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Thermal Study of a one-meter long Neon Cryogenic Pulsating Heat Pipe

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Abstract. Cryogenic Pulsating Heat Pipes (PHP) are excellent candidates for cooling superconducting magnets due to their lightness, simple configuration and thermal performance. Long cryogenic PHP using Neon as working fluid have been developed and are under consideration to be used as thermal links between a superconducting magnet (the hot source) and a cryocooler (the cold source) maintaining the latter out of the influence of the magnetic field. Tests in a horizontal 1 m long PHP composed of 36 parallel tubes have been performed. Using Neon as working fluid, the device shows high performance, even though the inner diameter of the tubes (1.5 mm) is larger than the critical diameter determined by the most commonly accepted criterion in the literature. During the tests, the condenser temperature was maintained at 27 K while the heat load was increased gradually at the evaporator part. The PHP was able to transfer a heat load of 50 W from the evaporator to the condenser with an equivalent thermal conductivity of 70 kW/mK.

1. Introduction

Invented by Akachi in the 90's [1], Pulsating (or Oscillating) Heat Pipes (PHP) are thermal links composed of a single capillary tube, arranged in many U-turns, connecting a heating part (evaporator) with a cooling part (condenser) (cf. Fig. 1). The fluid is close to saturation conditions and, due to the capillary dimensions of the tubing parts, liquid slugs and vapor plugs are distributed in an alternating pattern. Constant phase changes in the fluid causes variation in size of the slugs and plugs. This variation allows an oscillating flow to transfer the heat from the evaporator to the condenser.

Combined with a cryocooler as a cold source, cryogenic PHP are considered to be an efficient cooling solution for superconducting magnets as proposed in [2]. As references in the cryogenic field using Ne as working fluid, Mito et al. [3, 4] have tested a 160 mm long closed-loop PHP at different inclinations. It is composed of 10 parallel tubes with an inner diameter of 0.78 mm. Operating at temperatures between 26 and 32 K with a filling ratio between 16 and 95 %, the maximum equivalent thermal conductivity achieved was 8000 W/m.K. These authors also tested the same PHP configuration with an inner diameter of 1.58 mm. In this second case, the equivalent thermal conductivity was comprised between 6000 and 19000 W/m.K. Liang et al. [5] have tested a vertical twisted PHP of 0.6 m. With a liquid filling ratio of 30 %, the PHP attained an equivalent thermal conductivity between 3000 and 30000 W/m.K transferring 35.6 W from the evaporator to the condenser. Other authors have studied cryogenic PHP in focusing on the definition of the thermodynamic state of the fluid at different working conditions: the refrigerant is considered as locally superheated by [6, 7] in the evaporator part during dry-out phenomena;

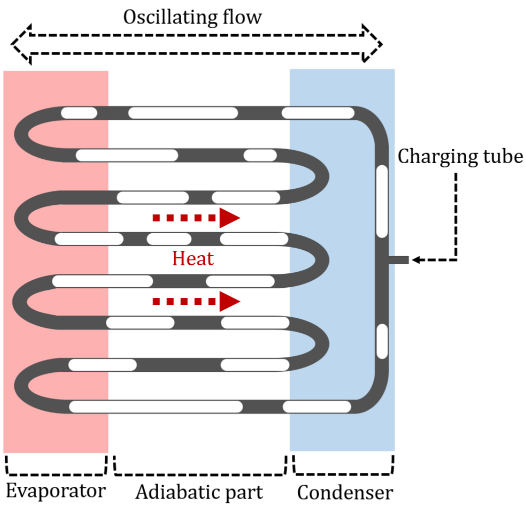

Figure 1. Structure of a PHP.

in the adiabatic part, liquid slugs are considered subcooled by [8] and vapor plugs at saturation conditions; and at low input power, when the vapor bubbles reach occasionally a temperature higher than the temperature of the evaporator, it is considered as a local adiabatic compression by [9, 8].

This paper reports the experimental study of a 1 m long horizontal closed-PHP composed of 36 parallel tubes with an inner diameter of 1.5 mm already tested by Bruce et al. in [8] with N_2. In this case, N_2 has been replaced by Ne as working fluid. The cryogenic facility is described in short and experimental results are presented.

2. The cryogenic PHP facility

Experimental setup The experimental test bench (presented in Fig. 2) is described with details in [8]. The closed-PHP tested is 1 m long including the adiabatic part, the condenser and the evaporator (330 mm long each one). The inner and outer diameters of the 36 stainless steel capillary tubes are 1.5 mm and 2 mm respectively. The evaporator and condenser parts are both made of two machined copper plates where the capillary tubes inside are tin soldered. A flexible heater is glued to the surface of the copper plate of the evaporator part and linked to a power supply. The cryocooler is thermally connected to the condenser with indium and flexible heaters are also glued to the surface of the cold head of the cryocooler to regulate its temperature with a controller. Sixteen sheets of superinsulation (MLI) are covering the experimental structure inside the cryostat, which is surrounded by a 80-90 K thermal shield with a vacuum close to 10^{-6} mbar. The cryogenic PHP is instrumented with several temperature and pressure sensors located as shown in Fig. 2. More details of the entire instrumentation system are given in [8].

Start-up conditions Tests are preformed using Ne as working fluid. At the beginning of every test, before inserting the fluid, the evaporator is heated with the power of 5 W from 27 K to 32 K while the temperature of the condenser is maintained at 27 K. Then, the PHP is filled to the desired filling ratio (considering the filling ratio as the amount of liquid inside the PHP divided by the volume of the PHP) using a buffer volume and a specific inlet gas system already described in [8].

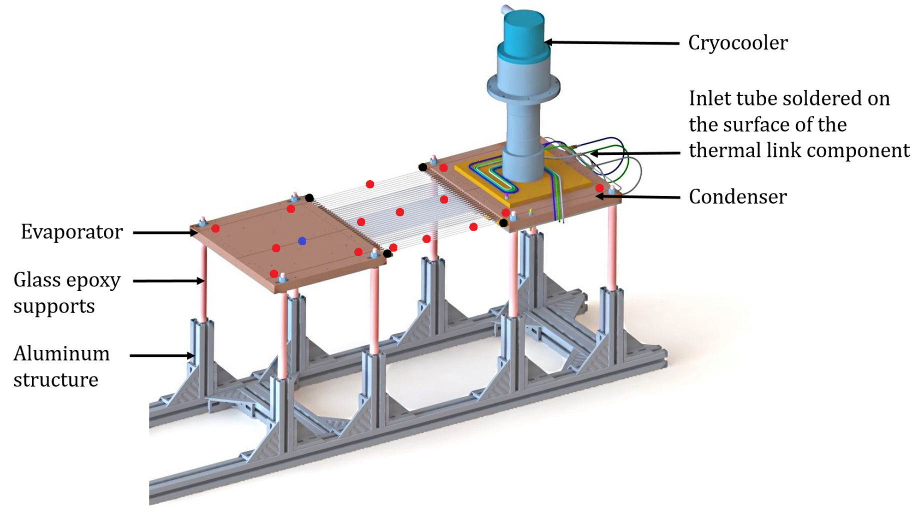

Figure 2. Illustration of the experimental facility and locations of the sensors. Types of sensors: ● Pt100 temperature sensor (error: ± 0.25 K), ● 1070 CX-SD Cernox temperature sensor (error: ± 16 mK) and ● Kulite pressure sensor (error: ± 0.01 % of the measurement).

3. Experimental results

Progressive heat load experiment An experiment has been performed increasing the input power of the heater fixed at the surface of the evaporator every 40-45 minutes, in 5-watts steps, from 5 to 55 W with a filling ratio of 28 % (± 3 %). Fig. 3 illustrates the evolution of the temperatures of the adiabatic section and the condenser and evaporator parts as well as the PHP pressure and its corresponding saturation temperature (calculated from pressure measurements using NIST Refprop Database) during the test. All the pressure sensors inside the PHP achieve almost the same mean value (less than 0.05 bar difference), due to this, only one pressure sensor is plotted. From this finding and according to the literature [9, 10], we make the assumption that the mean pressure is identical within the entire PHP and represents the pressure of the fluid at saturation conditions.

In the evaporator and condenser sections the temperature measurements correspond to the temperature of the copper plates. In the adiabatic section, according to [8], temperature sensors can identify with accuracy the real temperature of the fluid.

At the beginning of the experiment, the temperatures of the evaporator and condenser parts drop due to the insertion of the fluid which has been liquefied in the thermalized tube of the inlet system described in [8]. After 3 minutes, when the temperature of the evaporator is stable, the inlet valve of the PHP is closed, isolating the PHP from all the external volumes. Between 5 and 45 W, the condenser keeps stable at 27 K. The temperature of the evaporator and the pressure are also stable at every 5-watts step. A stable temperature in the evaporator indicates that the whole heat load is being transferred from one end (the evaporator) to the other (the condenser). Between 10 and 45 W, the saturation temperature corresponds to the higher values of the temperature measurements of the adiabatic part. Considering this, and according to the literature [8, 9], we assume that liquid slugs and surrounding liquid films of the vapor plugs are in a subcooled state in the adiabatic part. Momentary temperature peaks higher than the saturation temperature could correspond to local dry-outs (vapor plugs without liquid film). At 50 W, the temperature of the condenser transits from 27 K to 28.2 K. This is because we approach the limits of stable working conditions of the cold head (the temperature controller indicates 0% of input power), but it is not due to the limits of the PHP system itself. At 55 W, it can be observed that the temperature of the condenser continues to increase (reaching almost

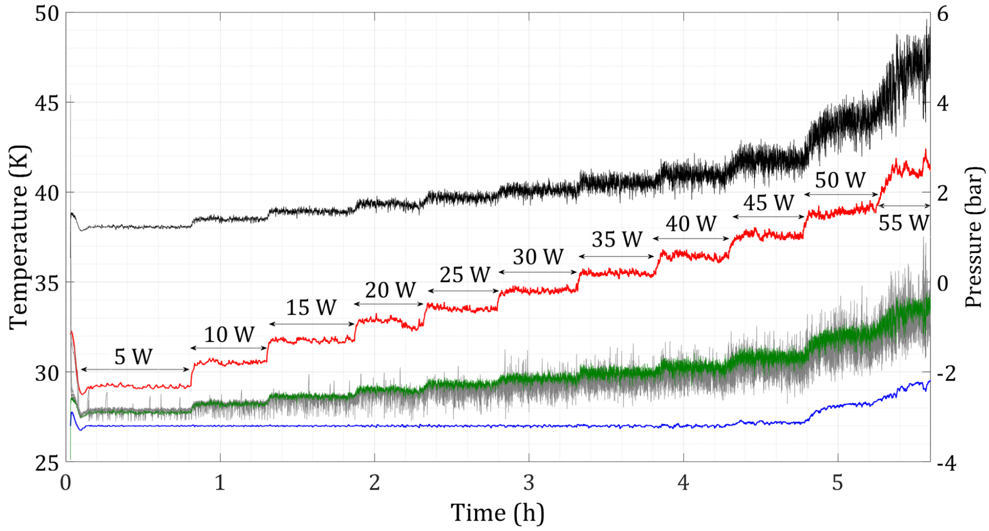

Figure 3. Evolution of the PHP pressure (—), the saturation temperature (—), the temperature of the evaporator (—) and the condenser (—) and the temperatures of the adiabatic part (—) of a test with an increasing heat load at the evaporator from 5 to 55 W.

30 K) and the evaporator's temperature is not stable (oscillating between 41.2 and 42.4 K). In addition, pressure oscillations are considerably higher, oscillating between 4.2 and 5.2 bar (pressure sensors stop to measure at 7 bar and the test is stoppped when the pressure is close to 6 bar for security reasons). At this point, the test was stopped before total dry-out took place. The temperature difference between the evaporator and the condenser increases at every 5-watts step, due to this, the temperature of the fluid in the adiabatic part oscillates with a higher amplitude, creating higher pressure oscillations. This increases the speed flow and the heat transfer according to the literature [11] before achieving the limits of the device. The equivalent thermal conductivity rises gradually during the test and attains its maximum at 50 W: 71 kW/m.K before decreasing again at 55 W when the PHP is not stable anymore.

Stability experiment A second test has been performed with a filling ratio of 29.5% (± 3.5 %) in order to check the stability of the device during long periods of time to be sure that the device will not dry-out after 40-45 minutes as saw in very long horizontal PHP in [7]. The evolution of the pressure and different temperatures during more than 9 hours with a fixed input power of 50 W is illustrated in Fig. 4. After inserting the working fluid (Ne) in the PHP, the system works at 5 W for 17 minutes. Then, when all the temperatures are stable, the PHP is closed and the input power is switched to 50 W.

As it has been noticed before, the temperature of the condenser rises at the beginning of the 50 W period (from 27 K to 28.4 K) and then keeps constant during the whole test. The temperature of the evaporator as well as the pressure follow the same tendency setting themselves at 39.2 K and 3.85 bar respectively. The computed saturation temperature also corresponds to the higher values of the temperature measurements of the adiabatic part which oscillate between 30 and 34 K. The equivalent thermal conductivity is 70 kW/m.K showing that horizontal PHP can work during very long periods of time offering high thermal performance without degradation. This indicates that the oscillating flow is maintained by the temperature difference between the evaporator and the condenser and the heat is transferred permanently.

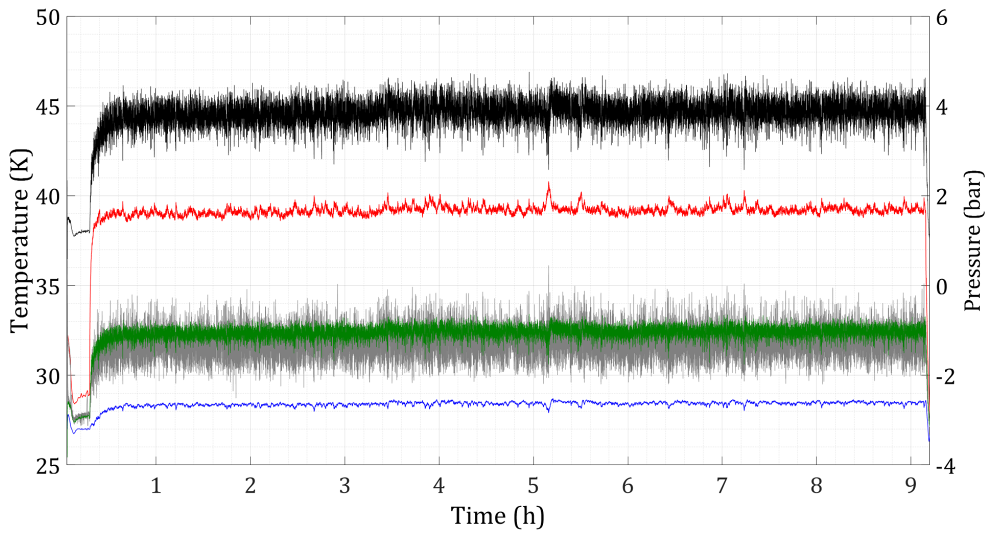

Figure 4. Evolution of the PHP pressure (—), the saturation temperature (—), the temperature of the evaporator (—) and the condenser (—) and the temperatures of the adiabatic part (—) of a test with a permanent heat load of 50 W.

4. Conclusions

A horizontal 1 m long PHP with Ne as working fluid has been tested. Experimental results show that the system can transfer at maximum 50 W of heat load from the evaporator to the condenser and can work in stable conditions during more than 9 hours. The maximum equivalent thermal conductivity is 70 kW/m.K and the repeatability of the experimental results is confirmed. Ne as working fluid shows impressive thermal performance even when the inner diameter of the tubes is larger than possible according to the most common criterion used for capillary tubes.

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