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Manufacture and Test of a High Temperature Heat Pipe

Shung-Wen Kang[1]*, Huan-Ming Yeh[1], Meng-Chang Tsai[2] and His-Hsiang Wu[1]

[1]*Department of Mechanical and Electro-Mechanical Engineering, Tamkang University, Tamsui, Taiwan 25137, R.O.C.*

[2]*Dual-use Industrial Technology Cooperative Development Program, National Chung-Shan Institute of Science and Technology, Taoyuan, Taiwan 32544, R.O.C.*

Abstract

Heat pipe play an important role in high temperature energy transfer system and storage system. It can be applied to the areas such as solar energy storage system and waste heat recovery. High temperature heat pipes with 420 mm in length, 13 mm in outer diameter and 2 mm in tube thickness have been developed and tested. The device was made of Inconel 600 equipped with a 316 stainless-steel 100 mesh wick. The working fluid was metal sodium with a filling ratio of 10% (2.86 g). Heat pipes start-up and thermal characteristics were investigated at different orientations with slopes of -15°, 0°, +45° and +90° while heat sink temperatures were kept at 27 °C air environment. The evaporator temperature of 800 °C was achieved when the input power was set at 790 W. It has been found that the lowest value of the heat pipes thermal resistance was 0.11 °C/W when the inclination angle was at 90°.

Key Words: High Temperature Heat Pipe, Metal Sodium, Stainless Steel Screen

1. Introduction

Heat pipes are effective means of heat transfer used in energy transport and in storage systems. A heat pipe is a simple device that can quickly transfer heat from one point to another. Heat pipes are often referred to as super-conductors of heat because they possess immense heat transfer capacities with minimal heat loss. Figure 1 shows the schematic of a heat pipe.

Combining the principles of thermal conductivity and phase transition, heat pipes efficiently manage the transfer of heat between two solid interfaces. At the evaporator, liquid in contact with the thermally conductive solid surface turns into a vapor by absorbing heat from that surface. The vapor then travels along the heat pipe to the condenser and condenses back into a liquid, releasing the latent heat. The liquid then returns to the evaporator through capillary action. The heat transfer capacity of a heat pipe is a hundred times that of a general metal. Heat pipes are now found in a wide range of applications for efficient heat transfer, dissipating heat recovery, and thermal management systems [1]. Based on the operating temperature, the high temperature range for a heat pipe is normally between 500 °C and 1000 °C [2]. There are a number of different applications that could use heat pipes in that range, including concentrated solar thermal energy systems, space nuclear power system radiators, fuel cells, and high temperature electronics cooling. Currently, heat pipe solar capture systems play a vital role in

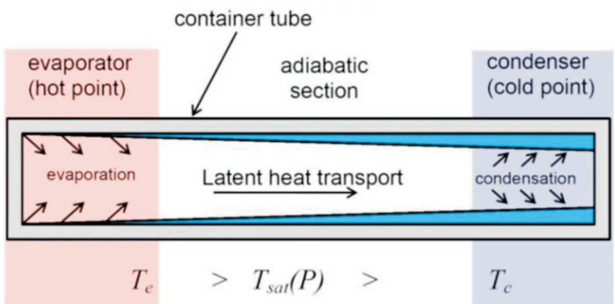

Figure 1. General heat pipe schematic diagram.

*Corresponding author. E-mail: swkang@mail.tku.edu.tw

capturing the benefits of solar energy. In the high temperature range there are only a few options of heat pipe working fluids i.e. Cesium, Rubidium, Potassium, Sodium etc. Sodium heat pipe can operate during 500~1100 °C. Heat pipes filled with Sodium have been recognized as a potentially effective heat transport approach for concentrating solar power systems that require near-isothermal input to power cycles or storage, such as dish Stirling turbines. Lee and Lee [3] fabricated a high temperature stainless steel-sodium heat pipe with a volume filling ratio of approximately 20%. They analyzed its performance of axial vapor temperature profile of a sodium heat pipe agrees well with Cotter's and Faghri's correlation. Walker et al. has developed alkali metal heat pipes to transfer the thermal energy generated by a spacecraft fission reactor to electrical convertors for power generation [4] Tiago et al. fabricated and tested four sodium thermosyphons. They also compared the experimental data with two calculation methods to determine the maximum heat transfer rate [5] Wang et al. made a high temperature special-shaped heat pipe coupling the flat plate heat pipe and cylindrical heat pipes. The startup characteristics, isothermal performance, and thermal resistance of the heat pipe were also investigated in the study [6]

The aim of the present work consisted in the development and investigation of a stainless steel-sodium heat pipe with a diameter of 13 mm for an input power of 790 W, which is capable of operating efficiently at -15°, 0°, +45° and +90° orientation in the gravity field at air room temperature.

2. Fabrication of the Heat Pipe and Experimental Method

2.1 Fabrication of the Heat Pipe

The heat pipe had a diameter of 13 mm and a length of 420 mm. The thickness of the hollow stainless tube was 2 mm. The stainless steel tube was kept oxygen-free to retain its high thermal conductivity. Bottom of the tube's end cap was welded using a high-speed rotation argon welding seal. The tubes were degreased by distilled water, ethanol and acetone. Before charging, helium leakage test was performed in the tube using the LEYBOLD PhoeniXL 300 leaking detector. The filling ratio of sodium was approximately 10% of the total inner volume of the heat pipe and its weight was 2.86 g. The heat pipe was then degassed to the desired chamber pressure (4×10^{-8} Torr). After degassing the non-condensable gases from the heat pipe, the top end was clamped and cut, and then welded using argon to seal the heat pipe. A photograph of the heat pipes charged with sodium and sealed is shown in Figure 2.

2.2 Experimental Setup and Method

The experimental setup used to determine the thermal performance of the heat pipe is shown in Figure 3.

The heat pipe consisted of an evaporator section, an adiabatic section, and a condenser section. The length of the evaporation section was 240 mm; the condenser section was 120 mm long and was kept under natural convection. Heat was applied to the evaporator part of the

Figure 2. Heat pipes charged with sodium and sealed.

Figure 3. Heat pipe in furnace and power supply.

heat pipe by using a furnace. The heat pipe was inserted into the central part of the furnace. Seven type K thermocouples were installed along the heat pipe and all temperature outputs were connected to a data recorder and continuously logged. Temperature measurement uncertainty was 0.1 °C. Schematic of thermocouples positions in furnace is shown in Figure 4.

The experiments were performed to record all the temperatures when an input power was 790 W. Performance tests are carried out for two aims. The one is to understand the behavior of the frozen start-up in unsteady state process and the other is to investigate axial temperature distributions in steady state under the radiation and free convection heat transfer condition in a room air in the cooling section of sodium heat pipes. The thermal resistance of a vapor chamber can be expressed as

$$R_{hp} = \frac{\Delta T}{Q_{in}} = \frac{\frac{1}{4}\sum_{0}^{3} ch_e - \frac{1}{3}\sum_{5}^{7} ch_c}{Q_{in}} \qquad (1)$$

where ch_e are the temperatures of evaporator, ch_c are the temperatures of condenser. The uncertainty analysis of the thermal resistance is performed as given by

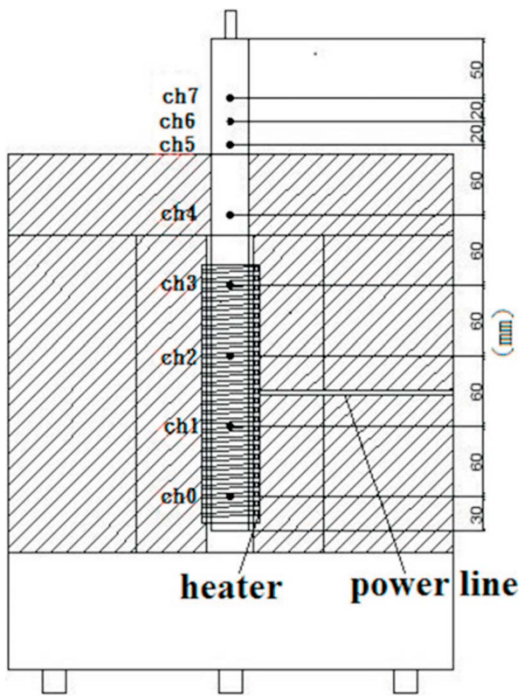

Figure 4. Schematic of thermocouples positions in furnace.

$$\frac{U_R}{R} = \frac{1}{2}\left[\left(\frac{U_q}{q}\right)^2 + \left(\frac{U_{\Delta T}}{\Delta T}\right)^2\right] \qquad (2)$$

where U_q and $U_{\Delta T}$ are uncertainties of the heat transfer rate and the temperature difference, respectively. The uncertainty of present experiment was calculated as 1.8~6.25%. Table 1 shows heat pipe specification and test characteristics.

3. Test Results and Discussion

3.1 Frozen Start-up Behavior

In order to compare the heat transfer characteristic among empty tube (0% sodium filled), thermosyphon (no wick) and heat pipe (with wick), an input power of 790 W was applied to the three test samples successively. The temperature of the heater was set at 800 °C and the samples were installed vertically. Figure 5 shows the heat pipe test at 800 °C.

The temperatures distribution measured during 30 minutes of each test are shown in Figure 6, 7 and 8, respectively

In this investigation, evaporator surface temperatures (ch0, ch1, ch2, ch3), the insulation surface temperature (ch4), and condenser surface temperatures (ch5, ch6, ch7) were obtained at the locations of 30, 90, 150, 210, 270, 330, 350 and 370 mm from the end of the evaporator side of the heat pipe. The temperatures distribution in Figures 6 shows that a conduction heat transfer mode can be applied for empty tube and its heat transport capability was poor. The temperature of ch0, ch1, ch2, and ch3 rose faster than the others and ch0 reached 900 °C at 15 minutes. The temperatures were approaching steady state in 30 minutes. The axial surface temperature distribution

Table 1. Heat pipe specification and test characteristics

Tube material	Inconel 600
Length	420 mm
Outer diameter	13 mm
Inner diameter	9 mm
Wick	Stainless-steel 316, 100 mesh × 1 layer
Filling ratio of sodium	10% (2.86 g)
Type of condenser	Environment (27 °C)
Heater power input	790 W

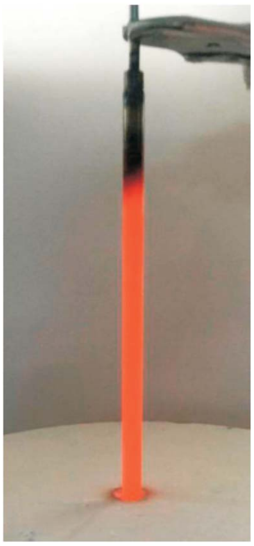

Figure 5. Heat pipe test at 800 °C.

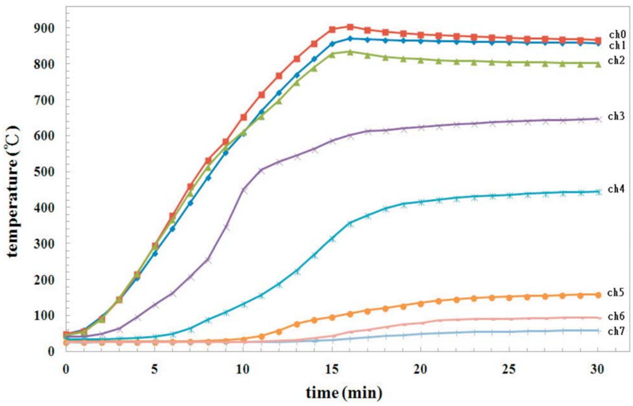

Figure 6. Temperatures measured with time (0% sodium filled, empty tube).

along the thermosyphon and heat pipe shows the behavior of the frozen start-up in Figure 7 and Figure 8.

The temperatures at the thermosyphon evaporator were increased rapidly up to the transition temperature in 13 minutes while temperatures at the condenser (ch6, ch7) remained at the initial temperature shown in Figure 7. When temperatures at the evaporator rose above the transition temperature, the increasing rate of temperature at the evaporator was slowed down and the temperatures of evaporator reached steady state. Figure 9 shows the transient axial temperature profiles along a heat pipe during a frozen startup period.

It is indicated that the evaporator temperatures (ch0, ch1, ch2, ch3) were the first to steadily increase. As the vapor began to be generated in the evaporator and move

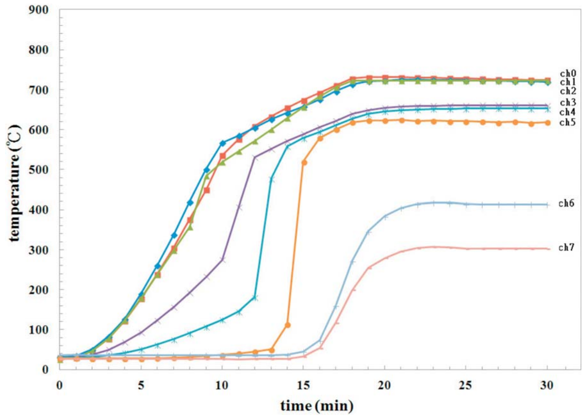

Figure 7. Temperatures measured with time (10% sodium filled, thermosyphon without wick).

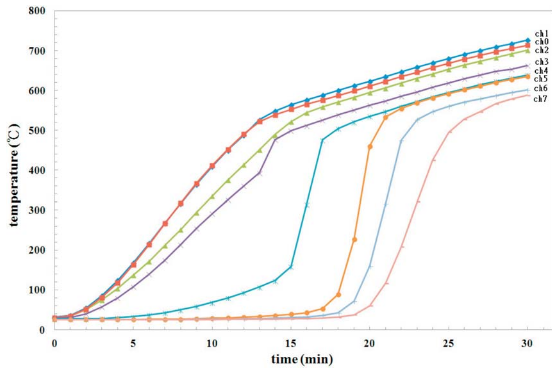

Figure 8. Temperatures measured with time (10% sodium filled, heat pipe with screen wick).

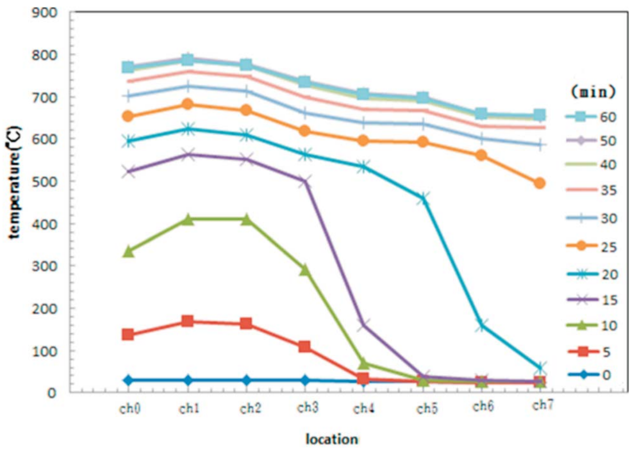

Figure 9. Transient axial temperature profiles along a heat pipe during a frozen startup period.

to the condenser, the temperature increased at the heat pipe condenser was accelerated from 15 minutes to 25 minutes. When the axial temperature profiles became nearly uniform, the axial heat pipe temperatures of sodium vapor may be increased further until steady state conditions were established, similar to a low temperature range heat pipe. These kinds of temperature profiles imply that the vaporization of sodium at the evaporator and the vapor flow in the vapor space are significant during this start-up period. Besides, for the formation of a vapor phase in the evaporation zone it is necessary to have a certain liquid superheating with respect to the equilibrium state on the saturation line. Evidently, the achievement of the necessary superheating requires a certain time. It should also be mentioned that at all test conditions no noticeable pulsations of the thermosyphon and heat pipe operating temperature were observed. Table 2 shows the temperatures measured at each measuring points at 30 minutes.

The temperature difference between ch0 and ch7 for empty tube, thermosyphon and heat pipe were 800 °C, 420 °C and 126 °C, respectively.

3.2 Effect of Inclination

The test run paused at each of the following inclination angle: +90° (the condenser was on top position and the evaporator was at the bottom), +45°, 0° (horizontal position), and -15° (the evaporator was on top position and the condenser was at the bottom), as shown in Figure 10.

Figure 11−14 show the axial surface temperatures on the heat pipe with time at inclination angle +90°, +45°, 0° and -15°, respectively.

It is observed that the axial temperature profiles became nearly uniform after 1 hour at all test conditions. Heat pipe experiences performance degradation when the evaporator end is lifted above the condenser end is shown in Figure 14. The manner in which the heat pipe works against adverse gravity effects depends on the wick pumping capability. For example, Figure 11 shows that, when the evaporator is located below the condenser, a favorable condition is created because gravity helps the liquid to move down to the evaporator, and the heat pipe exhibits maximal heat transport capability. Conversely, when the evaporator is located above the condenser, the wick must pump against gravity from the condenser to the evaporator. The heat pipe works if the wick has sufficient pumping capability. Table 3 is established to show temperatures and thermal resistance of the heat pipe at the 4 different inclination angles with an input power of 790 W after 8 hours test.

It is indicated that the smallest values of evaporator temperature and thermal resistance (0.11 °C/W) are at inclination angle of 90°.

4. Conclusions

The paper presents the results of testing a sodium heat pipe made of Inconel 600 equipped with a 316 stainless-steel 100 mesh wick. Heat pipe tests were performed when an input power of 790 W was applied to the heater at different orientations with slopes of -15°, 0°, +45° and +90° while heat sink temperatures were kept at 27 °C air environment. The main results may be formulated as follows:

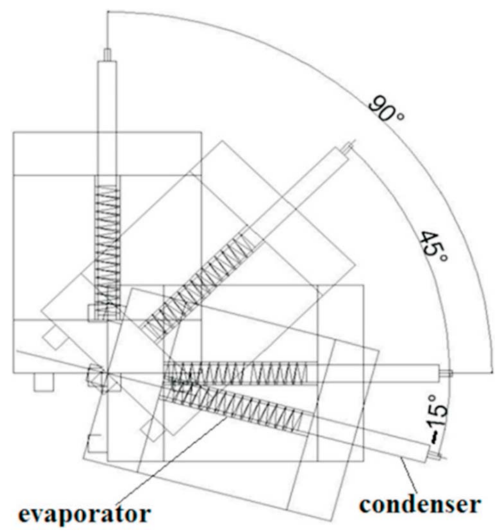

Figure 10. Schematics of different inclination configurations.

Table 2. Temperature measured for tube, thermosyphon and heat pipe with 790 W input power after 30 minutes test (°C)

Position	Ch0	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6	Ch7	Ch0−Ch7
Empty tube	857	866	801	646	444	158	94	57	800
Thermosyphon	784	772	758	717	714	604	455	364	420
Heat pipe	713	725	700	662	638	635	604	587	126

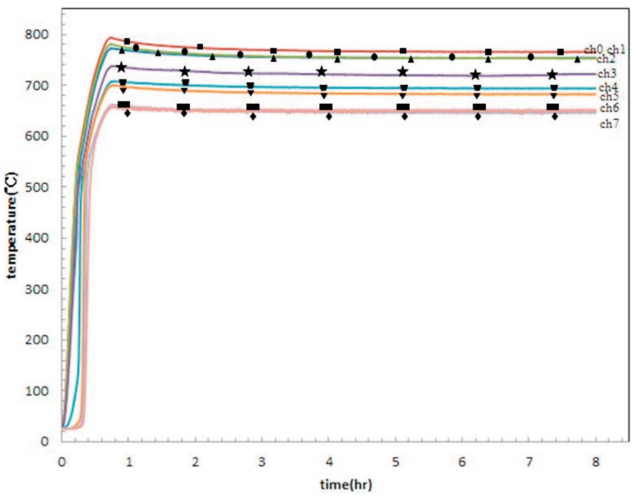

Figure 11. Temperatures measured with time at +90° inclination angle.

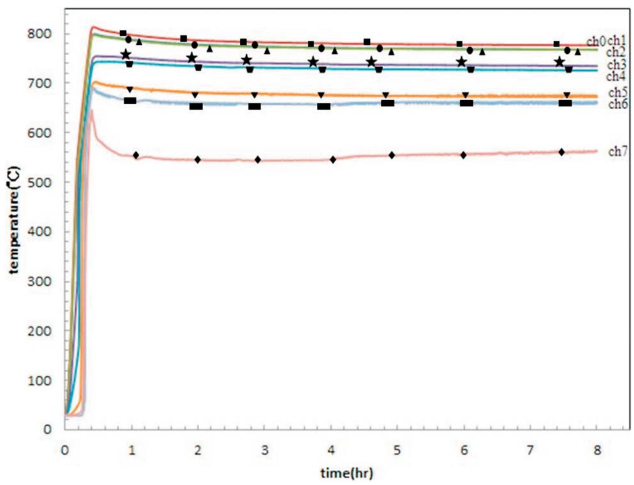

Figure 13. Temperatures measured with time at 0° inclination angle.

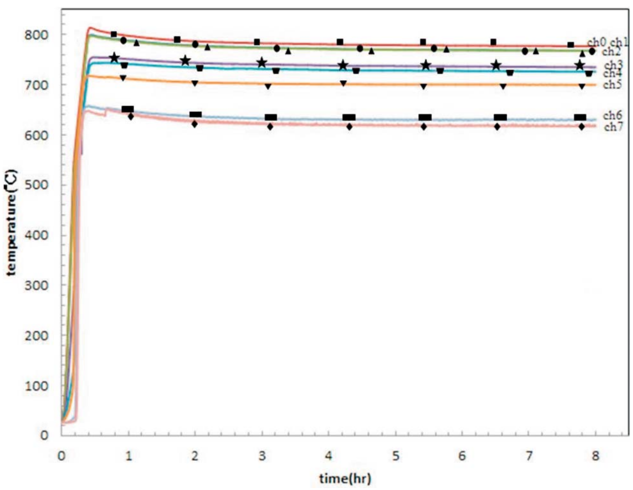

Figure 12. Temperatures measured with time at +45° inclination angle.

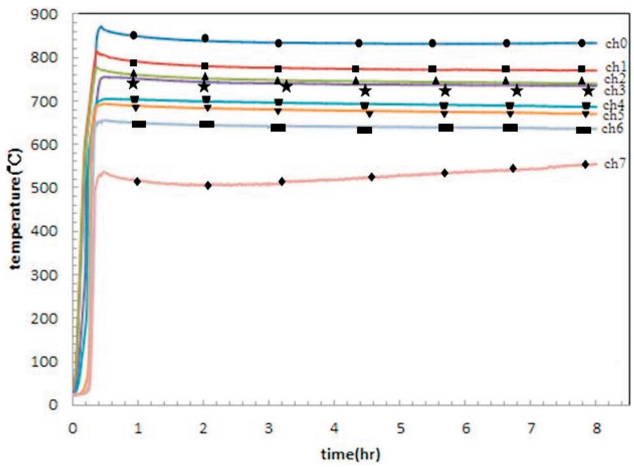

Figure 14. Temperatures measured with time at -15° inclination angle.

Table 3. Temperatures (°C) and thermal resistance (°C/W) of heat pipe at 4 different inclination angles with 790 W input power after 8 hours test

Angle	ch0	ch1	ch2	ch3	ch4	ch5	ch6	ch7	*R*
+90°	754	765	752	721	693	682	648	646	0.11
+45°	760	767	743	731	720	703	631	613	0.13
0°	768	776	767	734	725	673	661	563	0.16
-15°	833	769	739	686	670	635	612	553	0.20

Temperature and thermal resistance, the results are as follows:

1. It took 15 minutes for the heat pipe to reach the transition temperature. The temperature difference between evaporator and condenser for empty tube, thermosyphon and heat pipe were 800 °C, 420 °C and 126 °C, respectively after 30 minutes test.
2. The thermosyphon and heat pipe has shown a stable start-up at all orientations. No essential temperature pulsations were observed after going over into a stationary operating mode.
3. Thermal resistance became small as orientations with

slopes changed from -15° to +90°. A minimum value of the heat pipe thermal resistance of 0.11 °C/W was obtained at a heat load of 790 W at heat pipe favorable inclination angle of +90°.

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