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Experimental study of Large-scale cryogenic Pulsating Heat Pipe

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Abstract. Pulsating Heat Pipes (PHP) are passive two-phase heat transfer devices consisting of a long capillary tube bent into many U-turns connecting the condenser part to the evaporator part. They are thermally driven by an oscillatory flow of liquid slugs and vapor plugs coming from phase changes and pressure differences along the tube. The coupling of hydrodynamic and thermodynamic effects allows high heat transfer performances. Three closed-loop pulsating heat pipes have been developed by the DACM (Department of Accelerators, Cryogenics and Magnetism) of CEA Paris-Saclay, France. Each PHP measures 3.7 meters long (0.35 m for the condenser and the evaporator and 3 m for the adiabatic part), being almost 20 times longer than the longest cryogenic PHP tested. These PHPs have 36, 22 and 12 parallel channels. Numerous tests have been performed in horizontal position (the closest configuration to non-gravity) using nitrogen as working fluid, operating between 75 and 90 K. The inner and outer diameters of the stainless steel capillary tubes are 1.5 and 2 mm respectively. The PHPs were operated at different filling ratios (20 to 90 %), heat input powers (3 to 20 W) and evaporator and condenser temperatures (75 to 90 K). As a result, the PHP with 36 parallel channels achieves a certain level of stability during more than thirty minutes with an effective thermal conductivity up to 200 kW/m.K at 10 W heat load and during forty minutes with an effective thermal conductivity close to 300 kW/m.K at 5 W heat load.

1. Introduction

Pulsating Heat Pipes (PHP) are passive heat transfer devices composed of a single capillary tube without wick structure having a serpentine shape connecting a heating part (evaporator) with a cooling part (condenser) (cf. figure 1). Due to the capillary dimensions of the tube and the temperature and pressure conditions (close to the phase-change), there is a distribution of the fluid of alternating liquid slugs and vapor bubbles surrounded by a liquid film which allows the bubbles to flow. Phase-changes caused by thermodynamic unstable conditions are responsible of constant variations of the size of the bubbles and the liquid slugs creating an oscillating flow able to transfer the heat from the evaporator to the condenser. There exist two main configurations of PHPs: the closed-loop PHP and the open-loop PHP. The only difference is that the first one has both ends of the tube joined to each other and offers better heat transfer performances [1]. Depending on the position of the evaporator, PHPs can operate in bottom-heating mode, top-heating mode or in horizontal position, the closest configuration to non-gravity [2]. Despite the numerous researches undertaken, to date some aspects of the mechanism of PHP operation are still unknown.

Created by Akachi in 1990 [3, 4], PHPs have been developed for the cooling of electronics due to its reduced size and simple construction. Nowadays, they are being studied in the cryogenic field for cooling superconducting magnets [5–9] as well as for the vitrification of biomaterials [10] and in the aerospace field with experiments in low-gravity conditions during parabolic flights [2, 11, 12].

As references, Mito et al. [5] have developed a closed-loop PHP for cooling superconducting magnets. Their experiment consisted of a vertical PHP with straight sections of 16 cm, an inner diameter of 0.78 mm and 10 parallel channels. Tests were performed using H_2, Ne and N_2 as working fluids (filling ratios between 31 and 70 %) at operating temperatures ranges of 17-25 K (H_2), 26-32 K (Ne) and 67-80 K (N_2). The maximum equivalent thermal conductivities achieved were 3000 W/m.K for H_2, 8000 W/m.K for N_e and 18000 W/m.K for N_2. Jiao et al. [13] have tested a horizontal closed-loop PHP with straight sections of 20 cm, 16 parallel channels and an inner diameter of 1.65 mm. Working with N_2 (filling ratio of 48 %), the maximum thermal conductivity attained was 26000 W/m.K at a temperature range of 77-133 K. Fonseca et al. [14] have studied a horizontal cylindrical closed-loop PHP with straight sections of 22 cm composed of 40 parallel channels and an inner diameter of 0.5 mm which uses N_2 as working fluid (filling ratios between 28 and 46 %). The maximum equivalent thermal conductivity achieved was 35000 W/m.K at a temperature range of 77-85 K.

Three closed-loop pulsating heat pipes having different number of parallel channels (12, 22 and 36) have been developed by the CEA Paris-Saclay (France). Each PHP has straight sections of 3.7 m, an inner diameter of 1.5 mm and uses N_2 as working fluid (filling ratios between 20 and 90 %) at a temperature range of 75-90 K. The three PHPs are in a horizontal position for reducing gravity effect because they have been designed for cooling a superconducting toroid magnet (10 m long and 12 m of diameter) for space for the SR2S European project [15]. The PHPs would be the thermal link between the magnet (hot source) and the a cryocooler (cold source). Thus, due to the distance to the magnetic field, cryocooler's performances would not be affected.

This paper reports the experimental study of three large-scale pulsating heat pipes. The experimental facility is described, optimal working conditions are analyzed and dry-out phenomena is characterized in order to contribute to a better understanding of PHPs' operation.

2. Cryogenic PHP design

2.1. Experimental facility

The experimental facility is composed of three pulsating heat pipes with both ends connected to a T-junction to another capillary tube for the introduction of the working fluid at the condenser part. The capillary tubes are made of stainless steel and have an inner and outer diameters of 1.5 and 2 mm respectively. The only difference between PHPs is the number of turns (or parallel channels): 36, 22 and 12. The three pulsating heat pipes are in a horizontal position and have a total length of 3.7 meters (including the adiabatic part, the condenser and the evaporator). They are positioned in a supporting aluminum structure and fixed by glass epoxy supports (cf. figure 2).

Each evaporator section is made of two machined copper plates (40 cm x 30 cm x 4 mm) in which tubes are inserted and includes a Kapton heater with a maximum power dissipation of 100 W. The copper plates have an identical size but the Kapton heaters are proportionate to the number of turns of each PHP and cover strictly the area occupied by the tubes on each evaporator. This means that the mass of copper is the same for the three evaporators, but not the size of the heaters and the number of tubes. The three evaporators are separated by sixteen sheets of thermal superinsulation (MLI). The condensers are also made of copper plates and are thermally connected by indium threads to each other and to the cold source that is a cryocooler (Sumitomo CH110 77 K). Kapton heaters are also fixed around the cryocooler and serve to regulate its temperature with a LakeShore 336 Temperature Controller. The evaporators and

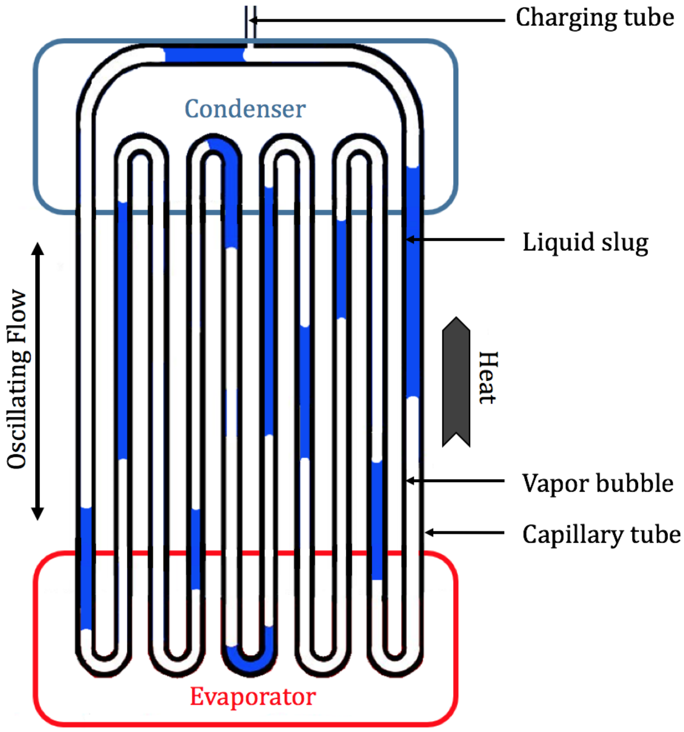

Figure 1. Schematic illustration of a Pulsating Heat Pipe.

adiabatic parts are covered with the same layer MLI blanket.

The horizontal cryostat, made of stainless steel, measures 6.4 m and has a diameter of 1 m. Its inner wall is covered with several layers of MLI and with an aluminum thermal shield. Several tubes through which liquid nitrogen flows constantly are fixed to the aluminum thermal shield. As a result, inside the cryostat the temperature remains close to 80-90 K during all test. In addition, the cryostat is permanently connected to a pumping system composed of a primary pump and a turbopump ensuring a vacuum with a value close to 10^{-8} mbar.

The working fluid is nitrogen. A specific inlet gas system connected to the charging tube has been designed to introduce and control the amounts of fluid inside the PHPs (cf. figure 3). The system is composed of a nitrogen gas tank (200 bars), a buffer volume (50 L) and an absolute pressure transducer to control the quantities of gas introduced in the PHPs, as well as several valves for introducing the gas and a vacuum pump for evacuating residual quantities of fluid before and after every test. The buffer volume allows to know the quantities of fluid injected in the PHP. It also reduces any local overpressure inside the PHP due to the volume difference between the buffer tank (50 L) and the pulsating heat pipes (0.02 - 0.07 L).

2.2. Instrumentation and experimental errors

The pulsating heat pipes have several temperature and pressure sensors. As an example, the locations of sensors in the PHP with 36 parallel tubes are shown in figure 4. There are two types of temperature sensors: calibrated 1070 CX-SD Cernox sensors and platinum resistance thermometers (or PT100 sensors). These sensors are fixed to the copper plates in the evaporators and condensers and to the capillary tubes in the adiabatic parts with copper powder epoxy to improve the thermal contact. The pressure of the PHPs is measured with Kulite® pressure sensors. The gas inlet system includes an absolute pressure transducer.

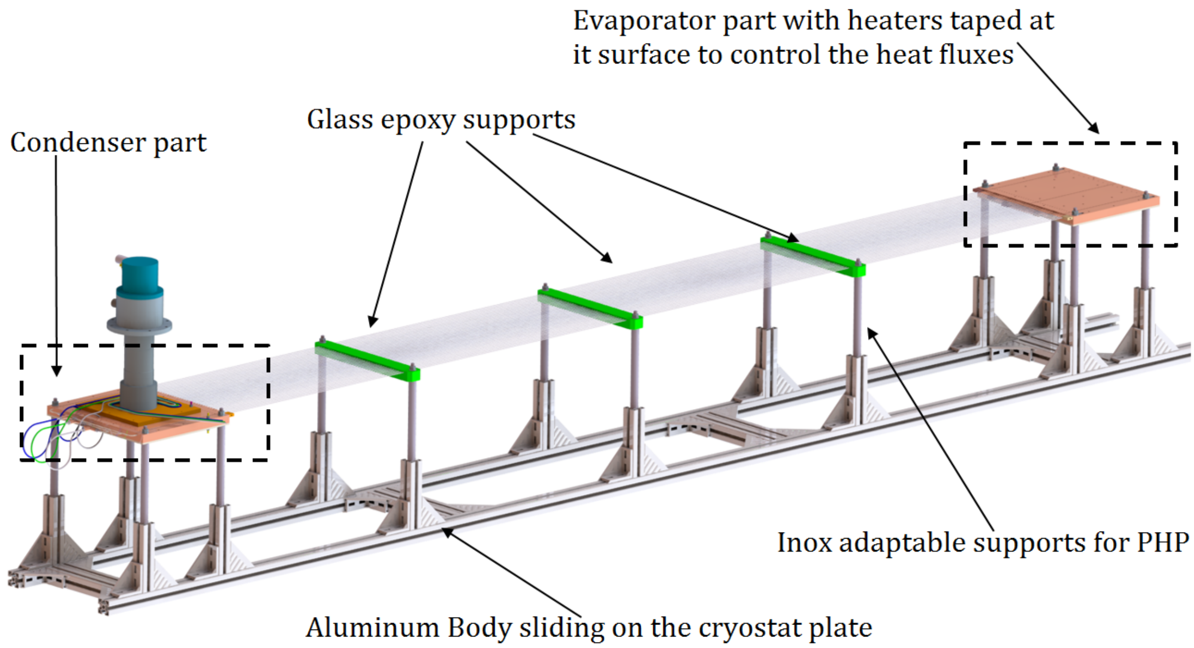

Figure 2. Schematic illustration of the experimental facility.

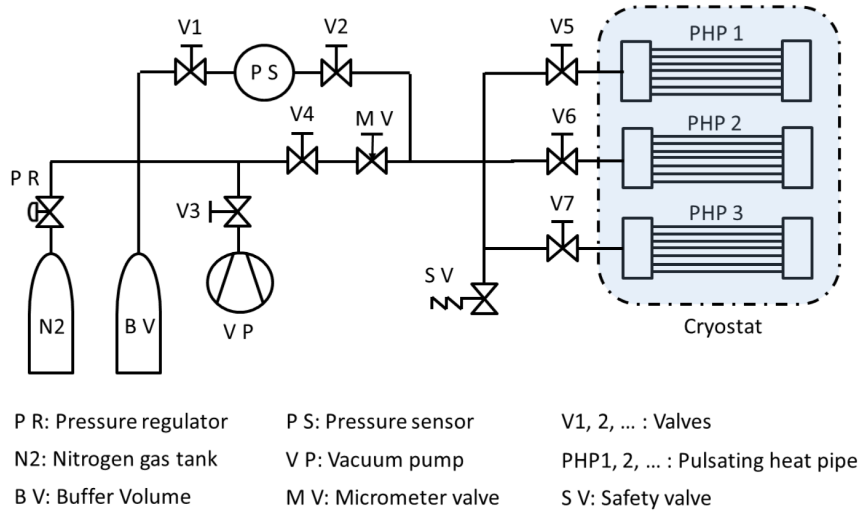

Figure 3. Inlet gas system.

The instrumental errors are presented in Table 1. The uncertainty of heating power is estimated to be a few orders of magnitude lower than heat load during tests. This uncertainty comes from radiative and conductive heat contributions which are difficult to quantify. There are two ways of radiative inputs: one from the tubes aimed to the circulation of liquid nitrogen in the cryostat (estimated to be 0.07 W considering an emissivity of 1) and another between each evaporator (which is almost negligible because of the presence of MLI layers). Nevertheless, a considerable difference in the evolution of the temperature between every evaporator out of test sessions can be observed. As mentionned before, the three evaporators have the same mass of

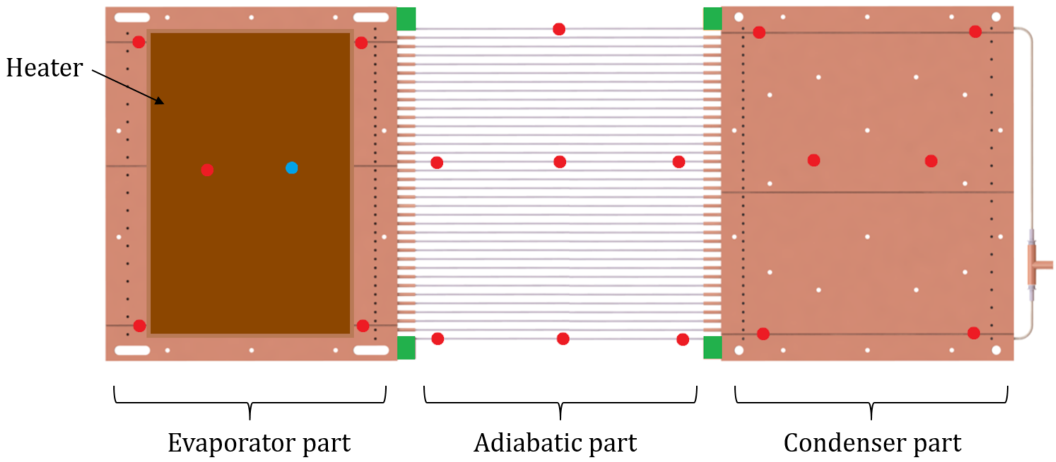

Figure 4. Locations of sensors in the PHP with 36 parallel tubes. Type of sensor: ● Pt100 temperature sensor, ● 1070 CX-SD Cernox temperature sensor and ■ Kulite pressure sensor.

Table 1. Accurancies and experimental errors.

Sensor	Measured range	Accuracy
Cernox CX-1070 temperature sensor	70 - 100 K	± 16 mK
Platinum resistance thermometer	70 - 100 K	± 0.55 ^{o}C at -200 ^{o}C
Kulite pressure sensor CP01	0 - 7 bars	± 0.01 %
Absolute Pressure Transducer MKS®	0 - 7 bars	± 0.5 %
Vacuum Transducer MKS	5.10^{-8} - 5.10^{-4} Torr	± 30 %

copper but not the same size of the heater and number of tubes. Due to this, the PHPs with 12 and 24 parallel tubes have a considerable copper mass at both sides of the each evaporator which is not used and, considering the specific heat of the copper (17 kJ/kgK at 70 K), it becomes more difficult to modify the temperature of the evaporator. Consequently, the evaporator of the PHP with 36 parallel tubes increases its temperature quicker than other evaporators. Thermal anchoring of wires is ensured with the aluminum shield which is at around 80 K. Conductive heat contributions are consequently almost negligible.

3. Experimental procedure

After evacuating the PHP and the charging tube by a vacuum pump, the filling procedure starts: the buffer tank is filled with the nitrogen gas tank at the corresponding pressure to the desired filling ratio in the PHP. This pressure is measured with the absolute pressure transducer opening only valve V1 (cf. figure 3). Then, after closing the nitrogen gas tank, opening valve V2 and the corresponding inlet valve of the chosen PHP, the gas is introduced into the pulsating heat pipe through the condenser where its temperature decreases in a few seconds to a temperature close to the saturation temperature. Before introducing the fluid inside the PHP, the evaporator is heated to achieve the desirable temperature difference between boths ends of the PHP: the condenser and the evaporator. With this method, there is a temperature and pressure difference between both ends of the PHP since the beginning of the test which contributes to the start-up of the oscillating flow, as showed in [16].

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4. Experimental results

The evolution of the PHP global pressure, the corresponding saturation temperature and the temperatures of the evaporator, condenser and adiabatic part during a test are illustrated in figure 5. The condenser's temperature is regulated at 80 K and the evaporator is heated at 84 K with a heat load of 10 W. Then, the PHP is filled with N_2 at a liquid filling ratio of 33 %. During the test, three different phases can be distinguished: the start-up, the oscillating phase and the dry-out. During the start-up phase, the condenser's temperature increases as N_2 gas is being injected from the buffer tank (which is at room temperature). After cooling in the condenser, the fluid reaches the evaporator decreasing its temperature. The oscillating phase lasts 35 minutes. During this phase, the temperature of the evaporator oscillates and increases very slowly from 83 K (reaching an equivalent thermal conductivity of 350 kW/m.K) to 84 K (160 kW/m.K). These equivalent thermal conductivities are almost 10 times higher than in [5], [13] and [14]. It is important to note that the total straight length of the device (3.7 m) and the total cross-sectional area of working fluid ($6, 35.10^{-8}$ m^2) are considered in the calculation of the equivalent thermal conductivity. In the adiabatic part, oscillations and temperature peaks appear with a maximum amplitude of 5 K. The pulsating flow takes place corresponding to the proper working conditions of a pulsating heat pipe, the heat is then transferred from the evaporator to the condenser. During the dry-out phase, the evaporator's temperature increases rapidly. This period starts 48 minutes after the introduction of the working fluid. In the adiabatic part the number and the amplitude of temperature peaks increase (reaching a maximum amplitude of 9 K) creating local dry-outs which stop the flow causing a global dry-out in the evaporator. At that point, the PHP can be divided into two independent thermodynamic systems: the evaporator system and the PHP system itself. In the first one, the temperature increases, the flow stops, the fluid is only in vapor phase and the heat is not transferred anymore. The evaporator is then far from the saturation conditions. In the second one, the temperature of the condenser and the adiabatic part decreases because the cryocooler is not receiving any more heat from the evaporator and several amounts of fluid are being liquefied. The global pressure decreases all along the test because of these liquefactions and the connection of the PHP to the buffer volume (in case of overpressure, little amounts of fluid can run out of the PHP to the buffer volume through the charging tube). At this point, dry-out phase has been characterized but conditions under which dry-out starts are still unknown.

The evolution of the PHP global pressure, the corresponding saturation temperature and the temperatures in the evaporator, condenser and adiabatic part of another test are illustrated in figure 6. In this second test the PHP is closed just after been filled[1], i.e. the buffer volume is not used. The temperature control system is off and the condenser's temperature is fixed initially at 80 K with a permanent heat load of 160 W. The evaporator's temperature is increased to 84 K with a heat load of 10 W. The PHP is filled with N_2 at a liquid filling ratio of 33 %. Three different phases can also be distinguished. The oscillating phase lasts 35 minutes too. The temperature of the evaporator oscillates and increases very slowly from 84 K to 85 K reaching an equivalent thermal conductivity between 290 and 190 kW/m.K. The temperatures of the adiabatic part also oscillate. In this case the global pressure increases during the start-up and the oscillating phase because the entire PHP increases its temperature. When dry-out occurs, the PHP can also be divided into two thermodynamic systems, the temperature of the evaporator increases rapidly while the temperature of the rest of the PHP decreases slightly, as well as global pressure. Temperature peaks (with amplitudes lower than 4 K) appear in the adiabatic part corresponding also to local dry-outs.

Two other tests in the pulsating heat pipe with 22 parallel channels have also been performed filling the PHP with a liquid ratio of 42 and 60 %. During the oscillating periods (16 and 21

[1] Isolated large pressure oscillations at the beginning of the test correspond to the moment of the closure of the PHP.

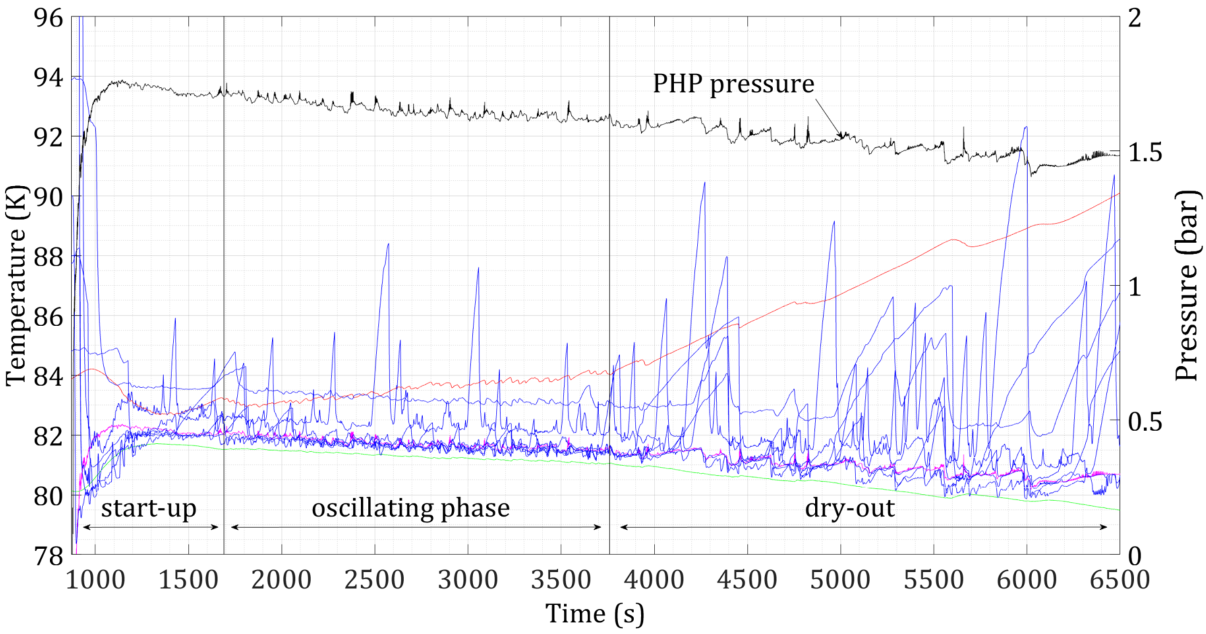

Figure 5. Evolution of the PHP global pressure (—), the saturation temperature (—), the median values of the temperatures of the evaporator (—) and the condenser (—) and the temperatures of the adiabatic part (—) of a test with the PHP connected to the buffer volume.

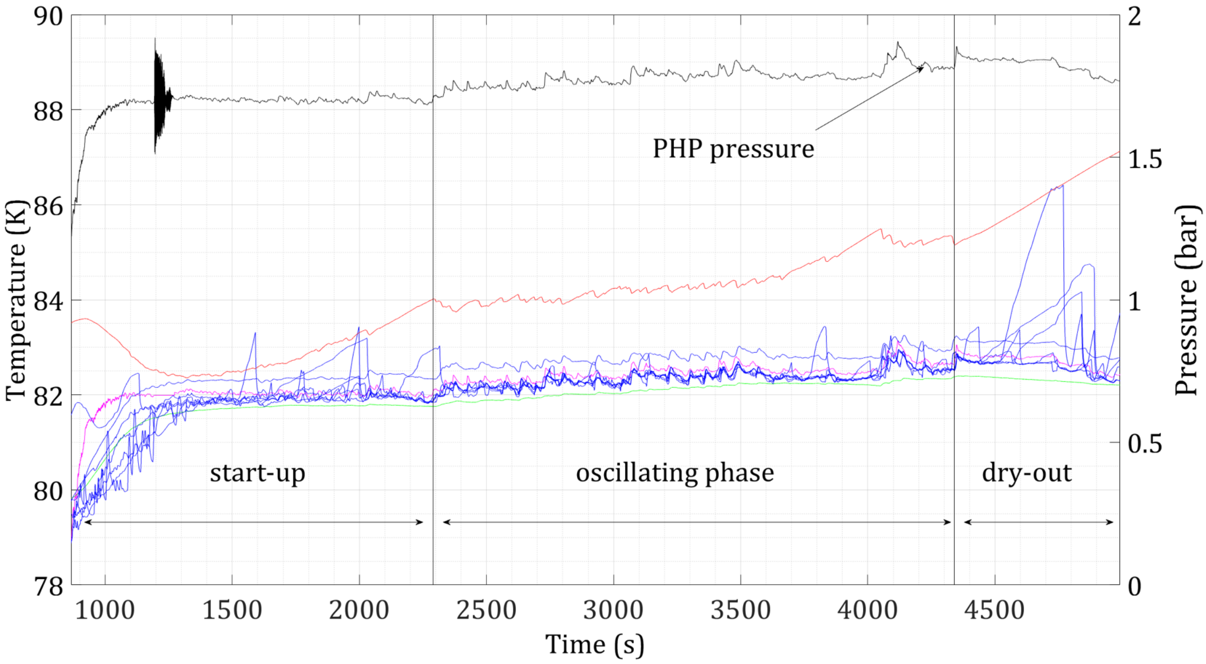

Figure 6. Evolution of the PHP global pressure (—), the saturation temperature (—), the median values of the temperatures of the evaporator (—) and the condenser (—) and the temperatures of the adiabatic part (—) of a test where the buffer volume is not used.

minutes), the equivalent thermal conductivities reached were 75 and 100 kW/m.K respectively. Tests in the pulsating heat pipe with 12 parallel channels have been performed too, but temperatures never attained any stability, confirming the importance of the number of parallel channels in the performance of pulsating heat pipes in horizontal position as shown in [1].

5. Conclusions

Three horizontal cryogenic pulsating heat pipes measuring 3.7 m long have been experimentally investigated using nitrogen as working fluid. The influence on the thermal performance of the applied heat, the number of parallel channels, the presence of a buffer volume and the working temperatures has been studied. The oscillating phase and the dry-out phase have been characterized. The conclusions are summarized as follows:

- Temperature peaks in the oscillating and dry-out phases represent the limit between the oscillations of the proper working conditions and the local dry-outs. The pulsating heat pipe connected to the buffer volume has a higher equivalent thermal conductivity and temperature peaks are more frequent. When the PHP with 36 parallel channels was connected to the buffer volume, the maximum equivalent thermal conductivity was almost 20 % higher than during a test where the buffer volume was not used.
- Increasing the number of parallel channels, the oscillating phase gets longer and thermal performances are higher. Thermal conductivities achieved with the PHP having 36 parallel channels and with the PHP having 22 parallel channels were 350 and 100 kW/m.K respectively during the oscillating phase, while the PHP with 12 parallel channels never attained an oscillating phase.

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