ARTICLE IN PRESS

Cryogenics xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Long and high conductance helium heat pipe

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Helium
Heat pipe
Superfluid
Rollin film
Space cryogenics

ABSTRACT

This paper reports on the development and the thermal tests of two superfluid helium heat pipes. They feature a copper braid located inside a 6 mm outer diameter stainless tube fitted with copper ends for mechanical anchoring. The copper braid is the support of the Rollin superfluid helium film which is essential in the heat transfer. The extremely low thickness of the liquid film allows for a low filling pressure, making the technology very simple without the need for any external hot reservoir and with the possibility to easily bend the tube. We present the design and discuss the thermal performance of two heat pipes tested for several filling pressures, adverse tilt angles and in 1.4–2.0 K temperature range. A minimum filling pressure (0.6 MPa) is needed to get significant transport capacity. A 12 mW transport capacity is achieved for 3.0 MPa filling pressure. It is shown that the long heat pipe (1.2 m) and the short one (0.25 m) have similar thermal performance in adverse tilt. At 1.7 K the long heat pipe, 120 g in weight, reaches a transport capacity of 5.7 mW/4.2 mW for a tilt angle of 0 / 60° and a thermal conductance of 600 mW/K for 4 mW transferred power. When the condenser reaches the super-fluid transition temperature, the Rollin film accelerates the cool down of the evaporator down to 1.7 K with a heating power applied to the evaporator.

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 Institut Nanosciences et Cryogénie – 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, which use the phase change specific heat of cryogenic fluids are particularly attractive. INAC/SBT has developed several two phase systems in a large temperature range. Initially a cryogenic loop heat pipe [1], 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 0.5 m. More recently helium pulsating heat pipe [2] 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 (1.4–2 K) focusing on the need of the SAFARI instrument of SPICA mission (3.5 mW at 1.7 K and typically 1 m distance). The development and the thermal performance of helium heat pipes using the heat transport capacity of the Rollin liquid film existing on a wick structure at a temperature bellow T_λ is presented in this paper. The concept comes from the idea proposed by DiPirro in 1998 [3] who demonstrated the interest of this concept using a Kevlar braid 0.1 m long as support of the film. Two heat pipes of different lengths (0.25 m and 1.2 m) have been designed, manufactured and tested. The design and their thermal performance are presented and discussed. The cool down of the heat pipe down to 1.7 K is also presented.

2. Presentation of the tested 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 [4] reported mea-

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http://dx.doi.org/10.1016/j.cryogenics.2014.04.002
0011-2275/

sured liquid film flow rates per wetted perimeter unit on a glass surface as function of working temperature (Fig. 1). The transfer rate is constant (8×10^{-5} cc/s/cm) in the 1.1–1.6 K temperature range. More recent work [5] gives much larger value (12.5×10^{-5} cc/s/cm). At 1.7 K the flow rate is slightly lower 7.5×10^{-5} cc/s/cm and 11.7×10^{-5} cc/s/cm using data from [4,5]. Using the superfluid helium density and the phase change enthalpy maximum transfer rates of 0.25–0.39 mW per centimeter of wetted perimeter are calculated.

Our prototypes feature (Fig. 2) a small diameter stainless steel tube, which contains a copper braid thermally linked to the copper ends (evaporator and condenser) of the tube. The braid 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. It is larger than required (3.5 mW). The use of a copper braid instead of a Kevlar braid facilitates the cool down of the evaporator at temperature too high for a Rollin film. The internal diameter of the tube is chosen to limit the vapor 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 heat pipes are filled with helium at room temperature using a small pipe brazed to the evaporator. A minimum filling pressure (0.06 MPa and 0.5 MPa for working temperatures of respectively 1.4 K and 2.0 K) is necessary to get the saturation pressure at the working temperature without any condensation. Assuming the condensation of a film with a typical thickness of 30 nm as measured by Grimes et al. [6], we calculate a filing pressure of 0.09 MPa and 0.52 MPa for working temperatures of respectively 1.4 K and 2.0 K. In the case of a working temperature of 1.4 K, the film may consist of more 30 % of the minimum amount of helium in the heat pipe. Larger filling pressures (0.6–3.0 MP) where chosen to increase the margin for the amount of liquid over the whole temperature range (1.4–2.0 K) under investigation. The relatively low filling pressure is acceptable 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 two built prototypes are presented in Fig. 3(a) and (b). The first one is straight and 0.25 m long. The second is 1.2 m long and has three turns so that it fits in our cryostat. The two heat pipes

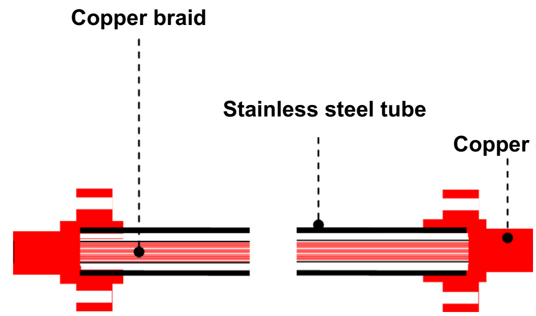

Fig. 2. Principle of the two heat pipes. Geometry of the short heat pipe: 0.25 m long, 4 mm internal diameter and 5 mm outer diameter. Geometry of the long heat pipe: 1.2 m long, 5 mm internal diameter and 5.5 mm outer diameter.

have approximately the same straight length (0.25 m and 0.21 m see Fig. 3).

The short heat pipe (0.25 m) weights 100 g. For the long one (1.2 m), the tube thickness was been minimized (0.25 mm) so that a weight of 120 g could be achieved.

2.2. Experimental set up, program and procedure

The heat pipes are tested in a helium bath cryostat (Fig. 4). 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 θ (maximum 60°), i.e. the evaporator located above the condenser. The heat pipe is protected against radiation 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.

The experimental program to investigate the steady state cold condition is performed in several tests series corresponding to different working temperature and adverse tilt angle θ. For each tests series, the heating power Q_{EVAP} applied to the evaporator is increased step by step. Typical results during a test series are presented in Fig. 5. In this figure the transport capacity Q_{EVAP_MAX} is 5.7 mW, because the following step (6 mW) leads to dramatic temperature rise. For each power step the two temperatures T_{COND} and T_{EVAP} are recorded after a thermal stabilization (~700 s). The parameters are measured within the following uncertainties:

Q_{EVAP}: +/−2%
T_{COND}, T_{EVAP}: +/−0.5 mK
$T_{EVAP} - T_{COND}$: +/−1 mK

3. Results and discussion

3.1. Effect of filling pressure

The effect of the filling pressure on the transport capacity Q_{EVAP_MAX} has been investigated on the short heat pipe. The results are presented in Table 1 at 1.7 K and in horizontal configuration ($\theta = 0°$).

At this temperature level, the heat pipe contains 25 μmol, 398 μmol, 418 μmol and 2787 μmol of liquid by volume respectively for 0.23 MPa, 0.60 MPa, 0.62 MPa and 3.0 MPa filling pressures (Table 1). Assuming a 30 nm thick film covering all the

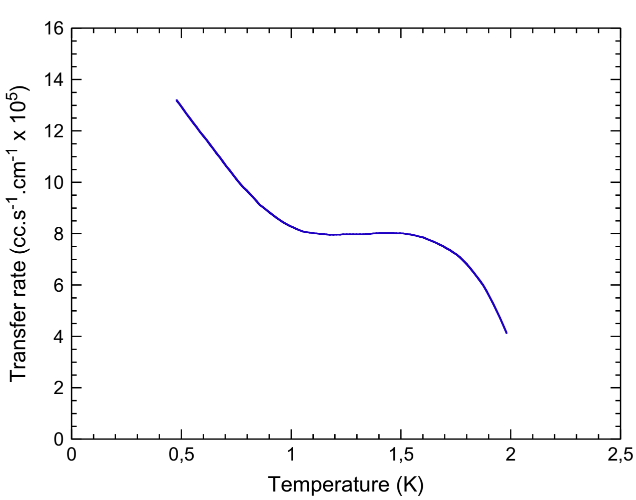

Fig. 1. Measured Rollin film flow rate as function of temperature (extracted data from [4]).

Please cite this article in press as: Gully P. Long and high conductance helium heat pipe. Cryogenics (2014), http://dx.doi.org/10.1016/j.cryogenics.2014.04.002