Abstract

This paper reports on the development and the thermal tests of three superfluid helium heat pipes. Two of them are designed to provide a large transport capacity (4 mW at 1.7 K). They feature a copper braid located inside a 6 mm outer diameter stainless tube fitted with copper ends for mechanical anchoring. The other heat pipe has no copper braid and is designed to get much smaller heat transport capacity (0.5 mW) and to explore lower temperature (0.7 – 1 K). The copper braid and the tube wall is the support of the Rollin superfluid helium film in which the heat is transferred. The low filling pressure makes the technology very simple with the possibility to easily bend the tube. We present the design and discuss the thermal performance of the heat pipes tested in the 0.7 to 2.0 K temperature range. The long heat pipe (1.2 m with copper braid) and the short one (0.25 m with copper braid) have similar thermal performance in the range 0.7 – 2.0 K. At 1.7 K the long heat pipe, 120 g in weight, reaches a heat transfer capacity of 6.2 mW and a thermal conductance of 600 mW/K for 4 mW transferred power. Due to the pressure drop of the vapor flow and Kapitza thermal resistance, the conductance of the third heat pipe dramatically decreases when the temperature decreases. A 3.8 mW/K is obtained at 0.7 K for 0.5 mW transferred power.

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1. Introduction

Operation of instruments and electronics onboard satellites and spacecrafts requires efficient cooling systems. When high performance is needed, either for the electronics of control systems or for measuring units or detectors, cryogenic temperature may also become necessary. Original cryocoolers have been developed at the Institute for Nanoscience and Cryogenics – Service des Basses Températures (INAC/SBT) for many years. These include the development of systems such as pulse tube cold fingers, sorption coolers and adiabatic demagnetization refrigerators. However, as heat removal across large distances (meter or more) may cause significant temperature gradients, the development of efficient thermal links at cryogenic temperature is also considered as a new technical challenge.

The two phase systems, in which a cryogenic fluid evaporates and condenses at their two ends, are particularly attractive because of limited thermal gradient. INAC-SBT has developed several two phase systems in a large temperature range. Initially a cryogenic loop heat pipe (Gully et al., 2011), using capillary forces for the fluid circulation has been designed and successfully tested using nitrogen around 80 K. The achieved thermal performance is 19 W at 80 K for a conductance of 4 W/K and a length of 0.6 m. More recently a helium pulsating heat pipe (Bonnet et al., 2011) using sustained oscillations of liquid plugs and bubbles into a multi-turn small diameter pipe has been manufactured and tested around 4 K. The achieved thermal performances are 145 mW at 4.2 K for a conductance of 0.4 W/K and a length of 0.1 m. At present INAC-SBT is exploring the low temperature range (0.7 - 2 K). The development and the thermal performance of helium heat pipes using the heat transport capacity of the Rollin liquid film covering the walls at a temperature below $T_\lambda$ is presented in this paper. The concept comes from the idea proposed by DiPirro et al. (1998) who demonstrated the interest of this concept using a Kevlar braid 0.1 m long as support of the film. Three heat pipes of different lengths (0.25 m, 0.4 m and 1.2 m) have been designed, manufactured and tested at INAC-SBT. Two of them are designed for large transferred power (4 mW) and 1.7 K working temperature. They have been tested in the 1.4 K - 2 K temperature range. Detailed results and analysis are given by Gully (2014). The other heat pipe is designed for small transferred power (0.5 mW) and to explore the low working temperatures (0.7 - 1.3 K). The design and their thermal performance are presented and discussed. The cool down of one heat pipe below $T_\lambda$ is also presented.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
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<tbody>
<tr>
<td>FP</td>
<td>filling pressure</td>
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<tr>
<td>L</td>
<td>length of the heat pipe</td>
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<tr>
<td>$Q_{\text{EVAP}}$</td>
<td>heating power applied to the evaporator</td>
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<td>$Q_{\text{EVAP,MAX}}$</td>
<td>transport capacity</td>
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<tr>
<td>$T_{\text{COND}}$</td>
<td>condenser temperature</td>
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<tr>
<td>$T_{\text{EVAP}}$</td>
<td>evaporator temperature</td>
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<tr>
<td>$T_\lambda$</td>
<td>transition temperature of helium superfluid</td>
</tr>
<tr>
<td>$\theta$</td>
<td>adverse tilt angle</td>
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</table>

2. Description of the heat pipes and experimental set up

2.1. Design and technology

We use the principle of superfluid film flow (Rollin film) driven by a gradient of chemical potential caused by the temperature gradient between the two ends of the film. Allen (1966) and more recently Shirron et al. (1998) reported measured liquid film flow rates per wetted perimeter unit, which lead at 1.7 K to a transferred power range of 0.25 mW to 0.39 mW per centimeter of wetted perimeter unit.

Two of our prototypes feature (Fig. 1) a small diameter stainless steel tube with two brazed copper ends and contain a copper braid which is composed of 650 continuous wires 70 µm in diameter. The total wetted perimeter of the braid and the tube is 16 cm which corresponds to a transport capacity in the range 4.0 – 6.3 mW using the above
data. The internal diameter of the tube is chosen to limit the vapour pressure drop along the tube and therefore to lead to a negligible temperature drop (0.7 mK along the two heat pipes for 4 mW at 1.7 K). Special care has been taken to optimize the thermal contact between the copper end caps and the braid. This last point is essential to achieve a good conductance.

The third prototype has the same diameter and does not contain any copper braid. The wetted perimeter is large enough to get a high transport capacity (0.4 - 0.6 mW).

The heat pipes are filled with helium at room temperature using a small pipe brazed to the evaporator. The filling pressure is low (FP = 0.6 MPa for the heat pipes with copper braid, FP = 0.15 MPa for the heat pipe without copper braid), but much larger than the pressure necessary to get a saturated liquid film of 30 nm as measured by Grimes at al. (1959). The filling pressure is very low and obviously no warm reservoir is necessary to limit the pressure at room temperature. Thus, the technology is very simple with the possibility to easily bend the tube.

The three built prototypes are presented in Fig. 3 (a), (b) and (c) with their length and weight.

2.2. Experimental set up

The heat pipes are tested in a helium bath cryostat (Fig. 3). The bath is pumped to reach about 1.2 K on the cold plate on which the heat pipe is mounted. The cryostat can be tilted to investigate the effect of adverse tilt angle $\theta$ (maximum 60°), i.e. the evaporator located above the condenser. To reach temperatures below 1.2 K, we use a 3He sorption cooler clamped to the cold plate.

The heat pipe is protected against radiative heat load by a cold thermal shield at a temperature close to the cold plate temperature. The condenser temperature $T_{COND}$ is kept constant during the tests series using a PID regulation. A heating power $Q_{EVAP}$ is applied on the evaporator end where the temperature $T_{EVAP}$ is measured. The experimental program aims at investigating the thermal performance of the heat pipe in steady state cold condition for different filling pressures, working temperatures and adverse tilt angles. The cool down issue is also investigated.
3. Results and discussion

3.1. Heat pipes with copper braid

The effect of adverse tilt angle $\theta$ on the transport capacity $Q_{\text{EVAP\_MAX}}$ is presented in Fig. 4a at 1.7 K temperature. For large adverse tilt ($\theta = 60^\circ$) the transport capacity remains large (4.5 – 4.7 mW) and in the order of the expected range (4.0 – 6.3 mW). When the tilt angle is reduced, the gravity forces become less important and the film thickness slightly increases according to the difference of elevation between the evaporator and the condenser as mentioned by Grimes et al. (1959). As a consequence the transport capacity gradually increases.

![Figure 3: Test cryostat with the heat pipe, 1.2 m long.](image)

![Figure 4: Transport capacity $Q_{\text{EVAP\_MAX}}$ of two heat pipes with copper braid; (a) as function of adverse tilt angle $\theta$ at 1.7 K working temperature; (b) as function of condenser temperature $T_{\text{COND}}$ with zero tilt angle ($\theta = 0^\circ$).](image)
The transport capacity $Q_{\text{EVAP\_MAX}}$ as function of working temperature is presented in Fig. 4b in horizontal position ($\theta = 0^\circ$) and for the investigated temperature range (1.4 – 2.0 K). The trend is the same for the two heat pipes and is consistent with the result of film flow rate measurements of Allen et al. (1966).

In the 1.7 – 2.0 K temperature range, the thermal conductance is the same for the two heat pipes (Fig. 5a), considering the calculated uncertainties. The thermal conductance at 4 mW heating power reaches 600 +/- 10 mW/K at 1.7 K. This corresponds to a limited temperature difference (7 mK). At 1.7 K and 4 mW, we can calculate, assuming laminar flow regime, the pressure drop of the vapor flow due to friction on the Rollin film. We find 3.1 Pa and 3.2 Pa respectively for the short and long heat pipes. Assuming the vapor at saturation temperature, the calculated temperature drop is on the order of 0.7 mK, which is negligible. At higher temperature (2.0 K), the temperature drop due to vapor pressure drop (0.2 mK) is also negligible. As a consequence the main temperature gradients are located in the two ends of the heat pipes. This is due to conduction heat transfer into the copper ends and Kapitza resistance between the braid wires and liquid helium. The geometry and the materials used being identical for the two heat pipes, it is logical to obtain the same experimental conductance. At smaller temperature (1.4 K for instance) the temperature drop due to vapor pressure drop becomes not negligible (6 mK) in comparison with the measured temperature difference (15 mK). In that case the temperature drop due to vapor pressure drop must be considered in the calculation of the thermal conductance of the heat pipe.

Cool down tests have been performed with the short heat pipe in horizontal configuration to investigate this important issue. A typical test result is presented in Fig. 5b. Before 200 s the condenser is stabilized at 4.2 K by the helium bath at atmospheric pressure and the heated evaporator ($Q_{\text{EVAP}}=6$ mW) temperature is about 1 K warmer than the condenser one, because of conduction process through the copper braid. At time 200 s the helium bath starts to be pumped and the condenser temperature drops gradually down to 1.7 K, the set point of the regulation. The evaporator temperature follows this trend using the conduction process which becomes less and less efficient. At time 5100 s the condenser temperature reaches 1.9 K. As a consequence the Rollin film starts to flow significantly (Allen et al., 1966) and progresses more and more on the copper wires towards the evaporator. This effect leads to a dramatic cool down of the evaporator, which is permanently heated close to the transport capacity of the heat pipe.

3.2. Heat pipe without copper braid

The thermal conductance of the heat pipe without copper braid is measured for 0.5 mW applied to the evaporator (Fig. 6). It remains large (~200 mW/K) at 1.3 K and on the same order of the thermal conductance of the heat pipe with copper braid. But when the operating temperature is reduced down to 0.7 K, the thermal conductance drop down to 4 mW/K. The Kapitza resistance between helium and the copper ends is found to be responsible for the thermal gradient.
Fig. 6. Thermal conductance as function of condenser temperature $T_{\text{COND}}$ for the heat pipe without copper braid with and 0.5 mW applied on the evaporator compared to the conductance of the long heat pipe with copper braid (Fig. 5a).

4. Conclusion

Three helium heat pipes of different lengths (0.25 m, 0.4 m and 1.2 m) have been designed, manufactured and tested at INAC-SBT. The technology is very simple with the possibility to easily bend the heat pipe. Two heat pipes contain a copper braid as support of the superfluid film to reach large transport capacity (typically 5 mW). They were tested in the 1.4 – 2.0 K temperature range. The other one does not contain any copper braid and was tested in the 0.7 K – 1.3 K temperature range. The following conclusions can be drawn:

- Heat pipes with copper braid: At 1.7 K the transport capacity is 4.5 mW for a tilt angle of 60°. When the tilt angle is reduced down to 0°, it reaches 6 mW. The transport capacity depends on the working temperature and follows the trend of the Rollin film flow rate measurement the literature. The thermal conductance at 4 mW heating power reaches 600 mW/K at 1.7 K. In the 1.7 – 2 K temperature range, the thermal conductance of the two heat pipes is found similar. The Rollin film eases the cool down of the evaporator down to 1.7 K with a heating power applied to the evaporator.

- Heat pipe without copper braid: the thermal conductance at 0.5 mW heating power is 200 mW/K and 4 mW/K at 1.3 K and 0.7 K. The temperature dependence is explained by the kapitza resistance between helium and the copper ends.

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References