Startup Characteristic of a Horizontal Alkali-Metal Heat Pipe from a Frozen State

Sung Deok Hong* and Chan Soo Kim
Korea Atomic Energy Research Institute, 111, Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon 34057, Korea
**Corresponding author: sdhong1@kaeri.re.kr*

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] designed an experimental apparatus to test the alkali-metal heat pipes with various-kind of wick structures. This paper report the experimental results using their test apparatus over a sodium heat pipe which is installed a screen type wick structure.

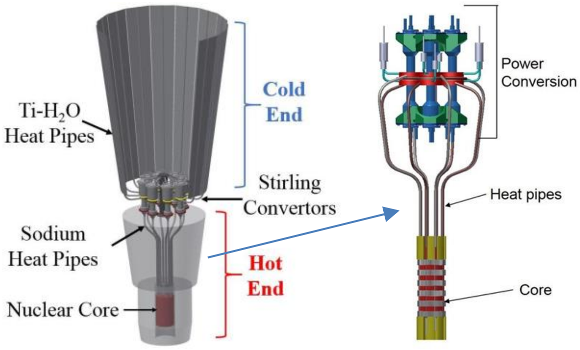


Fig. 1. Conceptual design layout of a Kilopower system [1, 2].

2. Heat Pipe

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, 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 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. A wick structure is the major design parameter determining the heat transfer performance of heat pipe. There are three types of wicks for heat pipe that carry significant power over a Stirling system: arterial wick, grooved wick and self-venting arterial wick [2,4].

3. Frozen Startup Limitation

The working fluid in the high-temperature heat pipe 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 heat pipe 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 heat pipe can start successfully. Cao and Faghri [6] proposed an equality could check the startup limitation.

$$\frac{\emptyset \rho_l A'_w h_{fg}}{C(T_{melt} - T_\infty)} \geq 1$$

Where,
$\emptyset$: poposity of the wick
C : heat capacity per unit length of wall and wick
A'_w: cross-sectional area of the fluid in the wick
T_∞: ambient temperature of the heat pipe
h_{fg}: latent heat of evaporation

4. Experimental Apparatus

4.1. Design of Experimental Apparatus

The experimental apparatus is composed of furnace type evaporator, a condenser, a water cooling system and adiabatic zone formed by Kaowool insulator as shown in

Figure 2. The operating condition of the test apparatus is as follows;

- o Fluid
  - - Heat pipe Sodium
  - - Condenser Water or Nitrogen
- o Evaporator
  - - Power ~ 6.0 kW
  - - Temperature ~ 1425 °C
- o Condenser
  - - Pressure ~ 10.0 bar
  - - Temperature (water) < 200 °C
  - - Flowrate (water) ~ 0.05 kg/s

The physical parameters that will be measured are the electric power, temperature, heat loss, and coolant flowrate.

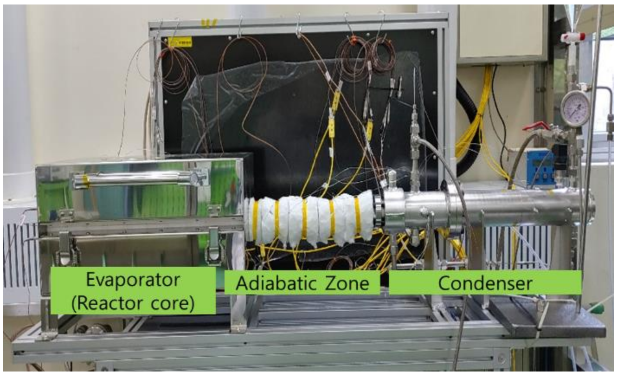


Fig. 2. HP experimental apparatus.

4.2. Evaporator

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 in Figure 3. Two variable AC autotransformers, Slidacs, are connected to the evaporator for control the power manually.

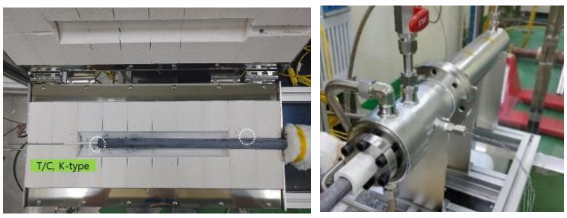


Fig. 3. Evaporator (left) and condenser (right)

4.3. Condenser

A water-pool type condenser is designed. The condenser has heat pipe guides, thermocouple port, an assembling flange and a sealing adapter (Figure 3). This condenser has total of 6kW heat rejection capacity when the temperature difference between coolant inlet and outlet is 50°C with flowrate of 0.03 kg/s.

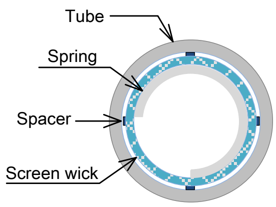
A water leakage problem is aroused in operation of a high-temperature graphite sealing adapter of this condenser when the surface temperature of alkali-metal heat pipe increase up to 750°C at normal operating condition. The leakage problem is resolved by replacing the adapter as a Lava-sealing type which is withstand up to 870°C of surface temperature.

4.4. Test Section

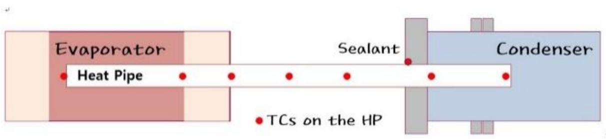
Sodium Heat Pipe (HP) has 3/4" diameter and 1.0 meter long tube geometry with screen type arterial wick [4]. The cross section view of the HP is represented in the Figure 4-a. Geometric data of the test section are listed in the Table I. The HP is filled with 50 grams of sodium that is the amount of emerging all the screen wicks installed in the HP internal. Figure 4-b shows the layout of test section installed in both evaporator and condenser with measurement points. 25cm of HP is inserted into the evaporator and 20cm inserted condenser, and the other 55cm is opened at adiabatic region. K-type thermocouples are attached on the HP wall surface. Stainless-steel bands fix the thermocouples except the evaporator section. In the evaporator, the thermocouples are attached to the HP wall surface manually through the holes prepared to thermocouples at the ceramic insulator in the evaporator.

Table I: Characteristic of the test section (heat pipe)

Parameter		Unit	Value
Container	Length	mm	1000.0
	Outer diameter	mm	19.1
	Thickness	mm	1.27
	Material	-	SUS316
Wick	Type	-	Screen wick
	Mesh		#400
	Screen thickness	mm	0.063
	Artery type		Annulus
	Material		SUS316



(a) Cross section view of HP



(b) Test section layout with measurement points

Fig. 4. Test section

5. Results and Discussion

A frozen startup failure is aquatinted on the screen wick sodium HP test. The test results shows in Figure 5. At 400 watts in the figure, only the sodium inside the HP in the evaporator starts to melt. When heated to 1000 watts, it can be seen that the surface temperatures of the HP reaches to 600°C, excluding only the condenser side. This is because the molten sodium actively transfers heat and the vapour heated in the evaporator circulates well to the adiabatic zone (insulated area). At this time, sodium did not melt (sodium melting point 98°C) for 5000 seconds in the condenser area, but it was slow but the temperature gradually increased. Even without increasing the power, the surface temperature gradually increased and the temperature of the TW8 inside the condenser increased by more than 100°C. As the sodium melts and heat transfer is actively progressing, the rise curve briefly decreases, and then there is a section where the temperature rises sharply again. This is because the water inside the condenser starts to boil at 100°C, the temperature is temporarily reduced due to excessive heat removal due to the latent heat of vaporization of water, and the surface temperature is raised again rapidly as film boiling occurs on the surface. (The temperature of the TW9 inside the condenser tends to increase more slowly, which was found to be the effect of the non-condensable gas generated in the result of later verification experiments.)

The temperature increase is made close to the temperature of the adiabatic section, but when the water in the condenser is almost vaporized and water was supplied to the condenser, the film boiling section disappeared and the surface temperature rapidly decreased. As shown in the figure, this process is repeated several times to maintain steady-state operation of the HP, but eventually failed. This is because the water inside the condenser removes heat more than the amount of sodium heat in the HP. In the process of repetitive injection of cooling water, the notable phenomenon is that when the temperature in the condenser decreases, the temperature inside the evaporator (TW10) rises alone. This shows that the end of the evaporator part is temporarily dryout due to the sonic limitation and the entrainment of the liquid sodium. It can be seen that this temperature rise and fall trend is opposite to the temperature inside the condenser. In other words, when the temperature inside the condenser rises, the sonic limit is moving in a direction that disappears. This is a typical frozen startup failure phenomenon [7]. The cause is excessive heat removal from the condenser. For successful operation of HP, it is necessary to change to a condenser that can operate at a temperature much higher than the melting point of sodium.

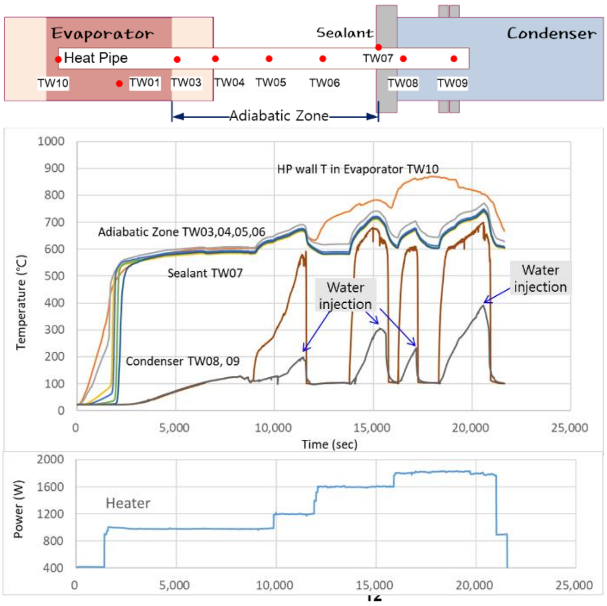


Fig. 5. Experimental results of a frozen startup failure for a screen wick sodium heat pipe

6. Conclusion

A sodium filled heat pipe is tested at a newly constructed heat pipe test apparatus. A frozen state startup failure is aquatinted on the test with sonic limitation and sodium liquid dryout phenomena at the evaporator section. Excessive heat removal of water condenser bring about this phenomena and confirmed the sonic limitation with repeatable injection of water in the condenser. In other words, when the temperature inside the condenser rises, the sonic limit is moving in a direction that disappears. For successful operation of HP, it is necessary to change to a condenser that can operate at a temperature much higher than the melting point of sodium.

ACKNOWLEDGEMENTS

This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (2019M2D1A1058139).

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, “Design of an Experimental Apparatus to Test the Alkali-Metal Heat Pipes for Space

Fission Power," KNS Spring Meeting, Jeju, 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.
[6] Y. Cao and A. Faghri," Closed-Form Analytical Solutions of High-Temperature Heat Pipe Startup and Frozen Startup Limitation," ASME J. Heat Transfer, Vol. 114, 1992.
[7] J. M. Tournier, M, S. El-Genk, "Startup of a Horizontal Lithium–molybdenum Heat Pipe from a Frozen State," Int. J. of Heat and Mass Transfer 46, 2003.