Development of a meter-scale U-shaped Oscillating Heat Pipe for GAPS

Shun Okazaki 1, Hideyuki Fuke 2, Hiroyuki Ogawa 5
Japan Aerospace Exploration Agency (JAXA), Kanagawa 252-5210, Japan

and

Takuma Okubo 3, Yoshiro Miyazaki 4
Fukui University of Technology, Fukui 910-8505, Japan

Thermal performance of a 6m-long Oscillating Heat Pipe (OHP) for balloon-borne General Anti-Particle Spectrometer (GAPS) experiment has been investigated. The developed OHP is a closed loop type and U-shaped due to the mission detector requirements. R410A is selected as the working fluid for the use at low temperature. We achieved a thermal conductance of 18.7 W/K for 150 W heat input with 16 turns at +20 deg-C. We also found for the first time that this large-scale OHP can be operated at low temperatures when the cooling section is cooled from +20 deg-C to -60 deg-C. In addition to the well-known advantages of OHP that it can be simply fabricated and has low sensitivity to the orientation, it is found that the OHP has an adjustability and flexibility to 3-dimensional alignment and wide temperature range.

Nomenclature

\[ h = \text{pressure head} \]
\[ p_H = \text{vapor pressure of the heating section} \]
\[ p_C = \text{vapor pressure of the cooling section} \]
\[ \rho = \text{density of the working fluid} \]
\[ g = \text{gravitational acceleration} \]

I. Introduction

The thermal performance of a meter-scale Oscillating Heat Pipe (OHP) for General Anti-Particle Spectrometer (GAPS) has been investigated. GAPS is a balloon-borne project, which aims to contribute to solve the dark matter mystery through highly sensitive cosmic-ray observation[1]. Due to the balloon flight environment different from spacecraft, the GAPS thermal control system has to work in gravity. The biggest challenge of the GAPS thermal control system is to cool the core detectors. The feature of the heat source is large amount of heat and low heat flux. The detectors are spread over a wide area of 2 m x 2 m x 2 m and their total heat dissipation is about 800 W. The detector must be cooled down to lower than -35 deg-C. Therefore, the working fluid must be suitable for the low temperature. The heat must be transported to the radiator attached to the payload sidewall which is 2 m apart from the detectors on average. The heat transfer route is required to be U-shaped; the two vertical sides of U-shape correspond to the heat input section and the radiator section, and the horizontal side corresponds to the adiabatic section. In our present design of GAPS heat transfer device using OHP, the number of OHP turn is about 100 in total. Since the radiator is expected to be cooled down to around -50 deg-C, a heat transport capability per turn larger than

1 Engineer, Institute of Space and Astronautical Science, 3-1-1 Yoshinodai.
2 Assistant Professor, Institute of Space and Astronautical Science, 3-1-1 Yoshinodai.
3 Graduate Student, Department of Electrical, Electronic and Computer Engineering.
4 Professor, Department of Electrical, Electronic and Computer Engineering.
5 Associate Professor, Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, AIAA Member.

1 American Institute of Aeronautics and Astronautics
8 W and a temperature difference between the heating section and the cooling section less than 10 deg-C are required.

Since the OHP has been researched mainly to understand its physical phenomena, most of the OHPs studied in the past were desktop-scaled less than 1 m with a flat shape and were operated at room temperature. For the basic study, we developed a scaled U-shaped OHP with a turn length of 1 m, and we could confirm that the OHP has a capability to satisfy the GAPS thermal requirements such as the U-shaped 3-dimensional routing and the cold temperature operation [2]. Based on this basic study, we have developed an OHP with an actual size of 6 m turn length. This paper reports the experimental results of the 6m-long U-shaped OHP.

II. Oscillating Heat Pipe (OHP)

An oscillating heat pipe (OHP) consists of a meandering capillary tube that does not need an internal wick. The capillary tube goes back and forth several times between a heating section and a cooling section. The OHP operation relies on the oscillation and/or circulation of vapor plugs and liquid slugs in the capillary tube. Vapor bubbles are generated and grow in the heating section, and then collapse in the cooling section. The generation and the collapse of vapor bubbles pump the liquid slugs, which cause the pressure and temperature fluctuations. The feature of the OHP is simple fabrication, lower sensitivity to orientation than conventional heat pipes, capability of large amount of heat transfer, and adjustability to the low heat flux[3]. The OHP can enhance its potential by utilizing it as the temperature controllable OHP with liquid reservoir[4]. The temperature of the heating section may be controlled by the temperature of the liquid reservoir. It is also expected that the reservoir is useful to keep the amount of effective working fluid by compensating for the leak. We consider that OHP is a suitable thermal control device for GAPS. As previously described, we have investigated the thermal performance of a U-shaped OHP with 1m turn length. We succeeded in operating the 1m U-shaped OHP in low temperature by using R410A as the working fluid.

III. Experimental Set-up

Figure 1 illustrates the set up of the tested OHP and the locations of the thermocouples. The test specimen consists of an OHP and a liquid reservoir. The reservoir connection point, the working fluid, the tube diameter, and locations of check valves are determined to be same as the 1m-length U-shaped OHP described in the previous sections. The reservoir is connected to the OHP adiabatic section close to the heating section. The OHP is a closed loop type and U-shaped. The lengths of the heating, cooling, and adiabatic sections are 2m each. R410A is used as the working fluid. The inner and outer diameters of copper capillary tubes are 1.0 and 1.6 mm, respectively. The number of tubes turn between the heating section and cooling section is scaled down to sixteen. Sixteen check valves are installed in the adiabatic section to force the working fluid flow in one direction. The capillary tubes at the heating and adiabatic sections are insulated by a Styrofoam cover. At the cooling section, the tubes where the working fluid rises are insulated and the tubes where the working fluid falls are not insulated. The vapor from the heating section should push the working fluid at the cooling section. Therefore, we considered that the working fluid which flows against gravity should be vapor because the density of the vapor is lower than the liquid. Thirteen heater sheets are attached to the heating section to simulate the heat source distribution of the GAPS detectors. The liquid reservoir is a stainless steel tank with a volume capacity of 300 ml. A Kapton heater is attached to the reservoir for the temperature control. A feedback controller is used to control the heat input to the reservoir heater. The temperatures measured by thermocouples are monitored every second. All tests were conducted in a temperature controllable room at atmospheric pressure.

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Fig. 1 Schematic illustration of the experimental OHP with thermocouples.

IV. Experimental Result

A. Performance at room temperature

The liquid reservoir temperature was controlled to be 10 deg-C higher than the temperature at the bottom of cooling section. The power consumption of the reservoir for the temperature control was less than 10 W. Figure 2 shows the temperature profile at the start-up with a heat input of 50 W. The cooling section temperature was kept to be 20 deg-C. After a steep increase of the vapor line temperature, the heating section temperature shows a start-up of oscillation. However, it was observed that the OHP operated only intermittently with the 50 W heat load.

Figure 3 shows the temperature profile when the heat input to the heating section was once set to 100 W for the start-up, then increased to 200 W in 50 W increments, and again decreased to 100 W in decrements of 50 W. It was observed that the steep increase of the heating section temperature is followed by a sharp descent to around 30 deg-C, and then the OHP operates stably. It is considered that the pressure of the vapor pushes up the liquid in the cooling section against the gravity, and thus the working fluid starts oscillation and circulation. When the heat input is increased to 150 W, the temperature of the top of heating section raises. This might indicate that a local dry-out occurs in the capillary tube around the top of the heating section. This local dried-out area seems to expand to the middle of the heating section when the heat input is increased to 200 W. From these results, we could confirm for the first time that the 6m-length U-shaped OHP can be operated in room temperature. The OHP shows a good repeatability with no temperature hysteresis in the heat input range of 100 – 200 W, which corresponds to 630 – 1250 W per 100 turns.
Fig. 2 Temperature profile at the start up with 50 W heat input.

Fig. 3 Temperature profile when the heat input is varied between 100 and 200 W in steps.

B. Performance at low temperatures down to -60 deg-C

Figure 4 shows a result of the temperature profiles when the cooling section temperature was decreased from +20 deg-C to -60 deg-C at a constant heat input of 150 W. It can be said that the OHP operates and shows a good thermal conductance above -20 deg-C. However, the thermal conductance of the OHP decreased down to 10 W/K with decreasing the cooling section temperature. This result indicates that the performance of the OHP is not good enough at low temperatures under the present configuration conditions.
C. Performance of cold start-up at each temperatures

We have carried out the cold start-up test of the OHP at various temperatures. A heat load of 100 W was applied at first, and then was increased to 150 W followed by 200 W. At anytime, the liquid reservoir temperature was controlled 10 deg-C higher than the cooling section temperature. The amount of the heat leak from heating section to the surroundings was measured by a “blank test” without working fluid. Figure 5 shows the conductance of OHP with cooling section temperatures at each temperature. The thermal conductance of the OHP with a liquid reservoir is expected to show an increase with the increasing heat input to keep the heating section temperature constant as is shown by 100 W and 150 W data. However, at all temperatures, the thermal conductance did not increase when the heat input was increased from 150 W to 200 W. It is supposed that the operating mode changes between 150 W and 200 W, since the temperature profile suggests a local dry-out around the top and middle of the heating section. At -40, -50 and -60 deg-C, the thermal conductance was only 4 W/K, which is almost same as the conductance of blank test. This result shows that the OHP did not work as a heat transfer device. When the heat input was increased to 200 W, the OHP started up at -40 and -50 deg-C. The thermal conductance of the OHP increases with increasing the cooling section temperature at every heat input. The OHP starts up at +20, 0 and -20 deg-C with 100 W heat load. Since the vapor pressure is low at low temperature, it is considered that the vapor generated in the heating section cannot push the liquid up into the cooling section. The pressure head generated between the heating section and the cooling section can be expressed by

$$h = \frac{p_H - p_C}{\rho g},$$

where $p$, $\rho$, and $g$ are the pressure, the density of the working fluid, and the constant of gravitation, respectively. The suffixes H and C indicate the heating section and the cooling section. The OHP is expected to start oscillation when the heating section is heated up to around the reservoir temperature, which is controlled to be 10 deg-C higher than the cooling section temperature. To realize the start-up of the OHP operation, the vapor of the heating section should sweep the liquid into the cooling section through the adiabatic section. Since the height of the U-shaped OHP is 2 m, the pressure head should be higher than 2 m. Figure 6 shows the pressure head calculated from the previous equation assuming that the temperature difference is 10 deg-C and the working fluid is R410A. The saturated vapor pressure and the density of R410A are taken from Ref. [5]. According to this calculation, even at the low temperatures around -60 deg-C, the pump head is higher than 2 m. Therefore we had expected that the OHP can operate at low temperatures. However, in practice, the OHP didn’t start up at all at -40 deg-C and didn’t start up efficiently at -30
deg-C with 200 W heat input. It is considered that some additional factor (such as the friction loss of tube flow and check valve) has to be taken into account to judge the capability of OHP start-up.

Fig. 5 Thermal conductance after start-up at various temperatures and with various heat inputs.

Fig. 6 Calculated pressure head of R410A assuming a 10 deg-C temperature difference between the heating and cooling sections.
V. Conclusion

Thermal performance of the 6m-length U-shaped Oscillating Heat Pipe developed for General Anti-Particle Spectrometer has been investigated. We found for the first time that this large-scale OHP operates at 20 deg-C with a sufficient heat conductance that satisfies the design conditions required by the GAPS mission instruments. The test results can be summarized as follows;

1) The OHP starts up at 20 deg-C. The thermal conductance of 18.7 W/K for 150 W heat input meets the GAPS design requirement.

2) The OHP can operate in low temperatures down to -60 deg-C, when the cooling section is cooled from 20 deg-C with a constant heat input of 150 W. The performance of the OHP becomes worse when the cooling section temperature is below around -20 deg-C.

3) The thermal conductance of the OHP decrease with the low cooling section temperature.

Although the developed OHP has achieved the mission requirements partly for now, we still consider that the OHP is a useful thermal control device for practical use and has a potential to fully meet the GAPS requirements. Through further studies, we are going to make improvements such as optimizing of the tube diameter and seeking for more suitable working fluid material. Once this large-scale OHP is realized, OHP is expected to be utilized for many applications.

References


2. Development of the Cooling System for GAPS detectors

