Review of Parametric Investigation of Cryogenic Heat Pipe

Bhavin Mehta, Milind Soni, Kandarp Changela

***Abstract:** with the advancement in cryogenics, applications like optical sensors, electronic circuitry are devised to operate at very low temperature and thereby efficient heat transfer devices are required to transfer heat through a very low temperature gradient. In such cases even high conducting materials, like copper fail to transfer heat at the required levels as the temperature gradient is not sufficient. Cryogenic heat pipes stand out as a prominent heat transfer device in such low temperature gradient heat transfer without any external power. Heat pipe consists of basic three components, like container, working fluid and wick structure. The various working fluids which can be used in cryogenic heat pipe are nitrogen, oxygen, argon, helium, neon and propylene. Many types of heat pipes are available and the operation of a particular heat pipe for an application is constrained by a number of parameters. The paper deals with the review of various parameters like heat load, use of various working fluids, use of various wick structures, tilt angle and its effect on the performance of heat pipe at cryogenic temperature range.*

***Index terms:** Heat Pipe, Cryogenics, Working fluid, Wick structure.*

I. INTRODUCTION

Heat pipe is a device which is used for transferring heat from a source to sink by means of evaporation and condensation of fluid in a sealed system. The amount of heat can be transported as latent heat of vaporization is usually several orders of magnitude larger than that which can be transported as sensible heat in a conventional heat transfer system. The heat pipe can therefore transport a large amount of heat with a small unit size [17].

It consists of basic three components. a) Sealed container b) Wick structure and c) Working fluid. The function of the container is to isolate the working fluid from the outside environment. The prime purpose of the wick is to generate capillary pressure to transport the working fluid from the condenser to the evaporator [17].

Working fluid is a medium which is responsible for the transfer of heat from one point to another point within heat pipe without considerable temperature difference.

II. ROLE OF HEAT PIPE IN CRYOGENIC APPLICATIONS

Cryogenic heat pipes designed to operate from 1 to 200 K, with working fluids as helium, argon, neon, nitrogen, and oxygen. These typically have relatively low heat transfer capabilities, due to very low values of the latent heat of vaporization and low surface tensions of the working fluids. In addition, startup of the heat pipe involves transitioning from a supercritical state to an operating liquid–vapor condition [18].

Heat pipes were developed especially for space applications during the early 60´ by the NASA. One of the major problems in space applications was the heat transfer from the inside to the outside, because the heat conduction in a vacuum is very limited. Hence there was a necessity to develop a fast and effective way to transport heat, without effect of gravity force. The idea behind it to create a flow field which transports heat energy from one spot to another by means of convection, as convective heat transfer is much faster than heat transfer due to conduction [18].

Operation of instruments and electronics onboard satellites and spacecrafts requires efficient cooling systems. Original designs of Cryo coolers have been developed at Commissariat à l'Energie Atomique – Service des Basses Temperatures (CEA-SBT) for many years, within the scope of technical research programs of the European space agency. These include the development of systems such as pulse tube cold fingers, sorption coolers, and continuous adiabatic demagnetization refrigerators. As distribution of cold power across large distances (1m for instance) may cause significant temperature gradients, the development of efficient thermal links to distribute it is simultaneously considered as a new technical challenge [17].

An integrated cryogenic cooling engine (ICICLE) system consists of a miniature vuillemier cycle cryogenic engine which operates on thermal energy which is provided by a radioisotope through a sodium heat pipe. The engine rejects heat to space by means of ammonia heat pipe radiator at 300 K and delivers by nitrogen heat pipes, 5 W of refrigeration at 75 K to cool different components of the communication system. One of the important applications of heat pipe is in surgery Cryoprobe. Cryo freezing has been used to produce tissue death in several types of tumors. The Cryoprobe can be used in the cryosurgery of tumors by insertion of probe in to the tumor and freezing from within or by applying the probe tip to the surface of tumor and freezing it from outside. Cryoprobe consists of reservoir which is charged with the liquid nitrogen. Liquid nitrogen flows through the inner core of the probe by capillary pumping on to gold plated copper tip and provides 77 K temperature at tip and gets vaporize. During vapourization latent heat is extracted from the tip by the cryogen and escape through the self venting nylon screw cap [18].

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III. Working fluids used in Cryogenic Heat pipe

Various working fluids which are used in cryogenic heat pipe are Nitrogen, oxygen, Argon, Neon, Methane and Propylene [1-15].

Nitrogen is a colorless fluid having boiling temperature of 77.36 K and freezing temperature of 63.2 K at atmospheric pressure. It is having latent heat of vapourization of 199.3 kJ/kg at normal boiling temperature. At normal boiling temperature the surface tension of liquid nitrogen is 8.9×10^{-6} N/m.

Oxygen is one of the working fluid used in cryogenic heat pipe having boiling and freezing temperature of 90.18 & 54.4 K respectively. It is having latent heat of vaporization of 213 kJ/kg. Due to high chemical reactivity, use of oxygen as working fluid in heat pipe is restricted.

Argon is a clear colorless liquid with properties similar to the liquid nitrogen. It boils at 87.3 K and freezes at 83.8 K at atmospheric pressure. Latent heat of vaporization is around 161.9 kJ/kg. Compared to liquid nitrogen, its freezing point is considerably high and value of latent heat of vaporization is less which restricts its use in heat pipe.

Neon is another fluid that can be used as working fluid in heat pipe. It is clear colorless liquid which boils at 27.09 K and freezes at 24.53 K. Its latent heat of vaporization is of 85.9 kJ/kg which is considerably less compared to that of liquid nitrogen.

Methane is colorless liquid which boils at 111.7 K and freezes at 88.7 K. Its density is around half of the density of liquid nitrogen. Its latent of vaporization is 511.5 kJ/kg.

Propylene may also be used as working fluid in heat pipes at low temperature. It consist of latent heat of vaporization as 437.94 kJ/kg.

Table. 1 Important Properties of different working fluids [20]

Name of Working fluid	Boiling point (K)	Specific Heat (kJ/kg- K)	Latent heat (kJ/kg)	Density (kg/cub. m)
Nitrogen	77.36	2.05	199.3	807.3
Oxygen	90.18	1.695	213	1141
Argon	87.28	1.136	161.9	1394
Neon	27.09	1.83	85.9	1206
Methane	111.7	3.461	511.5	424.1
Propylene	225.4	-	437.94	613.9

IV. Different Configurations tested so far

Since the loop heat pipe was invented in 1987 in Japan, efforts have been made to extend it for cryogenic use. In 1991, a loop heat pipe was demonstrated by R. Chandratilleke (1998) [1] to work at liquid nitrogen temperature. A cryogenic loop heat pipe (CLHP) was developed by Q. Mo et al (2006) [2] for aerospace applications. D. kwon *et al* (2009) [3] investigated a consumable-free method of operating a high temperature superconducting (HTS) coil in space. The HTS wire resides inside a cryogenic heat pipe which is used for isothermalization. S. samad *et al* (2006) [4] developed an extremely light stainless steel heat pipe of 0.1mm wall thickness and 5mm diameter to transport heat from the liquid hydrogen/deuterium target to the cooling machine.

S. samad *et al* (2005) [5] constructed a long gravity-assisted heat pipe. Deuterium (D2) material is used as a heat transport medium and high heat transfer is achieved by convection. This design drastically reduces the weight of the system.

A. Jiao *et al* (2009) [6] developed and experimented oscillating heat pipe. Y. Zhao et al (2011) [8] worked on loop heat pipe with improved condenser structure, which reduces flow resistance and increases cooling capacity of heat pipe. They achieved heat transfer capacity up to 41W with a limited temperature difference of 6 K across a 0.48 m transport distance. Q. Mo et al (2006) [9] also worked on loop heat pipe.

M. Bary et al (2005) [10] investigated effects of the operating temperature and the heat loads on the effective thermal conductivity and the liquid mass in the heat pipe. M. Bary et al (2009) [11] has developed gravity assisted Gold coated heat pipe and tested to cool a liquid hydrogen target for external beam experiments at COSY.

K. Natsume et al (2011) [12] developed oscillating heat pipe for conduction cooling of superconducting magnets with working fluids Nitrogen, Neon and Hydrogen in the operating temperatures range of are 67–91 K, 26–34 K and 17–27 K, respectively. The estimated effective thermal conductivities from the measurement data of the OHP were higher than one of the solids such as copper at low temperature.

G. El-Awadi et al (2009) [13] experimented on very lightweight, thin liquid hydrogen/deuterium heat pipe used in the Time of Flight (TOF) spectrometer at the COSY accelerator facility.

S. Kumar et al (2012) [14] experimentally investigated axial grooved cryogenic heat pipe at *national* level and proved that heat transfer through heat pipe is 2.9 times that of solid conduction at 100 K.

V. Working of Heat pipe

The basic heat pipe is a closed container which contains a capillary wick structure and a small amount of working fluid which is saturated at operating conditions. The heat pipe employs a boiling-condensing cycle and the capillary wick pumps the condensate to the evaporator.

The vapor pressure drop between the evaporator and the condenser is very small and therefore, the boiling-condensing cycle is essentially an isothermal process. Furthermore, the temperature losses between the heat source and the vapor and between the vapor and the heat sink can be made small by proper design. Therefore, one feature of the heat pipe is that it can be designed to transport heat between the heat source and the heat sink with very small temperature drop.

The capillary pumping head is derived from a difference in the radii of curvature of the fluid surfaces in the capillary in the evaporator and condenser wick sections. In order for the available capillary pumping head to be able to provide adequate circulation of the working fluid, it must be sufficient to overcome the viscous and dynamic losses of the system and it must compensate for adverse gravity effects.

Capillary pumping heads are normally small when compared to the pumping heads available in dynamic systems. Therefore, certain restrictions must be imposed on the application of heat pipes in gravity environments.

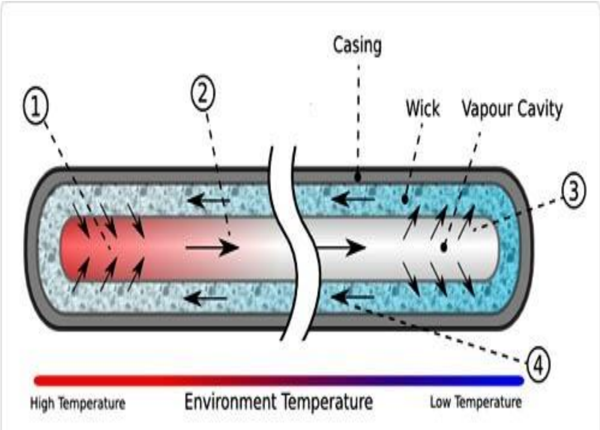

Fig. 1 Working of Heat pipe

VI. GENERAL PARAMETERS AFFECTING WORKING OF HEAT PIPE

Performance of heat pipe is affected by number of parameters. Some of the parameters are discussed here.

Effect of heat load on the effective thermal conductivity of heat pipe

Figure 2 shows the effective thermal conductivity (which shows the ability to transfer the heat with very small temperature difference) Keff of the hydrogen 200-cm, 7 mm diameter hydrogen heat pipe-target system as a function of the heat load for different condenser temperatures. The experimental results show that Keff increases with increasing heat load and with decreasing condenser temperature. The highest effective thermal conductivity is 1558 W/ cm K [10].

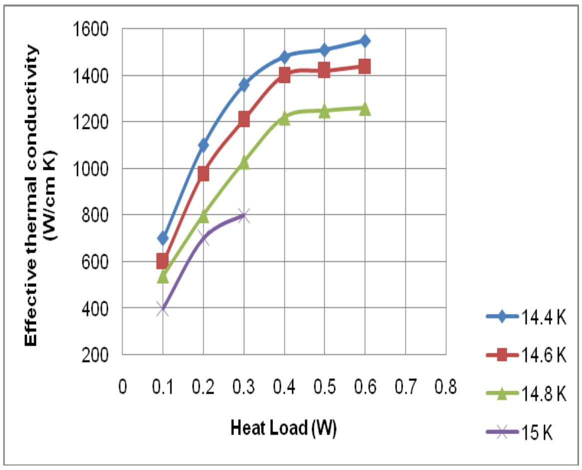

Fig. 2 Effect of Heat load on effective thermal conductivity of heat pipe

Effect of heat load and isolation on the temperature difference between the ends of heat pipes

The temperature difference ΔT between the external surface of the evaporator and the external surface of the condenser of the 5 mm diameter heat pipe–target system is measured as a function of the applied heat load on the evaporator at different condenser temperatures. Figure 3 shows the measured temperature difference between condenser and evaporator (ΔT) for different applied heat loads at the evaporator for different condenser temperatures in steady-state operating conditions with and without super isolation(i.e. involve several layers of insulation). ΔT increases with increasing the applied heat load at the same condenser temperature, increases with increasing condenser temperature for the same applied heat load (due to the reduction of the heat pipe thermal conductivity), and increases without using super isolation at the same condenser temperature and applied heat load (due to the increased radiation heat load on the heat pipe) [11].

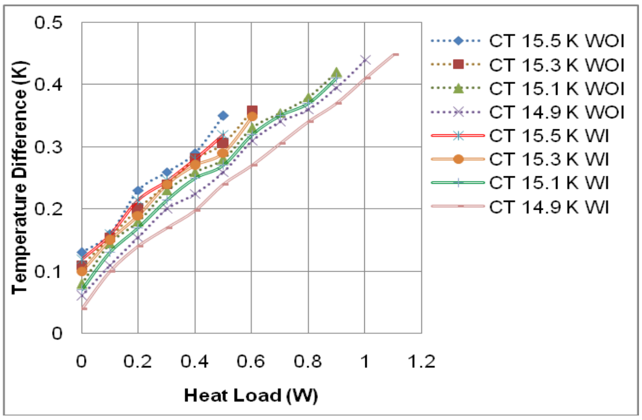

Fig. 3 Effect of heat load and isolation on the temperature difference between ends of heat pipes.

Effect of different working fluids & wick structure on temperature difference between the ends of heat pipes

The variation of the temperature difference between the condenser and evaporator ends of different heat pipes and copper rod with heat load is shown in Figure 4. An experiment was performed on the heat pipe without any working fluid (i.e., evacuated). During this experiment the fill line (through which working fluid is filled in to pipe) was kept open and thus the heat pipe was evacuated, and heat load of 0.54 W was applied. Now, as the heat pipe is empty, all the applied heat would be transported to the condenser section by only solid conduction. In this case the measured temperature difference between the condenser and evaporator ends is 101 K. On the other hand, with the heat pipe filled with working fluid, for the same heat load, the measured temperature differences are 3 K, 5 K and 9 K for different heat pipes. This clearly demonstrates the effectiveness of the heat pipes. For higher heat load, heat pipe with trapezoidal groove & oxygen can transfer the heat with least temperature difference compared to other heat pipes [15].

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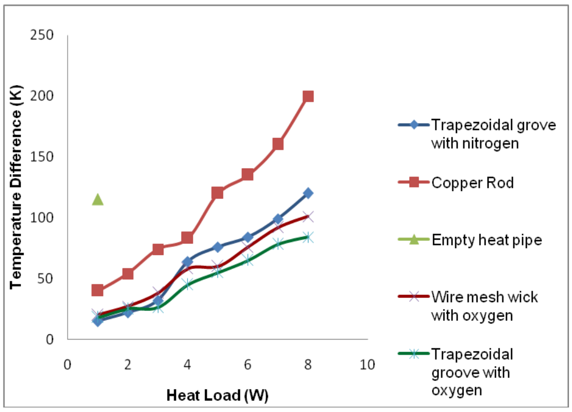

Fig. 4 Effect of different working fluids & wick structure on temperature difference between the ends of heat pipes

Effect of tilt angle and mashes of wick structure on the heat transfer capability of heat pipe

As shown in figure 5 with increase in tilt angle from 0 to 45°, the heat transport capability considerably increases. With further increases in tilt angle to 90°, the heat transport capability increases further but the increment is not considerable.

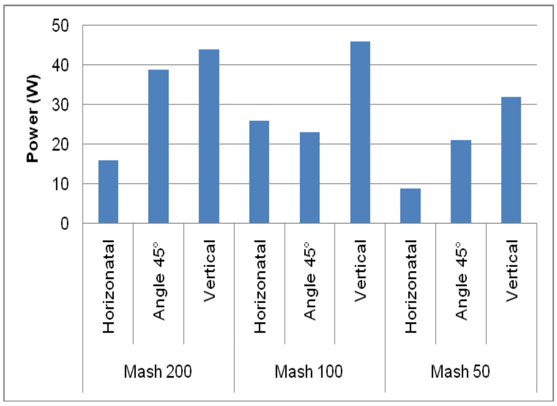

Fig. 5 Effect of tilt angle and mashes of wick structure on the heat transfer capability of heat pipe

Graph also states that optimum performance is achieved with wick structure having 100 mashes compared to 50 & 200 mashes. With decrease in size of mesh, more capillary pressure is generated but if the mesh size is reduced considerably then adverse effect of frictional resistance comes in to the picture [17].

VII. SUMMARY

The heat pipe is a very simple and very efficient heat transfer device. It can be considered a super thermal conductor that transmits heat by evaporation and condensation of a working fluid and which is several times higher than that by solid conductor. The performance of the heat pipe is affected by number of parameters like heat load, use of various working fluids, use of various wick structures, tilt angle etc. Through proper model, best operating conditions for different heat pipes can be identified and accordingly heat pipe can be designed and manufactured for different range of application.

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