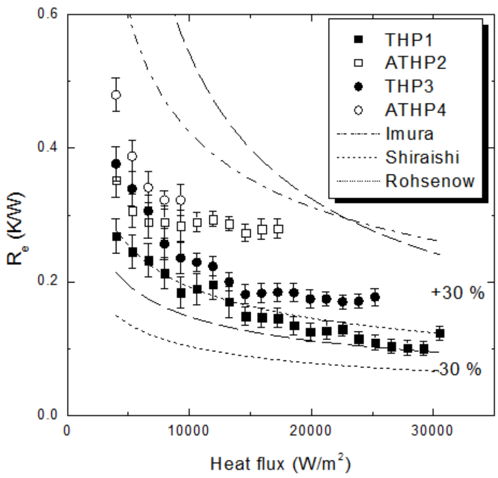
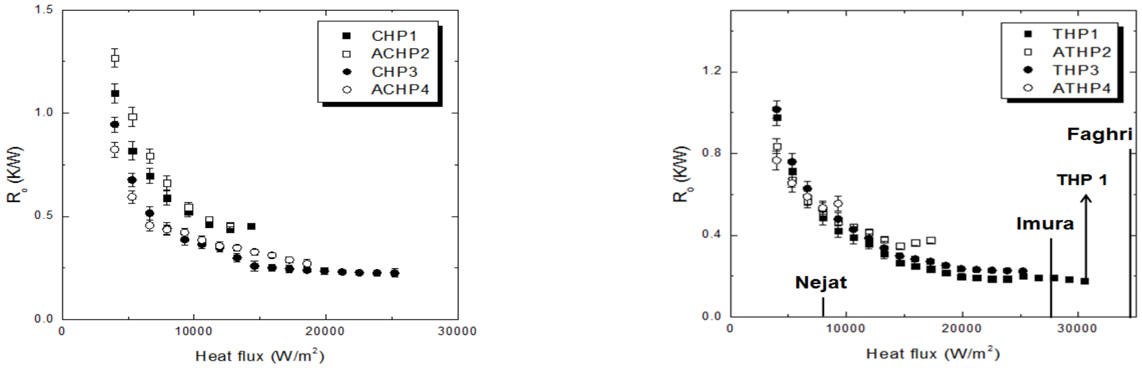


Fig. 3 Evaporator thermal resistance of thermosyphon heat pipe according to heat load

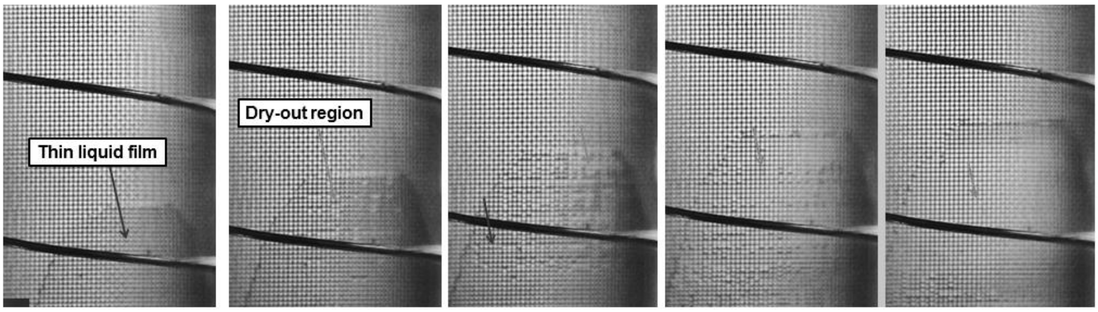
2.2 Thermal resistance of heat pipes

Fig. 4 shows the overall thermal resistance and heat transfer coefficient of heat pipes according to the heat load. Capillary heat pipes tend to decrease the thermal resistance according to filling ratio. Thermosyphon heat pipes have similar thermal resistance according to the filling ratio. Annular flow path makes a high friction between counter-current in the heat pipe. The limit of annular heat pipes has a low limit comparison with a conventional heat pipe.



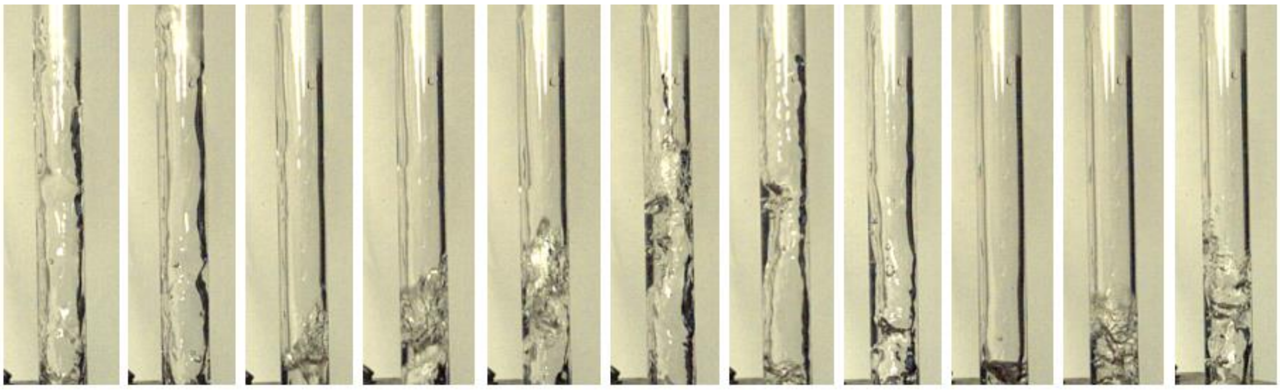
(a) Capillary heat pipe (b) Thermosyphon heat pipe

Fig. 4 Overall thermal resistance of capillary heat pipes and thermosyphon heat pipes according to the heat flux



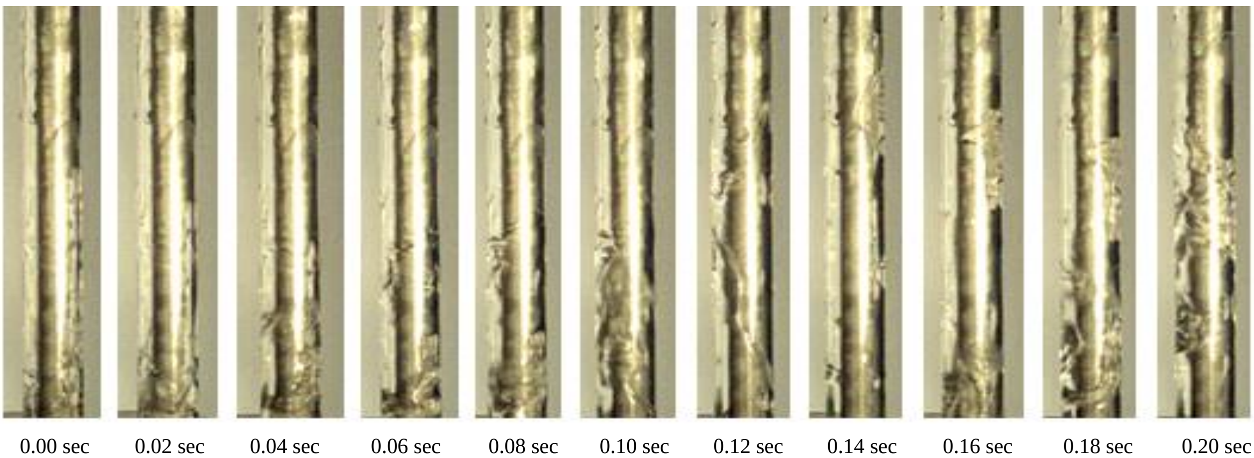
(a) 0.0 sec (b) 2.5 sec (c) 5.0 sec (d) 7.5 sec (e) 10.0 sec

Fig. 5 Wick film dry-out phenomenon of the evaporator section in capillary heat pipe.



0.00 sec 0.02 sec 0.04 sec 0.06 sec 0.08 sec 0.10 sec 0.12 sec 0.14 sec 0.16 sec 0.18 sec 0.20 sec

(a) Thermosyphon heat pipe



0.00 sec 0.02 sec 0.04 sec 0.06 sec 0.08 sec 0.10 sec 0.12 sec 0.14 sec 0.16 sec 0.18 sec 0.20 sec

(b) Annular thermosyphon heat pipe

Fig. 6 Entrainment limit of thermosyphon heat pipe at the adiabatic region

2.3 Operation limit of heat pipes

The wick heat pipe has the capillary limit due to the wick structure and it can be possible to show the liquid dray-out phenomenon at the surface of evaporator region. Fig. 5 shows the liquid film dry-out at the surface of the wick heat pipe.

Fig. 6 shows the entrainment limit in thermosyphon heat pipe due to the counter-current flow. It shows the counter-current flow limitation phenomenon in the tube.

4. Conclusions

Capillary heat pipes and thermosyphon heat pipes have annular flow path for PINCs application. It makes large friction due to the decrease of the flow path. Therefore thermosyphon heat pipe has the counter-current flow limit. The wick heat pipe has capillary limit due to the wick structure and it can be possible to show the liquid dray-out phenomenon at the surface of evaporator region. At the result of the flow and wick visualization with annular flow path effect, it is possible to understand the capillary limit and entrainment limit phenomenon in the heat pipes.

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