EXPERIMENTAL INVESTIGATIONS ON AN AXIAL GROOVED CRYOGENIC HEAT PIPE

by

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This paper deals with development and studies of a trapezoidal axial grooved nitrogen heat pipe. A special liquid nitrogen cryostat has been designed and developed for evaluating the performance of heat pipe where the condenser portion is connected to the cold sink externally. Experiments have been performed on the heat pipe as well as on an equivalent diameter copper rod at different heat loads. The steady-state performance of the heat pipe is compared with that of copper rod.

Key words: *cryogenic heat pipe, axial grooved wick, effective thermal conductivity*

Introduction

A heat pipe typically consists of a sealed container lined with a wicking material. The container is evacuated and backfilled with just enough liquid to fully saturate the wick, because heat pipes operate on a closed cycle and only pure liquid and vapour are present within the container. The working fluid will remain at saturation conditions as long as the operating temperature is between triple point and critical state. As illustrated in fig. 1 a heat pipe consists of three distinct regions: an evaporator or heat addition region, a condenser or heat rejection region, and an adiabatic region. For heat pipes that will not consume mechanical energy, the heat transfer performance is governed by wick structure. The narrower the wick structure, the higher is the returning force experienced by the condensed liquid. Because of their thin wick structure

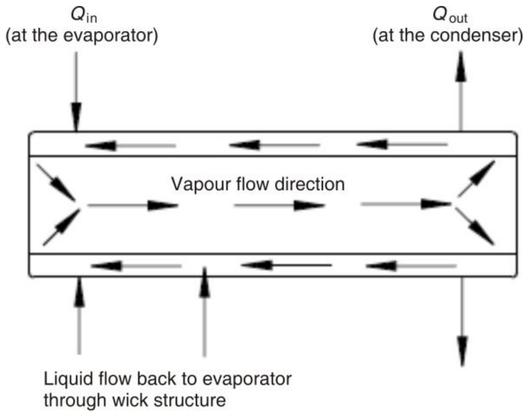

Figure 1. Schematic of a typical heat pipe

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and the small temperature drop for their vapour flow, heat pipes having thermal characteristics orders of magnitude better than any known solid have been developed.

The principle of heat pipe was conceived in 1944 by Gaugler and in 1962 by Trefethen [1]. However, it was not widely publicized until 1964 when Grover and his colleagues at the Los Alamos Scientific Laboratory independently reinvented the concept. Grover also demonstrated its effectiveness as a high-performance heat transmission device, named it the "Heat pipe", and developed its applications. Since then, over a thousand papers and patents have been published. A detailed theoretical analysis for determining various pressure drops and performance of heat pipes has been presented by Cotter [2]. Among the many outstanding advantages of using the heat pipe as a heat transmission device are: constructional simplicity, exceptional flexibility, accessibility to control, and ability to transport heat at high rate over considerable distance with small temperature drop. As a constant attempt to improve the heat pipe technology, a new method of placing heat pipe externally has been suggested and used.

Heat pipes can be categorized into cryogenic, moderate-temperature, and liquid-metals. The most important differences among these three classes of heat pipes are their respective useful temperature ranges and their maximum heat transport capabilities and temperature drop at the same heat transport rate in a heat pipe of similar geometry. The maximum heat transport capability of a typical cryogenic (*e. g.*, nitrogen) heat pipe is about an order of magnitude less than that of a typical moderate temperature (*e. g.*, ammonia) heat pipe of similar geometry, while both are operating under their most favorable conditions and is about three orders of magnitude less than that of a similar liquid-metal (*e. g.*, sodium) heat pipe. The use of cryogenic fluids in heat pipes presents several problems that do not normally occur either at ambient temperature or in liquid metal heat pipes. Most of these problems can be directly attributed to the relatively low surface tension, thermal conductivity, and latent heat of vapourisation or to the high liquid viscosity present in cryogenic heat pipes.

As reliable heat transfer devices, cryogenic heat pipes have promising application prospects in the thermal control of large superconducting magnets, satellites, coupling between infrared detector and cooler, spacecrafts, electronics, and structures. With the increasing heat dissipation of the instruments and equipment, higher heat transfer capacity, and lower cooling temperature have become important requirements. The thermal system in this paper is a new type of approach to provide cooling where condenser portion of cryogenic heat pipe is connected externally to sink. Many investigators [3-6] have carried out experiments on the cryogenic heat pipes. In all these investigations either the condenser is immersed in the liquid nitrogen or the condenser is connected to cryocooler whose operating temperature can be maintained at constant level by varying the cooling capacity. However, in most of the practical applications, where liquid nitrogen bath is used as cold reservoir, it is very inconvenient to immerse the heat pipe into liquid nitrogen bath. In that situation, the condenser has to be connected to the cold reservoir externally. In such cases the performance of the heat pipe is expected to deteriorate as the operating temperature tends to increase. Thus the operating temperature is a function of the heat sink temperature the contact resistance between the heat sink and heat pipe and the pressure-temperature characteristics of the selected working fluid. This present experimental investigation focus on the performance of a trapezoidal axial grooved heat pipe with the condenser connected to the reservoir externally and compared with that of an equivalent diameter copper solid rod.

Development of experimental setup

The experimental set-up shown in fig. 2 consists of a vacuum chamber with a liquid nitrogen bath cooling system, a high vacuum pumping system, and instrumentation and data acquisition system. A cylindrical liquid nitrogen vessel of 200 mm diameter and 300 mm length is welded to the top flange using a neck tube of 50 mm diameter and 80 mm length. The condenser section of the heat pipe to be tested will be attached to the bottom of the liquid nitrogen bath using clamps and screws. The top vacuum flange has two feed-throughs for connecting the leads of heater and other temperature sensors. Each feed-through has 37 pins. The feed-throughs are fixed to the top flange by screws with O-ring sealing. Heat load is applied to the evaporator section with the help of a manganin electric heater wound on the evaporator and a D. C. power source.

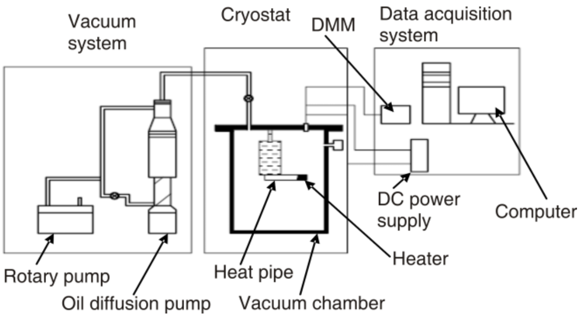

Figure 2. Experimental apparatus

The entire assembly of vacuum chamber and liquid nitrogen is made up of SS304. The vacuum chamber is evacuated using an oil-diffusion high vacuum pumping system. The vacuum level in the chamber is measured using a cold-cathode penning gauge. For measuring the temperature profile of the heat pipe PT100 sensors are used. The output of the temperature sensors and the power input to the heater are acquired by a PC using a Keithley scanner/DMM (model 2000). A photograph of the experimental facility is shown in fig. 3.

Figure 3. Photograph of the experimental facility

Fabrication of trapezoidal axial groove wick heat pipe

The axial grooves are made by electrical discharge mashining wire cutting method. The machined heat pipe is cleaned with a solution of 50% nitric acid and 5% hydrofluoric acid. End caps are welded at both the ends of heat pipe using argon arc welding. The fill tube is fitted into the hole provided at one of the end caps and is brazed. Initially the heat pipe is degassed for about 6 hours. Then the evacuated heat pipe is weighed. The filling is carried out by evacuating and then backfilling with nitrogen gas. In order to facilitate filling, the heat pipe is immersed in a liquid nitrogen bath. The heat pipe is weighed again and thus it is ensured that the required amount of gas is filled. The fill tube is then pinched off and brazed. The mass of the charge in the heat pipe is calculated by:

$$m = V_\mathrm{v}\rho_\mathrm{v} + V_\mathrm{l}\rho_\mathrm{l} \qquad (1)$$

where m is the mass of the charge, V_v and V_l are the volume of the vapour and liquid, respectively, and ρ_v and ρ_l are the density of the vapour and liquid, respectively. Assuming the operating temperature as 100 K, the mass of nitrogen to be charged is m = 2.24 grams. Design specification of the heat pipe is given in tab. 1. A detailed drawing of heat pipe assembly is shown in fig. 4(a) and 4(b).

Table 1. Designe specification of the heat pipe

Length of the heat pipe	180 mm
Length of the evaporator section	60 mm
Length of the adiabatic section	60 mm
Length of the condenser section	60 mm
Outer diameter of the heat pipe	12.72 mm
Inner diameter of the heat pipe	10.24 mm
Wick – Trapezoidal axial grooves	1.34 × 0.84 × 0.6 (depth) mm
Number of grooves	17

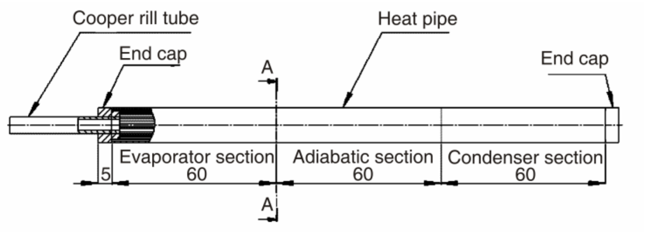

Figure 4(a). Detailed drawing of heat pipe assembly

Experimental procedure

The heat pipe is fixed to the bottom of the liquid nitrogen vessel with clamps and screws. The length of the heat pipe which is in contact with the liquid nitrogen vessel is regarded as length of the condenser. Over the evaporator length a manganin heater is wound uniformly and spirally. Two PT100 sensors are fixed each at the condenser and evaporator ends and one at the middle. The heat pipe is spirally wound with 10 layers of multilayer insulation (Jehier, France). The liquid nitrogen vessel surface is taped with aluminum adhesive foil and then wound with two to three layers of multi lager insulation. This is carried out in order to avoid the need for frequent filling of the liquid nitrogen vessel. The system is assembled and pumped down for about one day. The vacuum level attained is $1\cdot10^{-4}$ mbar. Liquid nitrogen is transferred into the liquid nitrogen vessel and allowed for the cool down of the heat pipe. After filling of liquid nitrogen, the vacuum level improves to $2.9\cdot10^{-6}$ mbar due to cryopumping. Then a heat load of 0.5 W is applied on the evaporator using a D. C. power supply. Data is acquired at regular intervals till a steady-state is reached. Experiments were carried out at different heat loads till the evaporator temperature goes above the critical temperature of the working fluid, which indicates dry-out of the evaporator.

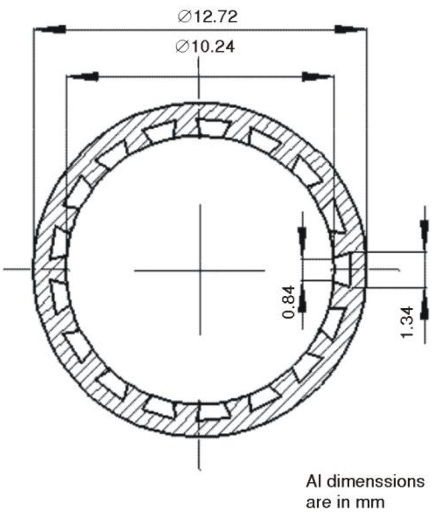

Figure 4(b). View of the cross-section A-A

Results and discussion

Steady-state performance of heat pipe

Even though, the heat pipe was tested with 10 layers of multilayer insulation wound on that, the preliminary experiments showed that there was some amount of spurious heat flux on the heat pipe. In order to nullify this effect and compare the performance of heat pipe with that of copper, experiments were repeated on a solid copper rod of the same outer diameter. Figure 5 shows the variations of measured temperature difference across the heat pipe and the copper rod against heat load. The mean operating temperatures is also plotted in the same plot. It can be observed that the performance of the heat pipe is better for the heat load less than 3 W. For the heat loads greater than 3 W, the heat pipe's mean operating temperature exceeds the critical temperature 126.1 K of the working fluid (nitrogen) and thus the heat pipe advantage is lost.

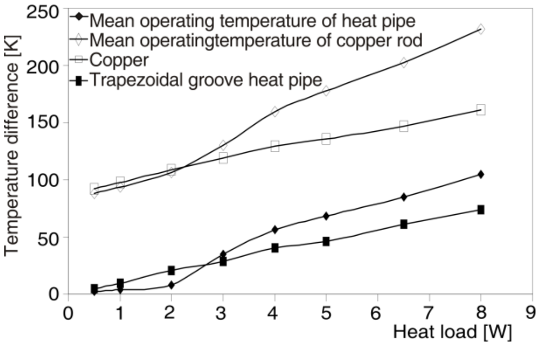

Figure 5. Temperature difference and mean operating temperature against heat load

Figure 6 shows the variation of the effective thermal conductivity against mean operating temperature. In order to compare the effectiveness of the heat pipe with the data of other investigators, the estimated effective thermal conductivity values are multiplied by a factor by which the experimental performance of the solid copper rod is lesser compared to the data available in the open literature. The effective thermal conductivity of heat pipe increases for the mean operating temperature up to 100 K and decreases beyond 100 K. When compared with the results of Armaly [7], the effective thermal conductivity in the present study is about 2.2 times less at the mean operating temperature of 100 K.

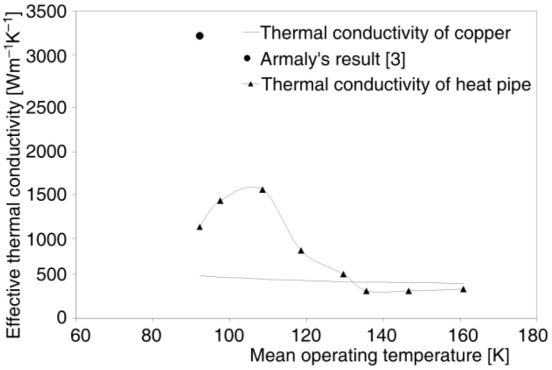

Figure 6. Effective thermal conductivity against mean operating temperature

Since, in the present investigations the heat pipe was connected to the cold sink externally, the mean operating temperatures of the heat pipe is well above the normal boiling point 77 K of liquid nitrogen. But even in these higher operating temperatures, the heat pipe's performance is better than that of copper and thus it is recommended to use the heat pipe even in the situations where the condenser need to be connected to the cold sink externally.

Conclusions

An experimental set-up for testing cryogenic heat pipes at about 77 K has been designed and developed. A nitrogen filled trapezoidal axial groove wick heat pipe was fabricated and tested. Experiments were conducted to determine the effectiveness of a heat pipe when it is connected to the cold sink externally. The thermal performance of using heat pipe is evaluated by the effective thermal conductivity of the heat pipe. This is 2.9 times improvement over simply utilizing conduction for cooling such as by using a solid copper rod at 100 K.

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