CRYOGENIC HEAT PIPES – A REVIEW OF THE STATE OF THE ART

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Abstract: *Cryogenic heat pipe is one of the satellite thermal control device, which is used mainly for the thermal control of optical surfaces, infrared scanning systems, or large superconducting magnets in the space environment. Actually, researches are being conducted in including other applications of cryogenic heat pipes, such as the cooling of electronic devices, particularly in microgravity environments. The technology of cryogenic heat pipes is now under investigation on the Satellite Thermal Control Laboratory of the Federal University of Santa Catarina. This paper presents a review of the cryogenic heat pipes researches available in the literature. A review of ground testing and microgravity experiments is presented as well as their contributions.*

Keywords: Heat Pipe, Cryogenics, and Satellite Thermal Control.

1 INTRODUCTION

In the middle of 1996, the Satellite Thermal Control Laboratory (NCTS/UFSC) began the development of a Passive Cryogenic Radiator (Couto, 1999), in the context of the Uniespaço Program, funded by the Brazilian Space Agency (AEB). Passive Cryogenic Radiators are used to cool down equipments, such as infrared sensors and CCD cameras, to the cryogenic temperature levels required for their optimum operation. But, in the most of the satellite designs, the infrared sensor (or the equipment to be cooled down) cannot be placed near the cryogenic radiator. Usually, cryogenic heat pipes are used to transfer the heat from these equipments to the cryogenic radiator (Brand & Schlitt, 1997, Voyer et al., 1997, Wright, 1980, Wright & Pence, 1973 and Zelenov et al., 1992). In addition, cryogenic heat pipes are used on the thermal control of focal plans of infrared sensors (Voyer et al., 1997), X-ray telescopes (Abrosimov et al., 1992), cooling of superconducting magnets (Ishigohka et al., 1999), among others.

The design of cryogenic heat pipes is now under investigation at the NCTS/UFSC, in order to develop a complete passive cryogenic satellite thermal control device for the payload of the Brazilian satellites, described at the Brazilian Policy for Space Activities (PNAE). The objective of the present work is to present a review of the state of the art of cryogenic heat pipes available in the literature. The starting point is the work presented by Peterson and Campagna (1987). They presented a review on cryogenic heat pipes, up to 1987. The problems they identified related to cryogenic heat pipes are: mathematical modeling of the startup phenomena, particular behavior of the thermophysical properties of cryogenic working fluids, and storage of cryogenic heat pipes in 1*g* for ground tests.

2 REVIEW OF THE STATE OF THE ART OF CRYOGENIC HEAT PIPES

Cryogenic heat pipes usually operates at temperatures below 200 K, which makes this device very sensitive to heat loads from the surrounding environment (satellite structure, for example). Small heat loads applied to the heat pipe evaporator can produce a large temperature variation. This is because cryogenic working fluids present a significant change of the thermophysical properties for small temperature variations. Therefore, the operational temperature range of cryogenic heat pipes is quite narrow, and usually lies between the critical point and the triple point (Chi & Cygnarowicz, 1970). Figure 1 (adapted from Gilmore, 1994) presents the operating temperature ranges for some cryogenic working fluids.

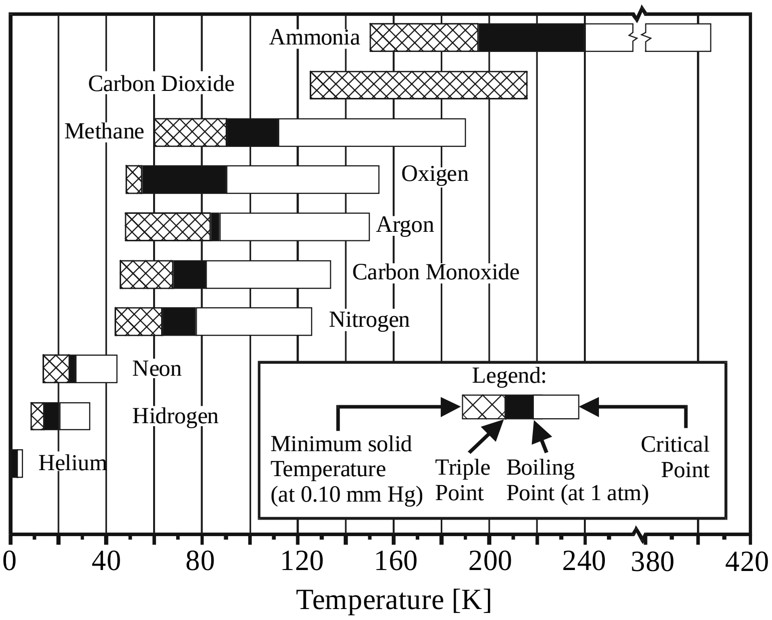

Figure 1 – Operating temperature ranges for cryogenic working fluids (Gilmore, 1994).

The most common working fluids used in cryogenic heat pipes are: helium, argon, nitrogen, oxygen, methane, ethane, Freon and super fluid helium 2 and 4. These fluids present some problems, such as: low surface tension, low thermal conductivity, low latent heat of vaporization, high viscosity and narrow temperature range. The surface tension and thermal conductivity for some cryogenic fluids are presented in Figs. 2 and 3. In addition, the compatibility of the working fluid and the container must be taken into account to prevent the non-condensable gas formation inside the heat pipe. Non-condensable gas can block part of the condenser, increasing the heat pipe operational temperature. Voyer et al. (1997) observed the formation of non-condensable gas in an aluminum/ammonia heat pipe, decreasing in 37 mm the length of the condenser (774 mm). Van Oost (1997) observed the formation of non-condensable gas in a stainless steel/methane and stainless steel/ethane heat pipe, affecting 1 % of the heat pipe length. Stainless steel/Nitrogen and stainless steel/oxygen presented no generation of non-condensable gas.

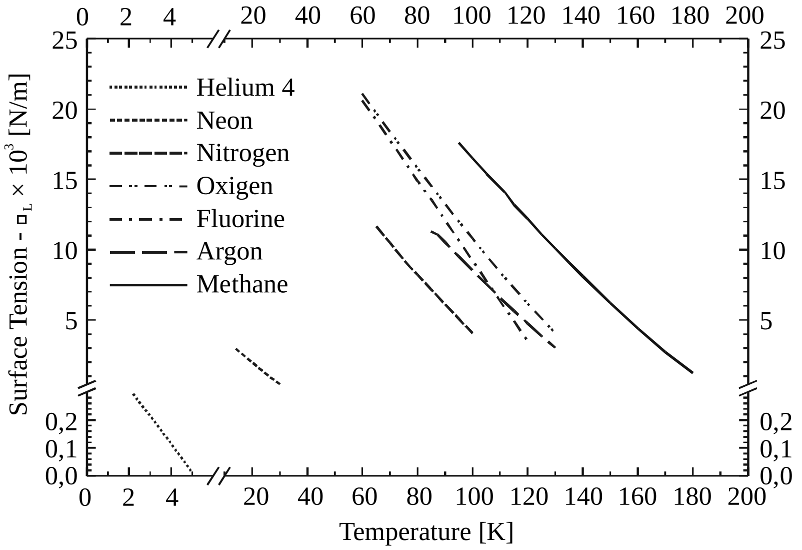

Figure 2 – Surface tension of cryogenic liquids at saturation point (Barron, 1985).

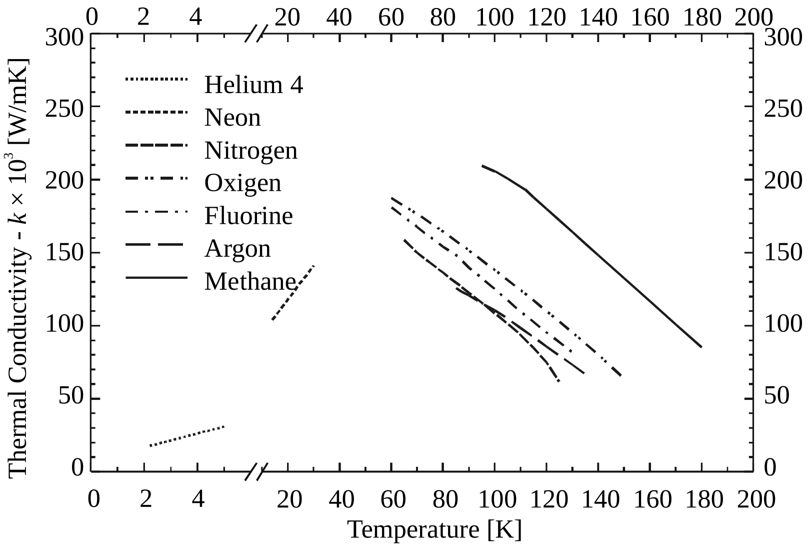

Figure 3 – Thermal conductivity of cryogenic liquids at saturation point (Barron, 1985).

Groll et al. (1986) and Röster et al. (1986) presented an experimental and analytical investigation about the fluid charge of a stainless steel/methane diode heat pipe. It was shown that for fluid excess the overall heat transfer coefficient decreases, and a liquid deficiency in the wick structure of the heat pipe might cause serious performance degradation or a complete failure. Experimental tests were carried out between 95 K and 175 K, with a maximum heat load of 12 W at the evaporator. These authors also presented a relation between the fluid charge coefficient (defined as the ratio between the total liquid volume and the liquid volume in the wick, $N \equiv V_l/V_w$) and operating temperature of the heat pipe.

Rosenfeld et al. (1995) presented a study on the supercritical start-up of a porous metal wick titanium/nitrogen heat pipe. The test was performed during mission STS-62 of the Space Shuttle (March 1994). This heat pipe reached a non-operational steady state thermal condition during microgravity tests. Only 30 % of the heat pipe length (condenser) cooled below the nitrogen critical point. In ground tests, the titanium/nitrogen heat pipe reached the start-up successfully. The authors concluded that the thermal conduction of the titanium/nitrogen heat pipe was insufficient to reduce its internal pressure below the critical pressure of nitrogen, under microgravity start-up. The successful start-up during ground tests was concluded to be due to enhanced thermal transport due to gravity-assisted convection/liquid collection effects. Figure 4, obtained from Barron (1985) presents the thermal conductivity of some solids at low/cryogenic temperatures.

Brennan et al. (1993) presents a microgravity experiment for two different aluminum/oxygen axially grooved heat pipes. The experiment, called CRYOHP, flown aboard the STS-53 space shuttle mission, in December 1992. Reliable start-ups in flight of the two heat pipes were performed, but slower than in ground tests. This shows that ground tests for transient start-up tend to be optimistic relative to the microgravity start-up behavior. The maximum transport capability of the two tested heat pipes are 5 W @ 88 K and 22 W @ 95 K.

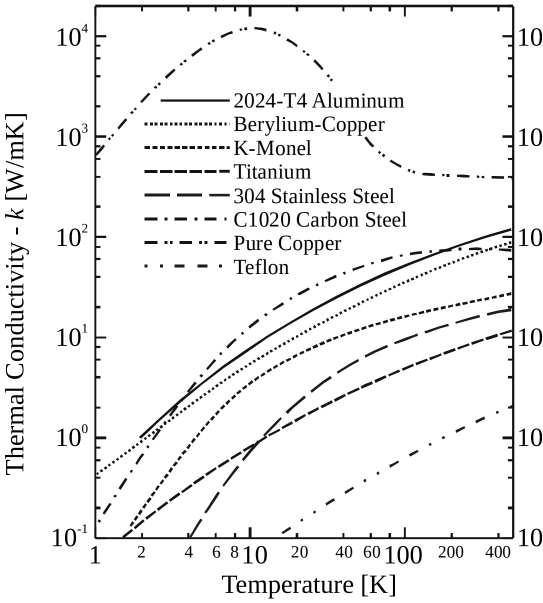

Figure 4 – Thermal conductivity of materials at low/cryogenic temperatures (Barron, 1985).

Cryogenic heat pipes are typically subjected to boiling or capillary limitations. The type of wicking structure utilized affects both limits. The most common wick structure used in cryogenic heat pipes are the metal fiber wick (Abrosimov et al., 1992, Gonchakov et al., 1999, Konev et al., 1999, Rosenfeld, 1995, Semena & Levterov, 1978, Van Oost, 1997, Zelenkov et al., 1992), and channel type wick (Alario et al., 1978, Brennan et al., 1993, Harwell et al., 1973, Ochterbeck et al., 1995, Olden et al., 2000, Voyer et al., 1997 and Yan & Ochterbeck, 1999). The metal fiber wick can provide a higher capillary pumping and a lower thermal conductivity, while, in the other hand, the channel type wick can provide a higher thermal conductivity and a low capillary pumping. A mixed wick structure, composed by metal screen covering axial grooves can provide a high heat transport capability before reaching the capillary limitation (Peterson & Campagna, 1987).

Rosenfeld et al. (1995) proposed a porous metal cable wick composed by six porous metal cable wick sections as the capillary structure. The porous metal cables were held in contact with the interior heat pipe wall by a full-length centered spring. This configuration was selected to provide higher adverse tilts capability than axially grooved cryogenic heat pipe design, a feature that allows easier ground testing.

The most challenging modeling problem in cryogenic heat pipes is the startup phenomena modeling. Differently from low and medium temperatures heat pipes, cryogenic heat pipes starts up from a supercritical state. The entire heat pipe must be cooled down before nominal operation begins. Cowell (1976 and 1977), Yan & Ochterbeck (1999), Ochterbeck et al. (1995), Rosenfeld et al. (1995) and Brennan et al. (1993) discussed the start-up process of cryogenic heat pipes. This process can be summarized in two stages, as follows:

1st Stage: In the first stage, the heat pipe is cooled by pure heat conduction, and the vapor temperature at the condenser and pressure is greater than the critical temperature and pressure ($T_{cond} > T_{crit}$, or $P > P_{crit}$). The cooling effect resulting from the condenser heat rejection is not immediately propagated through the heat pipe, but it is confined to a region extending from the condenser to some penetration depth δ. Beyond δ the temperature gradient is zero. When penetration depth equals the heat pipe length, the cooling effect of the condenser has propagated over the entire heat pipe. Then the temperature of the entire heat pipe decreases.

2nd Stage: In the second stage, the vapor temperature and pressure are lower than the critical temperature and pressure, and the heat conducted to the advancing liquid front cools the heat pipe ($T_{cond} < T_{crit}$, or $P < P_{crit}$). When the condenser temperature is lower than the critical temperature and the internal pressure is lower than the critical point, the vapor begins to condense in the condenser section. The advancing liquid layer is subjected to a capillary driving force that is induced by surface tension and opposed by the wall shear stress, an it advances with an average velocity that will vary with respect to the length of the liquid layer. If the liquid layer is less than the condenser length, the rewetting process is restricted to the condenser. The heat transfer in the remaining sections of the heat pipe is still pure heat conduction. When the liquid front reaches the interface between the condenser and the adiabatic section, two possible cases exists:

- *1st case*: If the liquid average velocity in the condenser is not enough to provide cooling to the dry region, the liquid front will stagnate and will not advance immediately. Thus, the wall temperature in the dry region remains independent of the rewetting.
- *2nd case*: With increasing time, the liquid average velocity in the condenser increases, because the liquid temperature continues to decrease with time, which results in the surface tension increasing, and thus, increasing the capillary driving force. Additionally, the heat flux from the adiabatic section to the condenser decreases, and the latent heat of vaporization increases. Thus, the liquid front eventually will advance again, until the heat pipe reaches its operational steady state.

This process was modeled by Yan & Ochterbeck (1999) and compared with the microgravity experimental data presented by Brennan et al. (1993). The model compared well with microgravity data, but, as it did not includes the effects of added hydrostatic height, which helps the start-up process in 1-*g* environment.

3 FINAL CONSIDERATIONS

Since the last review of cryogenic heat pipes activities (Peterson & Campagna, 1987), many experiments and operational devices were tested under microgravity environment. These experiments provided important data for future designs of cryogenic heat pipes.

By correctly choosing the working fluid and the container material can prevent the formation of non-condensable gas in the heat pipe. The problem of the low surface tension of the cryogenic working fluids can be overcame by correct choosing the wick structure of the heat pipe.

As the new trends for the space research next 20 years (Fisher, 1998) includes reduction of costs of the space missions; increase of the concentration of thermal dissipation, due to the constant reduction of the size of the space vehicles and to the miniaturization of electronic systems; increasing requirements of cooling systems at cryogenic levels of temperature with long operational life for interplanetary missions and constant growth of the electric potency installed in satellites, new experimental and analytical studies will be required for the near future. Models including effects of gravitational forces will give insight of the start-up phenomena to heat pipes subjected to planetary gravitational field.

Last, but not least important, the constant development of some present-day applications may require cryogenic heat pipes for controlling temperature/cooling in the near future. Examples of such applications are (Barron, 1985):

- Studies in high-energy physics: The hydrogen bubble chamber uses liquid hydrogen in the detection and study of high-energy particles produced in large particle accelerators. Actually, cryogenic heat pipes are used in the cooling of space telescopes;
- Electronics: sensitive microwave amplifiers are cooled to liquid nitrogen temperatures so that thermal vibration of the atoms of the amplifier element does not seriously interfere with absorption and emission of microwave energy. This equipment is used in missile detectors, in radio astronomy, and in space communication systems. Cryogenic heat pipes can be used in the thermal control of such devices;
- Mechanical design: By utilizing the Meissner effect associated with superconductivity, practically zero friction bearings have been constructed. These bearings use a magnetic field as the lubricant instead of oil. Also, superconducting magnets have been used to levitate high-speed trains at speeds up to 500 km/h. Cryogenic heat pipes can be used on the cooling of these magnets (Blumenfeld et al., 1999, and Mord & Snyder, 1992);
- Space simulation and high vacuum technology: To produce a vacuum that approaches that of outer space (from 10^{-12} torr to 10^{-14} torr), one of the more effective methods involves low temperatures. Cryopumping, or freezing out the residual gases, is used to provide the ultrahigh vacuum required in space simulation chambers for space propulsion systems. The cold of deep space is simulated by cooling a shroud within the environmental chamber by means of liquid nitrogen. Cryogenic heat pipes can be used to remove the heat form the chamber to the cryopump, providing a low/null vibration simulation chamber;
- Biological and medical applications: Liquid nitrogen cooled containers are used to preserve whole blood, tissue, bone marrow, and animal semen for long period of time. Cryogenic surgery (Hamilton & Hu, 1993) has been used for the treatment of Parkinson’s decease, eye surgery, and treatment of various lesions. This surgical procedures has many advantages over conventional surgery in several applications;
- Food processing: Freezing as a means of preserving food was used as far back as 1840. Today, frozen foods are prepared by placing cartoons on a conveyor belt and moving the belt through a liquid nitrogen bath or gaseous nitrogen cooled tunnel. Initial contact with liquid nitrogen freezes all exposed surfaces and seal in flavor and aroma. The cryogenic process requires about 7 minutes compared to 30 to 50 minutes required by conventional methods. Liquid nitrogen has also been used as the refrigerant in frozen trucks and railway cars;

These are a few of the areas involving cryogenic heat pipes engineering – a field in which new developments are continually being made.

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