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Experimental Study of a Screen Wick Alkali-Metal Heat Pipe with a Pressurized Gas-Cooled Condenser

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1. Introduction

For future space transportation and surface power applications, a small nuclear fission power system (Kilopower system) is leading the R&D efforts [1, 2]. Thermal energy of the reactor core is transferred to the Stirling convertors through a series of sodium heat pipes. The waste heat from the Stirling convertors is transferred to the radiator panels through water heat pipes and is rejected into the space (Figure 1). This system would have more than 10 year design life and have a plan to generate 1 to 10 kW of electricity through Stirling system.

Alkali-metal heat pipe is a good candidate of the heat transfer device in the space fission reactor because the heat pipe can rapidly transfer the high-temperature heat of 800°C from the fission reactor core to a Stirling system. While it has great credit on small nuclear fission reactors, still there are lack of experimental validation such as the heat transfer performances at a high-temperature operating condition, not strait or curved geometry and various wick structures. Hong and Kim [3] study a startup characteristic of an alkali-metal heat pipe that installed in a screen type wick structure with artery. They observed an excessive heat removal of a water condenser at a startup operation that bring about a sonic limitation by a sodium frozen in the water condenser.

In this paper, an experimental study conducted by changing the water-cooled condenser into a gas-cooled condenser is described. The gas-cooled condenser is better to control the sonic limitation at a start-up operation than water-cooled condenser.

2. Heat Pipes

Heat pipes are two-phase flow heat-transfer devices where a process of liquid to vapor and vice versa circulates between evaporator and condenser with high effective thermal conductivity. With the working fluid in a heat pipe (HP), heat can be absorbed on the evaporator region and transported to the condenser region where the vapor condenses releasing the heat to the cooling media.

Alkali-metal HP is a good candidate of the heat transfer device in the space fission reactor because the HP can rapidly transfer the high-temperature heat of 800°C from the fission reactor core to a Stirling system. A wick structure is the major design parameter determining the heat transfer performance of HP. There are three types of wicks for HP that carry significant power over a Stirling system: arterial wick, grooved wick and self-venting arterial wick as shown in the figure 2 [2, 4].

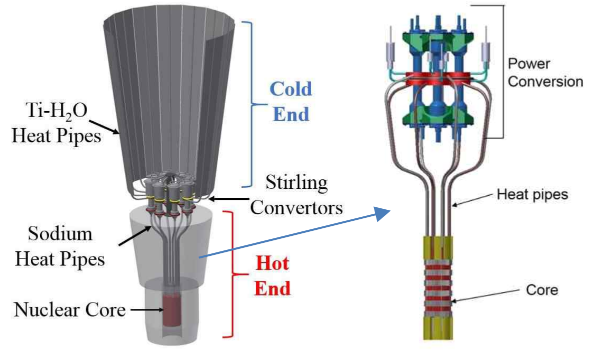
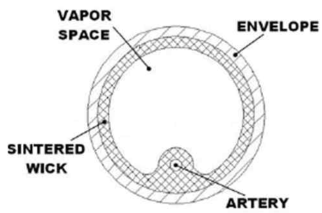
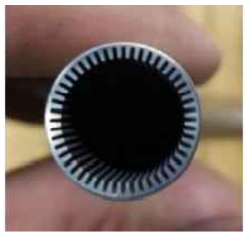


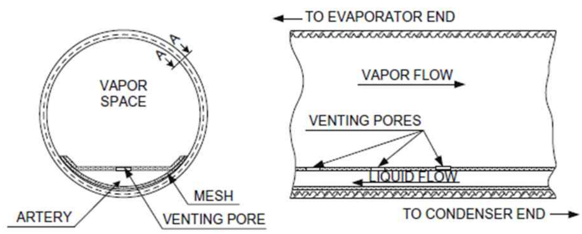
Fig. 1. Conceptual design layout of a Kilopower system [1, 2].



(a) Arterial wick



(b) Grooved wick



(c) Self-venting arterial wick

Fig. 2. Heat pipe wicks suitable for use in a space fission reactor.

3. Frozen Startup Limitation

The working fluid in the high-temperature HP usually in the solid state at ambient temperature, due to the high melting temperature of the working fluid. Therefore, frozen startup is a routine occurrence during the high-temperature HP operation. When the temperature in the evaporator section exceeds the melting temperature of the working fluid, the fluid liquefies and evaporation begins to take place at the wick-vapor interface. The vapor flows from evaporator to the adiabatic and condenser sections and is condensed at the wick-vapor interface, releasing its latent het energy. The vapor condensed may flow back to the evaporator section due to the capillary pumping action of the liquid-saturated

wick structure [5].
However, the vapor condensed onto the frozen wick structure maybe frozen out, and not be able to flow back to the evaporator section. At the same time, the working fluid in the wick structure close to the evaporator liquefies due to axial heat conduction, and may back to the evaporator section, which is increased the amount of liquid available for vaporization. These two processes determine if a particular HP can start successfully

4. Experimental Apparatus

The experimental apparatus is composed of an evaporator, a gas-cooled condenser, and a gas circulation loop connected to the gas-cooled condenser as shown in the figure 3.

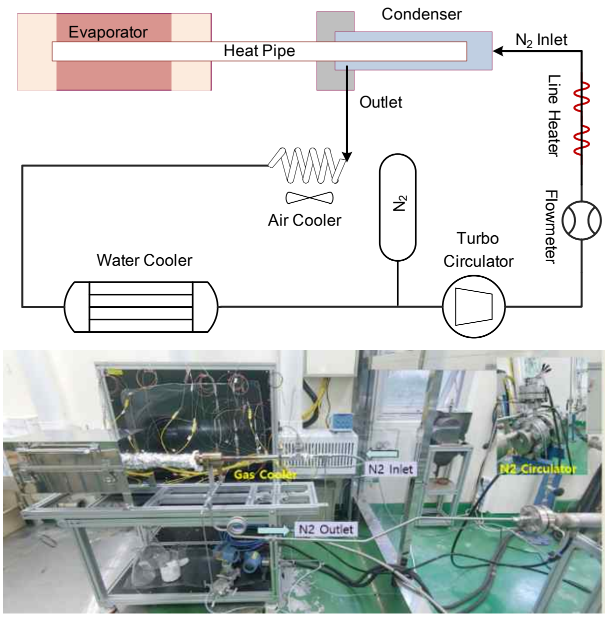


Fig. 3. Experimental apparatus layout and picture

The evaporator is a furnace type heater simulating reactor core thermal condition (Max. temperature to 1425°C). A Kanthal heater molded with Ceramic Kaowool material can generate up to 6 kW thermal power. The heater is surrounded by thick Kaowool-insulator to minimize heat loss to the environment as shown. Two variable AC autotransformers, Slidacs, are connected to the evaporator for control the power manually.

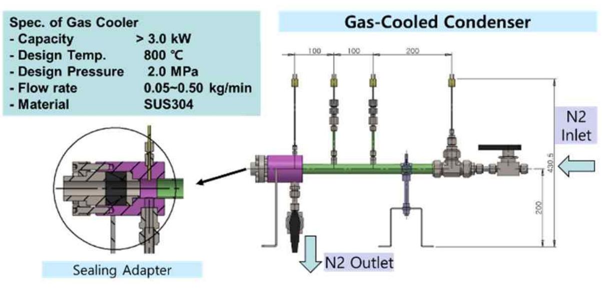
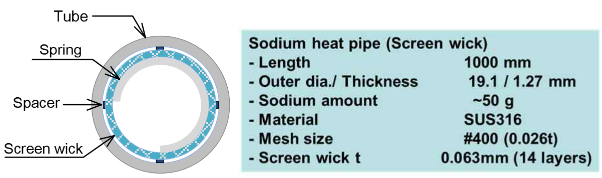


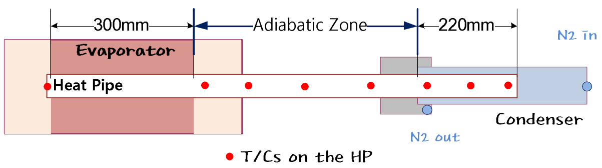
Fig. 4. Gas-cooled condenser with a sealing adapter

The gas-cooled condenser has a high-temperature (870°C) sealing adapter and four thermocouple ports as shown in the figure 4. It has 3kW heat rejection capacity at least and is connected to the high-pressure nitrogen loop that is pressurized to 2.0 MPa.

Heat pipe has 3/4" diameter and 1.0-meter long tube geometry with screen type arterial wick. The cross sectional view and major specification of the HP is represented in the figure 5-a. The HP is filled with 50 grams of sodium that is the amount of submerged all the screen wicks installed in the HP internal [3]. Figure 5-b shows the layout of test section installed in both evaporator and condenser with the surface-temperature measurement points. 300mm of HP is inserted into the evaporator and 220mm inserted condenser, and the other 480mm is opened at adiabatic region. K-type thermocouples are attached on the HP wall surface.



(a) Cross sectional view and major specification



(b) Test section layout

Fig. 5. Screen wick heat pipe and test section

Results and Discussions

Hong and Kim [3] study a startup characteristic of an alkali-metal heat pipe that installed in a screen-wick with artery. They used a water-cooled condenser at the test. A frozen state startup failure is aquatinted on the test with sonic limitation and sodium liquid dryout phenomena at the evaporator section as showen in the figure 6. Excessive heat removal of water condenser brings about this phenomenon and confirms the sonic limitation with repeatable injection of water in the condenser.

Experimental study conduct by changing the water-cooled condenser into a nitrogen gas-cooled condenser and experiments are conducted with the HP kept horizontal. Unlike the operating characteristics of the water-cooled condenser during start-up operation, the temperature of the adiabatic section reached a maximum of 790 °C without sonic limitation at 1200 watts (figure 7). This is a major difference (from a water-cooled condenser) in which the surface temperature of the cooling part does not rise more than 100°C. When the circulator is operated after the experiment time exceeded 6000 seconds, the surface temperature of the HP generally decreased, and the descending speed was higher as the condenser was closer. The overall drop in surface temperature is not a sonic limiting condition. Therefore, when the power of the heater is increased to prevent the surface temperature of condenser-3 from falling below 100℃, the condenser-3 rapidly increased, and even if the power was gradually increased to 2800 watts, the surface temperature overall increased without sonic limitation. This indicates that the start-up operation is easily proceeding with the use of the gas-cooled condenser. When the power is increased to 3000 watts, a sonic limiting phenomenon gradually appeared, and the surface temperature of the end of the evaporation part of the HP in the heating part rose to 930℃, but the surface temperature of condenser-3 decreased to 226℃. If we look closely at the temperature rise graph of the evaporation unit and the surface-temperature decrease graph of the condenser-3, it can be seen that the sonic limit is very slow from 2800 watts, but it was already in progress. The heat removal capability of the HP can be calculated using the following energy balance equation by inputting the measured inlet/outlet nitrogen temperature and nitrogen flow rate of the gas cooler.

$$Q = \dot{m}C_p(T_{out} - T_{in})$$

Before the sonic limit appeared, the amount of heat removed from the condenser only with nitrogen gas is calculated as a maximum of 2100 watts. Through this experiment, one improvement point that can alleviate the sonic restriction is derived. That is, the improvement of the nitrogen supply temperature. The temperature of the supplied nitrogen without preheating of the inflow nitrogen is reduced to 20℃ or less, and the surface temperature of the condenser-3 of the HP in the cooling part was reduced to 100℃, resulting in a sonic restriction as sodium solidified (sodium melting point, 98°C). This is the main reason for sodium solidification that the heat removal amount of the cooling part increases as the heat removal amount of the cooling part increases, and the heat transfer at the end of the heat conduction tube becomes active and the condenser-3 surface-temperature decreases also. Therefore, it is necessary to maintain the nitrogen supply temperature more than 100℃ higher than the sodium condensation temperature using a preheater.

To check the nitrogen preheating effect, a preheater is installed and the experiment was continued. During the experiment, the temperature of the nitrogen inlet of the condenser could be preheated to 70~100℃ using a preheater. When the circulator is started, the surface temperature of condenser-3 dropped to 280℃, but it rose again without increasing the power and found stability around 300℃ (figure 8). In the absence of preheating, the result is in contrast to the previous experiment, which continued to drop to around 100℃. As the condenser inlet nitrogen-temperature rises, the condenser outlet temperature also rises close to 600℃, increasing the nitrogen flow rate and conducting the experiment. At 2900 watts of power, but the sonic limiting phenomenon (the surface temperature of the evaporation unit continues to rise above 900°C alone, but the surface temperature of condenser-3 continues to drop to 150°C) is detected very slowly.

In order to investigate the effect on gravity, the screen-wick HP was adjusted to -1° (upper heating part experiment) and the experiment was conducted using a gas-cooled condenser and a preheater. In the case of the screen wick, the gravitational effect should be almost absent because the capillary force caused by the surface tension of the fluid acts as the main driving force. The experimental results were also not significantly different from the horizontal experiment. Rather, the heat removal ability was higher than that of the previously performed horizontal experiment, so no sonic limitation occurred at power of 3000 watts or higher, and the real-time heat removal amount was measured 100 to 200 watts higher than that of the horizontal experiment (figure 9).

This is the result obtained by improving the operation of increasing the heat removal amount of the condenser in order to maintain the surface temperature of the insulation section missed in the horizontal test at 750℃, which is the optimum temperature, in the gravity test. That is, it is because the nitrogen flow rate has been gradually increased by adjusting the nitrogen flow rate to maintain the surface temperature of the adiabatic section below 800℃ during the experiment as shown in the trend of the measured surface temperature and nitrogen injection flow rate in the insulation section. Due to this, the surface temperature of the insulation section maintained a stable state, and the nitrogen temperature at the outlet of the condenser decreased due to an increase in the flow rate, but as the flow rate increased, the heat removal amount increased to a maximum of 2230 watts when 3070 watts of power is applied. Since there was no further increase in power, it can be seen from the gradually increasing temperature graph of the evaporation section that a sign of sonic restriction appears. In other words, the power of 3070 watts is practically close to the limiting performance of the HP.

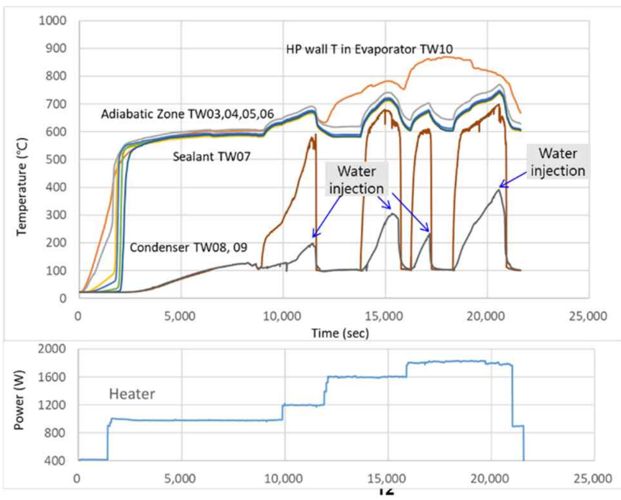


Fig. 6. A frozen startup failure by a sonic limitation (with a water-cooled condenser) [3]

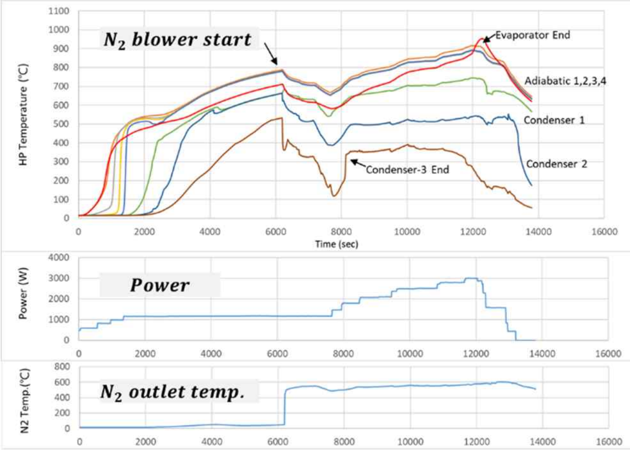


Fig. 7. Experimental results of a screen wick sodium heat pipe with a gas-cooled condenser (w/o N preheating)

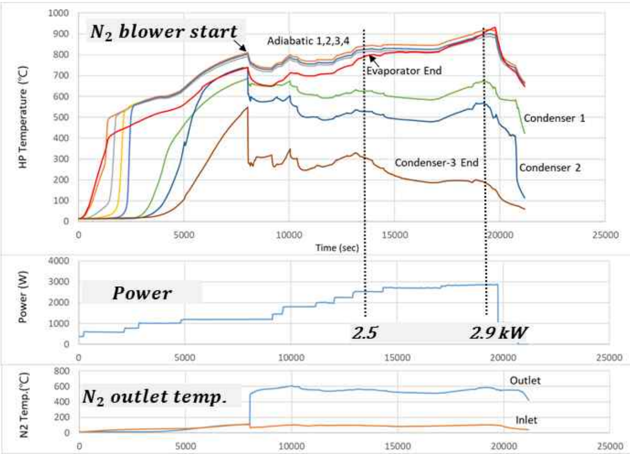


Fig. 8. Experimental results of a screen wick sodium heat pipe with a gas-cooled condenser (with preheater)

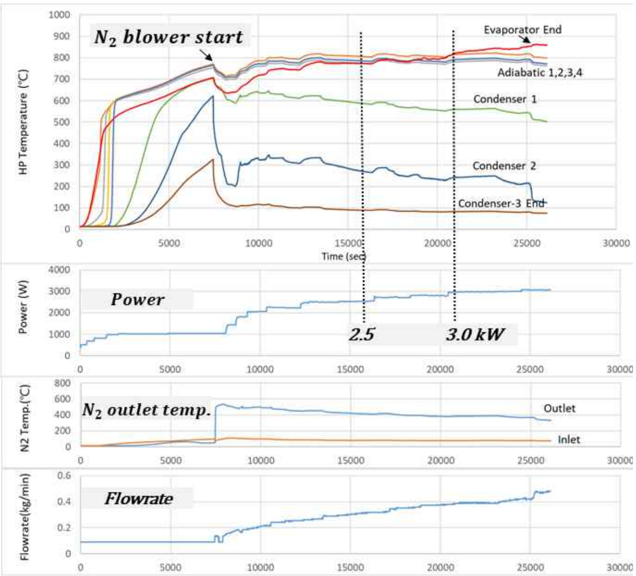


Fig. 9. Gravity effect test results with -1° angle

5. Conclusion

An experimental apparatus is constructed by combining an Alkali-metal screen wick sodium HP and a gas-cooled condenser. The HP is maintained horizontally and the experiment was performed. Unlike the operating characteristics of the water cooler during start-up operation, the surface temperature of the insulation section reached a maximum of 790°C without sonic limitation at 1200 watts, and the surface temperature of the condensation part of the heat conduction tube in the cooler exceeded 500°C and the steady state operation proceeded. The experiment proceeded smoothly to 3000 watts of power, and when the power was increased, a sonic limiting phenomenon appeared.

The temperature of the supplied nitrogen gas without preheating of the inflow nitrogen was less than 20°C, and when the heat removal capacity was small, it is operated normally. However, when the heat removal capacity from the condenser increased by more than 2000 watts, the surface temperature of the heat conduction tube inside the condenser decreased to 100°C, gradually solidifying the sodium, causing a sonic restriction. Therefore, in order to relieve the sonic limit, it is necessary to use a preheater to always maintain the nitrogen supply temperature 100°C higher than the sodium solidification temperature.

In order to investigate the effect on gravity, the result of the experiment in which the condenser of the screen-wick HP is adjusted to -1° was not significantly different from the horizontal experiment. In the case of screen wick, since the capillary force caused by the surface tension of the fluid acts as the main driving force, there should be almost no gravitational effect, which is experimentally proven.

ACKNOWLEDGEMENTS

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REFERENCES

[1] M. A. Gibson, S. R. Oleson, D. I. Poston and P. McClure, "NASA's Kilopower Reactor Development and the Path to Higher Power Missions," in IEEE Aerospace Conference, Big Sky, MT, 2017.
[2] K. L. Walker, C. Tarau, and W. G. Anderson "Alkali Metal Heat Pipes for Space Fission Power," Nuclear and Emerging Technologies for Space (NETS-2013), Albuquerque, NM, February 25-28, 2013
[3] S. D. Hong and C. S. Kim, "Startup Characteristic of a Horizontal Alkali-Metal Heat Pipe from a Frozen State," KNS Autumn Meeting, Changwon, Korea, 2020.
[4] L. Mason and C. Carmichael, "A Small Fission Power System with Stirling Power Conversion for NASA Science Missions," Nuclear and Emerging Technologies for Space (NETS-2011), Albuquerque, NM, February 7-10, 2011.
[5] Amir Faghri," Heat Pipe Science and Technology," Taylor and Francis, 1995.