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**CRYOGENIC LOOP HEAT PIPES FOR THE COOLING
OF SMALL PARTICLE DETECTORS AT CERN**

H. Pereira, F. Haug, P. Silva, J. Wu, T. Koettig

Abstract

The loop heat pipe (LHP) is among the most effective heat transfer elements. Its principle is based on a continuous evaporation/condensation process and its passive nature does not require any mechanical devices such as pumps to circulate the cooling agent. Instead a porous wick structure in the evaporator provides the capillary pumping forces to drive the fluid [1]. Cryogenic LHP are investigated as potential candidates for the cooling of future small-scale particle detectors and upgrades of existing ones. A large spectrum of cryogenic temperatures can be covered by choosing appropriate working fluids. For high luminosity upgrades of existing experiments installed at the Large Hadron Collider (LHC) (TOTEM) and planned ones (FP420) [2-3] being in the design phase, radiation-hard solutions are studied with noble gases as working fluids to limit the radiolysis effect on molecules detrimental to the functioning of the LHP. The installation compactness requirement of experiments such as the CAST frame-store CCD detector cooling system impels also the design of a compact shaped LHP [4]. This paper reports on the design and experimental results of a general purpose LHP for temperatures as low as 110 K, for which the performances were measured using a Gifford-McMahon (GM) cooler as the cold source, combination envisaged for the cooling of future particle detectors..

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ABSTRACT

The loop heat pipe (LHP) is among the most effective heat transfer elements. Its principle is based on a continuous evaporation/condensation process and its passive nature does not require any mechanical devices such as pumps to circulate the cooling agent. Instead a porous wick structure in the evaporator provides the capillary pumping forces to drive the fluid [1]. Cryogenic LHP are investigated as potential candidates for the cooling of future small-scale particle detectors and upgrades of existing ones. A large spectrum of cryogenic temperatures can be covered by choosing appropriate working fluids. For high luminosity upgrades of existing experiments installed at the Large Hadron Collider (LHC) (TOTEM) and planned ones (FP420) [2-3] being in the design phase, radiation-hard solutions are studied with noble gases as working fluids to limit the radiolysis effect on molecules detrimental to the functioning of the LHP. The installation compactness requirement of experiments such as the CAST frame-store CCD detector cooling system impels also the design of a compact shaped LHP [4]. This paper reports on the design and experimental results of a general purpose LHP for temperatures as low as 110 K, for which the performances were measured using a Gifford-McMahon (GM) cooler as the cold source, combination envisaged for the cooling of future particle detectors.

KEYWORDS: Loop heat pipe, particle detector cooling, radiation-hard

INTRODUCTION

At CERN LHP and heat pipes have been identified to be excellent technological choices for the cooling of some small particle detectors. The envisaged high luminosity upgrade of the LHC will also require an upgrade of its detectors with adapted or new cooling schemes. For the installed TOTEM experiment (Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC) we propose a largely passive cooling system based on loop heat pipes and cryocoolers. TOTEM measures scattered proton particles with low-temperature silicon micro-tracking strips at very small angles downstream from the interaction point of the CMS (Compact Muon Solenoid) detector in the vacuum beam pipe at distances of up to 240 m. FP420 (proton tagging detectors at 420m from the interaction points of the ATLAS and CMS experiments at the LHC) is a proposed experiment of similar technical lay-out. In both cases radiation hard solutions have to be envisaged as the LHC collider at full luminosity produces a hostile radiation

environment with some 100 MGy/year [2]. LHP and heat pipes can be designed to avoid the detrimental radiolysis by this strong radiation environment by choosing appropriate working fluids and structure materials.

For a CERN astroparticle physics experiment “CAST” (CERN Axion Solar Telescope) we have started the design of a cooling system by applying heat pipes or loop heat pipes. CAST aims to detect hypothetical axion-like particles, with a two-photon interaction, produced in the Sun by the Primakoff process [5]. The CAST frame-store CCD detector cooling system must be capable of maintaining the CCD chip at a temperature between 140 K and 230 K while maintaining the heat radiation shield and gas cold-trap at 100 K [4]. This cooling system has highly geometrical constraints forcing it to be compact and supple. The remarkable design flexibility of the LHP to accommodate specific design requirements comes as an advantage in this case.

Potential working fluids and their useful temperature range have been reviewed (FIGURE 1). The LHP is modular which permits a person to easily change and modify components of its structure and the experimental set-up is flexible allowing changing fluids. The studies performed are of generic nature aiming to demonstrate the advantages of a passive cooling device. We have used argon, krypton and propane as working fluid and covered temperature ranges from ambient to 110 K. The laboratory set-up, the LHP designed and the experimental results are presented.

EXPERIMENTAL SETUP

The LHP measures 350 mm in length from the heat sink to the heat source. The evaporator external area where the heat load is input conforms to an 18-mm diameter cylinder with 30-mm length. The sintered porous structure inside the evaporator which provides the pumping effect for the working fluid is a 5- μ m pore size stainless steel hollow cylinder (10-mm diameter, 20-mm length and 3.5-mm wall thickness). The condenser and the transport vapor and liquid lines are 4 mm inner diameter tubes. Both evaporator and condenser are copper to ensure good thermal conduction between the heat sink and the heat source, respectively. The compensation chamber and the transport lines are made from stainless steel.

FIGURE 1. Operating temperature ranges for noble gases and propane (triple point to critical point).

FIGURE 2. LHP experimental apparatus schematic and dimensions.

A test station has been designed and built [6] to measure the heat transfer performance of the LHP. FIGURE 2 shows a schematic diagram of the apparatus. To charge the LHP the working fluid storage bottle is connected via a buffer volume to determine the filling mass quantity.

The LHP is installed inside a vacuum vessel to reduce convective and conductive heat transfer with the environment. A stack of super-insulation foils covers the LHP to minimize thermal radiation heat loads.

The heat sink is provided by an industrially produced Gifford-McMahon manufactured by Cryomech [7] – model AL25. It is specified for a cooling capacity of 27 W at 120 K and a minimum temperature of 25 K without load. A connecting copper block provides mechanical support and heat contact for the LHP condenser line. MINCO [8] thermal foil heaters are glued around the LHP evaporator section to simulate the heat load. Several PT100 temperature sensors are placed along the LHP. The read-out of the temperatures is done using a system based on a DAQ-CARD and LabView data acquisition software.

The test station system is designed to allow for easy change of inclination angle. The vertical direction is in accordance with gravity, 0° corresponds to a configuration in which the evaporator is below the condenser, and on the horizontal direction the evaporator and condenser are on the same horizontal plane (90°).

RESULTS

Working Fluid Mass

The optimal working fluid filling mass can be estimated by calculating the necessary fluid inventory such that the compensation chamber is able to store the variations in liquid volume between the cold and hot cases of the LHP operation. The working fluid mass affects the performance characteristics of the LHP and its start-up behavior [9]. However, an experimental approach to find the optimal fill quantity proved to be the more appropriate solution in this case.

With argon as the working fluid, the LHP was filled with in increments from 2 to 29 g, and its heat transfer performance tested for each fill. The ideal filling quantity was determined to be 20 g where the highest performance could be observed. The heat transfer

FIGURE 3. Evaporator temperature for increasing heat loads of an argon-filled LHP with different working fluid masses. Vertical position - condenser above evaporator - with heat sink at 110 K.

is only limited by the upper limit of the heat sink cooling power of the GM cooler at 110 K. The same principle was applied for krypton and the optimal LHP filling mass was found to be 35 g while for propane we found 9 g.

FIGURE 3 shows the argon-filled LHP evaporator temperature for different working fluid masses as a function of the heat load at vertical position for a heat sink temperature of 110 K which was kept constant. For quantities of filling mass up to 15 g the LHP is only able to transfer 10 W since the lack of mass leads to a boil out at the evaporator. For a mass well above 20 g the condenser is the limiting factor which is partially flushed and cannot provide enough heat transfer surface. Hence, the LHP operating temperature of the evaporator rises significantly.

Start-up and Steady-State Heat Transfer

The LHP did not pose any start-up problems in transferring heat after a few minutes when applying only 1 W without further assistance or need to impose start-up power. Once the temperature difference between the compensation chamber and the evaporator is large enough to build up a pressure difference required to initiate circulation the LHP starts to operate [10].

FIGURE 4 shows a typical start-up curve which demonstrates the capability of the LHP constructed to reach steady-state and transfer heat. When evaporation of the working fluid sets in, the wick pumps liquid with increasing mass flow. The successful start-up can be easily viewed in observing the temperature in the vapor line which rapidly increases and stabilizes. Due to this mass flow increase the temperature in the evaporator slightly decreases until it is stabilized due to the subcooled liquid pumped from the condenser.

FIGURE 4. LHP temperature evolution at startup and during heat load increase for a propane-filled LHP at vertical position with heat sink temperature of 210 K.

Inclination Angle

The LHP was filled with the respective optimal mass of argon, krypton and propane. The heat transfer performance for different inclination angles, from 0° (gravity assisted with the condenser above the evaporator) to 90° (horizontal plane) was then determined.

As expected the LHP performance changes in response to a gravitational adversity but does not fail totally in response to unfavorable conditions. Without adequate subcooling at larger angles the LHP continues to transfer heat but the evaporator operating temperature rises significantly, up to 10 K for 75° inclination angle and 25 K for a horizontal position in the case of argon as working fluid (FIGURE 5).

At angles above 75° the increase in the evaporator temperature is due to a specific orientation of the particular design of the compensation chamber. For these angles, the liquid supply coming from the condenser is not flowing directly into the evaporator core, as it first has to fill the compensation chamber volume before reaching the primary wick. This leads to a lower performance of the LHP as expected. A simple rotation of the compensation chamber along its axis in the overall assembly of the LHP should solve this problem and will be done in the next test campaign.

The inability to perform at angles above 90° is once again due to the very specific design of the compensation chamber. This volume should have a clean flow path between the subcooled liquid coming from the condenser and the evaporator core to provide reliable operation in transient modes. Above 90° the lack of gravity assistance and of a secondary wick structure do not allow for the fluid to be pulled up to the evaporator core and hence prime the primary wick structure thus resulting in a working failure.

FIGURE 5. Evaporator temperature for increasing heat loads of an argon-filled LHP with different inclination angles. Working fluid mass 20 g, heat sink at 110 K.

FIGURE 6. Evaporator temperature for increasing heat loads of a krypton-filled LHP with different inclination angles. Working fluid mass of 35 g, heat sink at 150 K.

The LHP filled with argon is capable of transferring 20 W from 0° to 75° inclination angle and about 10 W at 90° within acceptable temperature differences between the evaporator and the condenser (FIGURE 5).

Filled with krypton the LHP is able to transfer up to 25W up to 75° without a large temperature gradient between the heat source and cold source (FIGURE 6). At 90°, as for the argon, the temperature gradient between evaporator and the cold sink are high.

When filled with propane the LHP transfers 30 W up to 60° inclination angles. For more than 10 W heat load at 75° the evaporator temperature increases considerably (FIGURE 7).

FIGURE 7. Evaporator temperature for increasing heat loads of a propane-filled LHP with different inclination angles. Working fluid mass of 9 g, heat sink at 210 K.

FIGURE 8. Evaporator temperature for increasing heat loads for different working fluids at different heat sink working temperatures (argon at 110 K, krypton at 150 K and propane at 210 K). Vertical position .

It was verified that fluids with a higher surface tension are responsible for a lower LHP heat transfer performance for higher inclination angles (75 and 90°). Such a phenomenon can be interpreted as resulting from the necessity of an increasing heating power in order to vaporize the liquid at the surface of the porous wick structure for increasing surface tension, leading to an increase in temperature of the evaporator for higher inclination angles.

Type of Working Fluid

FIGURE 8 shows the LHP evaporator temperature for different working fluids. The heat sink temperatures were: argon 110 K, krypton 150 K and propane 210 K. The evaporator temperature for each fluid is close to constant with increasing heat load which demonstrates the good heat conductance of the LHP.

The LHP was able to transfer up to 20 W when filled with argon, 25 W when filled with krypton and 30 W when filled with propane in a gravity assisted orientation. The limitation of heat transfer in each case is only due to the limited cooling power of the GM cryocooler used to perform the tests.

CONCLUSIONS

The LHP was designed to be able to operate vertically (fully gravity assist) or under inclined positions. With some adaptations it can be applied where geometrical constraints and passive systems are an advantage to active ones and where radiation hard solutions are of importance. The LHP in this configuration can be used for any application where heat transfer is required between two points at the tested temperatures. The tested LHP was able to immediately start-up at inclinations from 0° to 90° without any auxiliary means. An initial small heating power supplied to the evaporator is sufficient. This makes the design very attractive with respect to LHP requiring auxiliary start-up systems. The LHP was designed for a 30 W heat transfer with propane as the working fluid, however, performances in excess of 30 W were measured. The limiting factor was the laboratory set-up with a GM cooler of insufficient performance, a problem that as to be solved for the envisaged future test campaigns. The compensation chamber of the LHP will be modified and a secondary wick will be implemented to explore the anti-gravity range with noble gases and propane.

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