Experimental investigation of vertical neon pulsating heat pipe for superconducting magnet cooling application

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Abstract. Pulsating heat pipes (PHPs) are two-phase flow, thermal transport carriers characterized by ease of fabrication, flexibility of compactness and variable heat transfer capability. Conventionally, cooling of superconducting magnets is realized by using cryogen cooling system. Cryogenic PHPs are emerging as the new-age economical alternative that can passively contribute in efficient transport of generated heat to active cryocoolers. Nevertheless, a number of challenges must be addressed to materialize this union. For this objective, a multi-purpose experimental test-rig has been developed which will allow different critical parameters of cryogenic PHPs to be investigated. The preliminary tests are conducted using neon as the working fluid. The PHP capillaries, made of SS304, have an outer diameter of 2.5 mm and a projected length of 400 mm with the adiabatic part having twice the length as compared to that in the condenser and evaporator. It consists of 20 parallel tubes forming a closed-loop and are tested in gravity-assisted environment. Employing the Sumitomo RDE-418D4 4K Cryocooler, the condenser temperature is controlled at the neon saturation temperature, around 27 K. The thermal performance of this cryogenic PHP is recorded at different evaporator heat load conditions. We report here the temperature evolution of PHP evaporator, and condenser as well as the pressure oscillations with time.

1. Introduction
Pulsating heat pipes (PHPs), also termed as oscillating heat pipes, are two-phase flow heat transport carriers constructed from serpentine-shaped capillary tubes having one end corresponding to fluid saturation condition (condenser), other end inducing a temperature difference (evaporator) and central thermally-redundant transportation section (adiabatic part). These are characterized by absence of wicks, unlike the conventional heat pipes, rendering a relative simplicity in terms of fabrication and flexibility of size. Depending on the choice of working fluid and operating conditions, PHPs offer variable heat transfer capability. This heat transfer device was first patented by Akachi [1] in 1990 but employing cryogens as the working fluid has attracted attention recently in the last few years [2, 3].

Cryogenic PHPs can provide excellent solutions for efficient transport of heat generated over a distance to an active cryocooler. One such interesting cryogenic application is in the cooling of superconducting magnets where the conventional technology can be replaced by cryogenic PHP [4, 5]. Nevertheless, materializing this feat requires in-depth investigation of the different aspects of cryogenic PHPs.

Different research groups across the world have contributed in investigation of nitrogen, neon, hydrogen, helium, argon and oxygen PHPs [4-11]. Here at DACM of CEA Paris-Saclay, experimental
tests on the world’s longest horizontal cryogenic PHPs with nitrogen and neon as the working fluids have been successfully conducted [10-14]. Continuing the comprehensive cryogenic PHP data generation, this work aims at contributing in the development of vertical neon PHP eventually planned for utilizing in upgradation of the superconducting magnet cooling technology. The following sections describe the neon PHP design parameters, the test-rig developed and the preliminary test results.

2. PHP design parameters
The most critical parameter in PHP design is the diameter of its capillary tubes. Conventionally, the choice is based on the dimensionless Bond number criteria defined as [15, 16],

$$Bo = \frac{g(\rho_l - \rho_v)D^2}{\sigma} \leq 4,$$

where, $$\rho_l$$ is the fluid saturation liquid density; $$\rho_v$$ is the fluid saturation vapor density; $$\sigma$$ is the fluid surface tension; $$D$$ is the PHP capillary tube inner diameter. It can be seen that the critical tube diameter is primarily governed by the two-phase working fluid properties. These properties, in turn, depend on the functional saturation conditions. In case of the commonly used cryogenic fluids, the critical tube diameter increases with decrease in saturation temperature, as graphically shown in Figure 1.

![Figure 1: Variation of critical tube diameter with saturation temperature for nitrogen, neon, hydrogen and helium based on Bond number criteria](image)

For developing a neon PHP, Figure 1 illustrates that it is supposedly operational for tube diameters below $$D_{crit} = 1.27$$ mm corresponding to saturation conditions at atmospheric pressure. Accordingly, capillary tubes made of stainless steel 316L having inner diameter of 1.0 mm ($$Bo = 2.5$$) and an outer diameter of 2.5 mm have been selected. The closed-loop neon PHP consists of 20 parallel tubes having a projected length of 400 mm with adiabatic part having twice the length (200 mm) as compared to that in the condenser (100 mm) and evaporator (100 mm). The PHP is fabricated in-house as a single-unit from nearly 10 m long capillary tube. The condenser and evaporator made from pure copper have overall dimensions of 210 mm × 120 mm × 10 mm.

3. Experiment test-rig
An experimental test-rig has been developed to test the thermal performance of neon PHP – schematic of which has been shown in Figure 2. The heat sink is the Sumitomo RDE-418D4 4K two-stage cryocooler while Kapton heaters attached to the PHP evaporator act as the heat source. The condenser is connected to the cryocooler 2nd stage whose temperature is maintained at the desired value by a temperature controller. Cernox™ thin film resistance temperature sensors measure the real-time condenser and evaporator temperature. The PHP, condenser and evaporator assembly is covered with multi-layer insulation to imbibe the cryogenic radiation heat load. Additionally, an aluminum radiation
shield – wrapped in multi-layer insulation as well – is attached to the cryocooler 1st stage assisting in radiative heat load inhibition. The cryostat is connected to a turbo-molecular pump to maintain high vacuum. A stainless steel feedthrough pipe facilitates the insertion of neon gas within the PHP. An absolute pressure transducer at the entry of feedthrough pipe indicates the PHP pressure.

Figure 2: Schematic of the neon PHP experimental set-up

The cryocooler is turned on once the cryostat vacuum is in the range of ~10^{-4} mbar. The condenser is observed to reach 27.1 K in approximately 8 hrs. Meanwhile, the dry-scroll pump is connected to the feedthrough pipe to pump out any impurities within the PHP capillaries. The quantity of the neon gas inserted essentially depends on the desired filling ratio (FR). Filling ratio is defined as the ratio of saturated liquid volume within the PHP to the total volume of PHP. This can be controlled by regulating the mass of neon gas that enters from the buffer. Therefore, buffer volume is filled with neon gas from the supply bottle up to a pre-determined pressure value. The dry-scroll pump valve is closed and the buffer volume is then kept connected to the feedthrough pipe until again a pre-set pressure has been obtained in the buffer volume. Based on the law of mass conservation, the actual FR can be evaluated using simple calculations [11]. As soon as the neon gas enters the PHP assembly, it begins to liquefy at the condenser and consequently enhances the cooling of adiabatic part and evaporator.

4. PHP performance
This section describes the thermal performance of neon PHP at two different filling ratios. However, prior to the PHP testing, it is necessary to characterize the cooling load of the cryocooler at liquid neon temperatures without any components attached.

4.1. Cooling load characterization of Sumitomo RDE-418D4 at 50 Hz
In order to map the Sumitomo RDE-418D4 cryocooler cooling load characteristics, a Kapton heater is attached at the 2nd stage and two Cernox™ thin film resistance temperature sensors are placed at the cryocooler 1st and 2nd stage respectively. The temperature variation in both the stages is recorded for different heat loads imposed at the 2nd stage and no load at the 1st stage. The performance plots mapped for 50 Hz power supply have been depicted in Figure 3.
Figure 3: Cooling load characterization of Sumitomo RDE-418D4 cryocooler at 50 Hz for heat load on 2nd stage only

4.2. Ne-PHP test run

After characterization of the cryocooler alone, the test-rig schematically shown in Figure 2 is assembled and the cool-down procedure as mentioned in Section 3 is followed. The experimental results for condenser temperature maintained at 27.1 K and two filling ratios of 20.9 % and 73.5 % have been presented here. At each FR, once the condenser, evaporator and adiabatic part reach homogenous thermal state, heat load is applied at evaporator to start the PHP. This heat load is applied in steps from 1 W to 19 W.

The temperature evolution of the PHP evaporator and condenser with time along with the pressure have been illustrated in Figure 4 and Figure 5 for FR = 20.9 % and FR = 73.5 % respectively. Initially, at no load condition and 27.1 K, the initial pressure measured in the PHP corresponds to the saturation pressure at 27.1 K thereby confirming the existence of saturation conditions within the PHP. With heat input at evaporator, the liquid neon in the evaporator vaporizes and rises to the condenser to be re-condensed. This commences the characteristic PHP liquid-vapor oscillatory behaviour which can be noticeably observed from the temperature and pressure periodic amplifications. For both the tested FR, as the evaporator heat load is scaled up, PHP pressure and condenser-evaporator temperature difference increases as the two-phase flow orientation shifts from liquid dominance to that of vapor. Moreover, not only the quantitative value but the amplitude of oscillations are also higher at higher heat loads.

Comparing the thermo-hydraulic performance for the two FR values (Figure 4 vs Figure 5), the PHP resorts to maintain higher condenser-evaporator temperature difference to transfer the same amount of heat load at FR = 73.5 % compared to FR = 20.9 %. Likewise, the PHP working pressure at FR = 73.5 % is more than that of FR = 20.9 % for identical evaporator heat loads. The liquid-vapor oscillations are observed to be more damped at smaller FR value and lower heat loads. However, at higher FR, frequency of the oscillations is observed to be prominent even at lower heat loads.

Typically at high heat loads, a dry-out of PHP is anticipated because the oscillations of the pressure and temperature grow increasingly impulsive. This could not be observed for the designed neon PHP since at 19 W we approach the cooling capacity limit of cryocooler (heat sink limit) for both the FR values.
5. Conclusions
A vertical neon pulsating heat pipe has been successfully fabricated and experimentally tested in this work. The PHP is fabricated as closed-loop single unit from approximately 10 m long stainless steel capillary tube having 1.0 mm inner diameter. The neon PHP is run at 27.1 K condenser temperature with two filling ratios of 20.9% and 73.5%. Experimental results reveal that the designed neon PHP has the ability to transport 18 W while maintaining the condenser and evaporator temperature difference of 4.4 K for FR 73.5% and 5.4 K for FR 20.9%.
6. References

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