Effect of the application of an electric field on the performance of a two-phase loop device: preliminary results

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Effect of the application of an electric field on the performance of a two-phase loop device: preliminary results

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Abstract. In the last decade, the continuous development of electronics has pointed out the need for a change in mind with regard to thermal management. In the present scenario, Pulsating Heat Pipes (PHPs) are novel promising two-phase passive heat transport devices that seem to meet all present and future thermal requirements. Nevertheless, PHPs governing phenomena are quite unique and not completely understood. In particular, single closed loop PHPs manifest several drawbacks, mostly related to the reduction of device thermal performance and reliability, i.e. the occurrence of multiple operational quasi-steady states. The present research work proposes the application of an electric field as a technique to promote the circulation of the working fluid in a preferential direction and stabilize the device operation. The tested single closed loop PHP is made of a copper tube with an inner tube diameter equal to 2.00 mm and filled with pure ethanol (60% filling ratio). The electric field is generated by a couple of wire-shaped electrodes powered with DC voltage up to 20 kV and laid parallel to the longitudinal axis of the glass tube constituting the adiabatic section. Although the electric field intensity in the working fluid region is weakened both by the polarization phenomenon of the working fluid and by the interposition of the glass tube, the experimental results highlight the influence of the electric field on the device thermal performance and encourage the continuation of the research in this direction.

1. Introduction

Pulsating Heat Pipes (PHPs) are novel promising two-phase passive heat transport devices potentially suitable for the thermal management of power electronics in future space applications. Patented in their most common configuration by Akachi [1-2], Pulsating Heat Pipes (PHPs) consist of a meandering tube of capillary dimensions closed end-to-end to form a closed loop. The loop is first evacuated and then partially filled with a working fluid, which naturally resides in the tube in the form of liquid slugs alternated to vapour plugs. When input heat power is provided to the evaporator section, the vapour bubble expand and push the adjacent liquid slugs to the condenser section, where heat is released to the cold source and condensation process takes place.

Although classified as a sub-class of the family of heat pipes, PHPs governing phenomena are quite unique and not completely understood. In spite of the significant efforts that have been made in last decades, a large number of issues still remain unsolved, such as their characteristic unstable behaviour at low and high heat fluxes [3]. The unstable behaviour seems to be affected by a large number parameters and becomes less and less evident as the number of turns increases. A symmetrically heated single closed loop PHP is therefore the most unstable device that belongs to the PHPs family. Khandekar et al. [4] were the first to address the problem of the existence of multiple operational pseudo-quasi-steady states in a single closed loop PHP. In particular, the experimental tests performed on a single closed loop PHP with an inner tube diameter equal to 2.00 mm and partially filled with pure ethanol (60% filling ratio) highlighted how the device operation evolves towards a thermodynamic equilibrium state characterized by the complete segregation of working fluid phases between the heat power input and output regions [4]. Therefore, the working fluid oscillations stop completely and the device thermal performance rapidly deteriorates. Theoretically, this dynamic equilibrium condition may be disturbed by an externally triggered perturbation or internally generated interface instability. If the applied disturbance is strong enough, it may break the menisci surface tension and cause the redistribution of phases. Then, the system could come back to a previous equilibrium state depending on the extent of spatial phase distribution homogeneity achieved through the mixing of the working fluid. In literature, a large number of techniques have been proposed in order to face the problem and stabilize the device operation.

The techniques range from an asymmetrical arranged diameter configuration [5-6] to the use of flow control check valves [7]. However, none of the techniques listed above result in an enhancement of the thermal performance to justify the major complexity added to the system.

The present research work aims at inquiring the effect of the application of an electric field on the thermal behaviour of a single closed loop PHP. In particular, the electric force that arises from the application of an electric field on a two-phase flow drives the vapour phase (of lower dielectric permittivity) towards a region of weaker electric field intensity and in some circumstances it may break the menisci surface tension and give the opportunity of separating phases [8-9]. The redistribution of phases may renew the level of internal pressure perturbations, which are regarded as the primary working fluid driving mechanism inside the two-phase loop.

2. Experimental set-up

2.1. Test-cell

The basic features of the single closed loop PHP are sketched in Figure 1. The evaporator and condenser are made with copper tubes in order to minimize the thermal resistance between the tubes and the heat source and heat sink while the adiabatic section is made with glass tubes in order to allow the visualization of the working fluid. The tubes have an internal diameter of 2.00 mm and have capillary dimensions for the selected working fluid, i.e. ethanol. The working fluid was selected in order to compare the obtained results with those presented in literature.

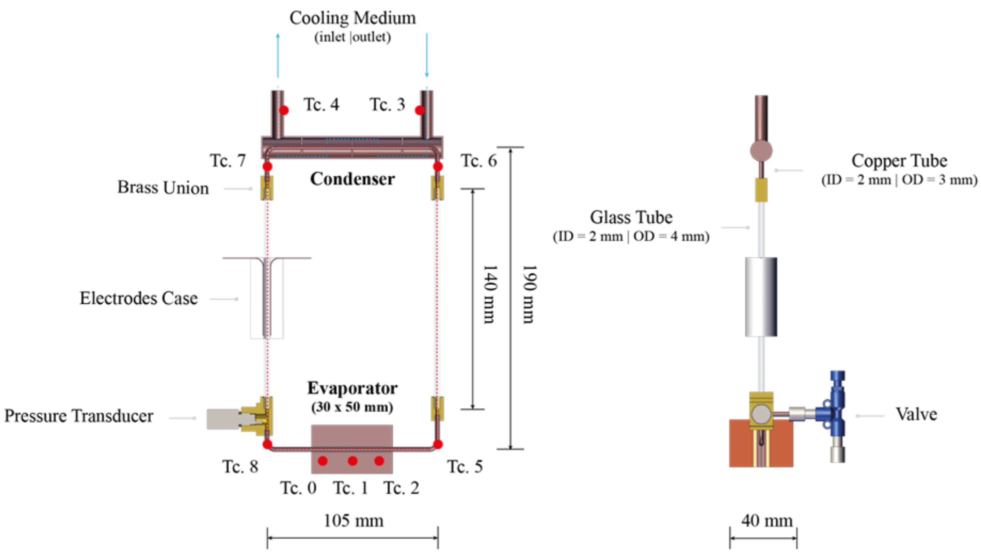


Figure 1. Single closed loop PHP test-cell.

The copper and glass tubes are connected through four brass unions: the copper tubes are brazed to the unions while the glass tubes are bonded with a high-temperature resistant epoxy adhesive (Loctite®, Hysol 9492). The brass T-junction on the left hand side of the evaporator allows to derive two ports: the former joins a copper tube used for the emptying and filling procedure; the latter hosts a pressure transducer (Kulite®, ETL/10T-312M-4BAR-A). The device is equipped with nine T-type thermocouples located as sketched in Figure 1. The thermocouples post-calibration accuracy is 0.1 K.

The single closed loop PHP was first evacuated by a two-stage ultra high vacuum pump (Edwards®, XDS35i and EXT255H) until a pressure level around 10^{-4} Pa was reached and then it was partially filled with a volumetric ratio of 0.5 ± 0.025. The selected working fluid was preventively degassed by continuous boiling: the incondensable gases were vented by several suction cycles as they accumulated in the free volume of the degassing tank. The residual incondensable gases content results in an overpressure above the saturation temperature of ethanol, which is lower than the margin of accuracy of the pressure transducer (0.5% full scale output).

Evaporator section

The evaporator section consists of two copper plates with semi-circular cross-section channels in order to embed the central portion of the copper tube. The copper plates and tube, which are maintained in thermal contact by a high thermal conductivity paste, constitute the evaporator copper block. Two silicone rubber heaters (Minco®, HR5364R125L12A) located at each side of the copper block provide the selected input heat power to the system. The copper block is thermally insulated by two Mica® fiber sheet and two Bakelite® back plates in order to reduce the heat loss to ambient air. The silicone rubber heaters were fed by a dc power supply (Agilent®, 6575A) with a power up to 35 W.

Condenser section

The condenser section is embedded inside a double-pipe heat exchanger, which consists of two concentric copper tubes of different diameter. The working fluid (red line in Figure 1) flows through the inner pipe while the cooling medium (blue line in Figure 1) flows through the annular space in between the tubes. In order to increase the heat exchange area as well as the cooling medium residence time inside the heat exchanger, three copper baffles are brazed to the inner copper pipe.

The condenser section was supplied by water coming from a constant temperature bath and circulator (Hake®, DC10-K20). The water temperature was set at 15 °C. The water mass flow rate was calculated to be equal to 6 g/s after considering the load losses along the circuit.

2.2. Data acquisition

The output signals were recorded by a data acquisition system (National Instrument®, cRio-9074) and real-time monitored by a suitable LabView® program. The temperatures and pressure signals were acquired at 10 and 20 Hz, respectively. The ambient temperature was measured by a four-wire resistance temperature detector and acquired at 1 Hz, as well as the heating power.

3. Electric field characteristics

The expression for the electric force per unit volume that acts on a generic medium is [8]:

$$\boldsymbol{f_e'''} = \rho_f \boldsymbol{E} + \frac{1}{2}\varepsilon_0 E^2 grad\varepsilon_r + \frac{1}{2}\epsilon_0 grad(bE^2) \tag{1}$$

where:

$$b = \rho(\frac{d\varepsilon_r}{d\rho})_T \tag{2}$$

The first term in Equation 1, also known as Coulomb force, depends on the sign of the electric field and generally predominates over the other force contributions when free charge is present in the medium. The other force contributions encompass dielectrophoresis and electrostriction: the former is associated with non-homogeneities of the dielectric permittivity of the medium, which in turn are coupled with thermal gradients or phase discontinuities; the latter is associated with non-uniformities of the electric field distribution. The electrical properties of the medium directly influence the formulation and different interfacial and volume force combinations can arise. The matter is widely structured and the interested reader can find additional details in the cited reference [8].

In a dielectric fluid, a non-uniform electric field is required so that a net force can arise at the liquid-vapour interface of a small inclusion: the force drives the phase of lower dielectric permittivity towards the region of higher electric field intensity. However, even the presence of a bubble of different dielectric permittivity than the surrounding medium may be sufficient to originate a gradient in an originally uniform electric field distribution.

3.1. Electrodes design

The electric field is generated by two wire-shaped electrodes laid parallel to the longitudinal axis of the left glass tube and fitted in a Teflon® case in order to prevent the dielectric breakdown phenomenon through the ambient air. The case, as sketched in Figure 2, consists of two symmetric sections, each having a semi-circular cross-section hole in order to embed the glass tube and a longitudinal groove in order to maintain the wire in the correct relative position.

The electrodes were supplied by a power supply (Spellmann®, RHR30P30/220) with constant DC voltage levels up to 20 kV. The voltage was acquired at 1 Hz.

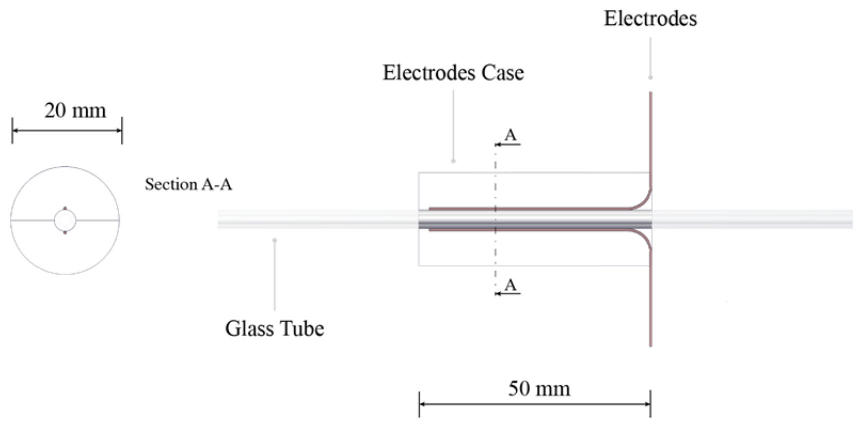
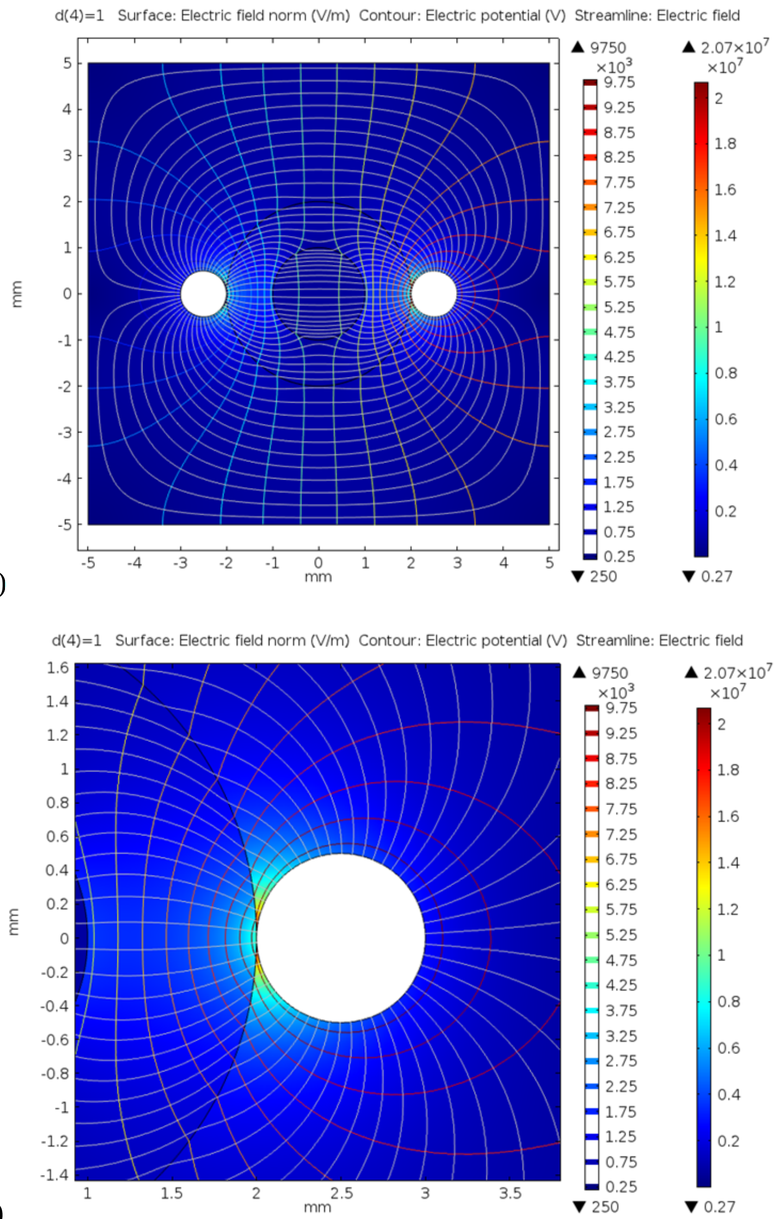


Figure 2. Electrodes case geometrical features.

The optimum electrodes geometry was investigated by performing a two-dimensional electrostatic simulation with the aid of COMSOL Multiphysics® software. The simulation was carried out by ranging the electrodes diameter from 0.25 mm to 1.00 mm with steps of 0.25 mm. The electrodes were connected to ground and to a terminal fed at 10 kV, respectively. The glass tube was considered as completely filled by ethanol. The dielectric permittivity of ethanol is 25 while the dielectric permittivity of the glass tube is 4 when evaluated at ambient temperature.

The electric field trend relative to the 1 mm diameter configuration is sketched in Figure 3. The electric field intensity is largest close to the point of contact between the electrodes and the glass tube while is smallest in the working fluid region. The greater polarization of the working fluid as compared with the glass tube significantly weakens the electric field intensity in the working fluid region regardless of the electrodes diameter. The electric field space distribution with varying electrodes diameter is sketched in Figure 4, where the x and y-axis represent to the line joining the electrodes and the average value of the electric field, respectively. According to Equation 1, the higher the electric field within the working fluid region the higher the electric force per unit volume. Therefore, the 1 mm diameter electrodes configuration was selected.



a) b)

Figure 3. Electric field intensity: a) overall and b) magnified view.

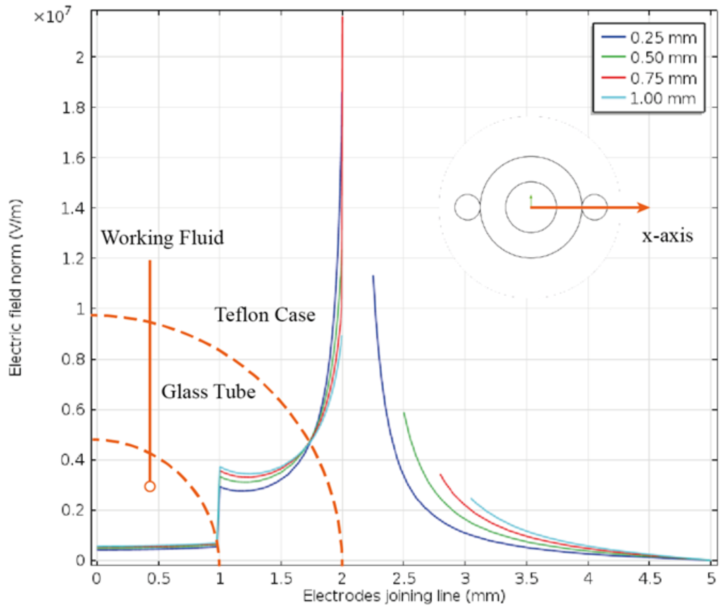


Figure 4. Electric field space distribution along the line joining the center of the electrodes with varying electrodes diameter.

4. Experimental results

The experimental results are presented in terms of temperatures and pressure temporal trend. The warm colors lines represent the temporal evolution of temperatures in the evaporator section while the cool colors lines represent the temporal evolution of temperatures in the condenser section.

The single closed loop PHP thermal performance is evaluated in terms of the equivalent thermal resistance, i.e. $R_{th} = (\bar{T}_e - \bar{T}_c)/\dot{Q}$, where $\bar{T}_e$ and $\bar{T}_c$ are the average evaporator and condenser temperatures in a pseudo-steady-state*, respectively, and $\dot{Q}$ is the input heat power.

4.1. Thermal characterization

A general characterization of the thermal performance of the single closed loop PHP was performed by gradually increasing the input heat power up to 35 W with consecutive steps of 5 W. Before moving to the next step, the input heat power was kept constant for thirty minutes in order to allow the system to reach a new operational pseudo-steady-state. The equivalent thermal resistance associated with each step was evaluated by averaging the evaporator and condenser temperatures. The same procedure was repeated until the evaporator temperatures started to increase abruptly, i.e. until dry-out happened in the evaporator section and the performance limit of the device was reached.

The experimental results without electric field are reported in Figure 5. It is worth to note that three distinct operational regimes can be recognized relative to the input heat power supplied to the evaporator section as already noticed by Khandekar et al [10] and Mameli et al [11].

When the input heat power is set at 5 W, after an initial start-up phase, the single closed loop PHP operation is characterized by alternating periods of working fluid motion and stop-over. The occurrence of such a regime, also termed start and stop regime, relies on the fact that the input heat power is not sufficient to give rise to a stable circulation. The working fluid motion starts after a sufficient temperature gradient is set-up between the evaporator and condenser. However, the onset of oscillations leads to the mixing of hot and cold working fluid portions, which lowers again the temperature gradient and stops the working fluid motion. As the working fluid motion is continuing, the equivalent thermal resistance tends to its highest value, i.e. 8.2 K/W.

* A pseudo-steady state is reached when all temperatures output signals shows an average value constant in time.

When the input heat power is set at 10 W, the single closed loop PHP operation is characterized by successive flow reversals: the vapour pressure is strong enough to establish a net circulation of the working fluid but it is not able to keep it stable all time. As there are no stop periods, the heat exchange is enhanced and the equivalent thermal resistance decreases to 5,5 K/W.

When the input heat power is set at 15 W, the single closed loop PHP operation is characterized by the circulation of the working fluid in the anticlockwise direction. As the circulation is stable, the equivalent thermal resistance moves towards its lowest value, i.e. 2.8 K/W. The occurrence of circulation, in addition to be clearly visible through the transparent section, can be also inferred by observing the temporal evolution of the temperatures measure by the thermocouples: the temperatures in the up-header branch of the device and close to the evaporator (Tc. 5) and in the down-header branch of the device and close to the condenser (Tc. 7) exhibit the highest and lowest values, respectively, as the circulation of the working fluid occurs in a specific direction.

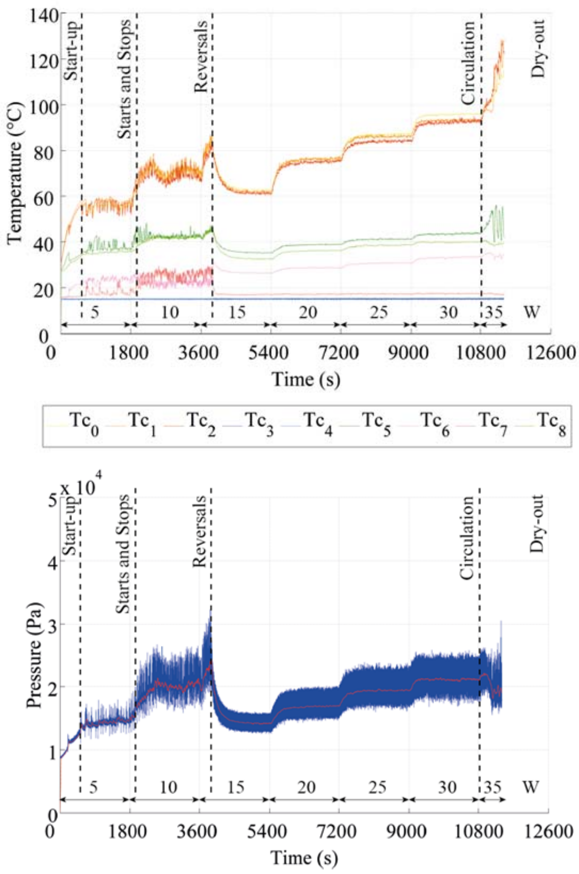


Figure 5. Thermal characterization: temperatures and pressure temporal trend.

4.2. Effect of the electric field

The objective of the present work is to understand if the application of an electric field is able to stabilize the device operation. Then, the attention was focused on the flow regimes that are characterized by an unstable behaviour, i.e. the start and stop and flow reversal regimes. The effect of the application of an electric field was investigated by carrying out long-run experimental tests at a fixed input heat power. The electrodes were powered by increasing the voltage up to 20 kV, with steps of 2.5 kV. Before moving to the next step, the voltage was keep constant for 15 minutes in order to allow the system to reach a new hypothetical operational pseudo-steady state.

The experimental results in terms of temperatures and pressure temporal trend are reported in Figure 6 and summarized in terms of equivalent thermal resistance in Figure 7. The black line represents the equivalent thermal resistance of the device in the absence of an electric field while the colored points correspond to the equivalent thermal resistance of the device in the presence of an electric field, where each color is associated with a specific value of the voltage supply.

It is worth to note that the effect of the application of an electric field is strongly reliant on the input heat power provided to the evaporator section and, accordingly, on the related flow regime. On one hand, for input heat power values associated with an unstable behaviour of the device, the effect of the application of the electric field traduces in an increase of the equivalent thermal resistance, regardless of the voltage supply to the electrodes. On the other, for input heat power values associated with a stable behaviour of the device, the effect of the application of the electric field traduces in a decrease of the equivalent thermal resistance at a high voltage supply. Although the equivalent thermal resistance changes may seem small, they result in a sensible variation of the temperature difference between the evaporator and condenser.

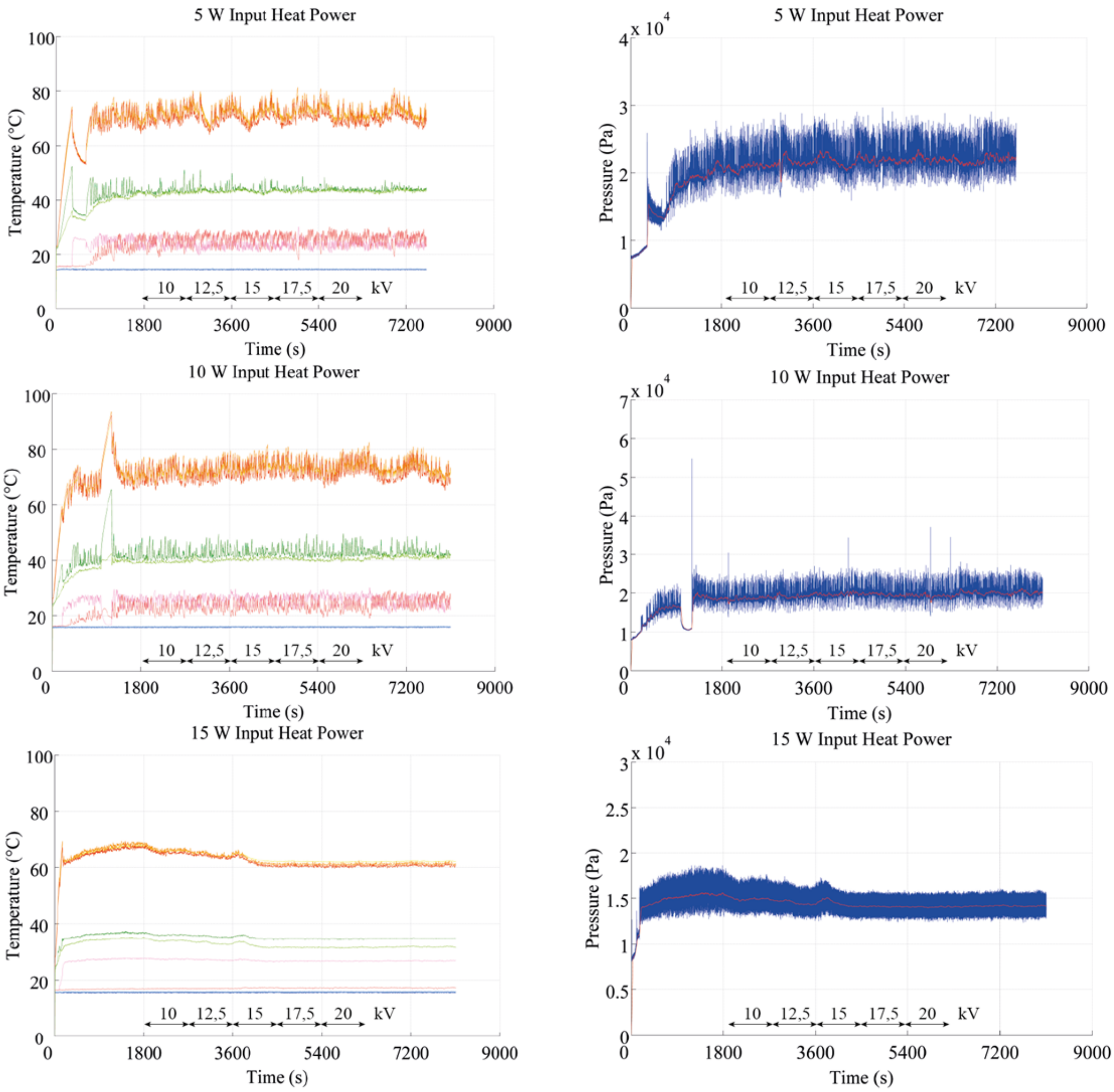


Figure 6. Effect of the electric field: temperatures and pressure temporal evolution.

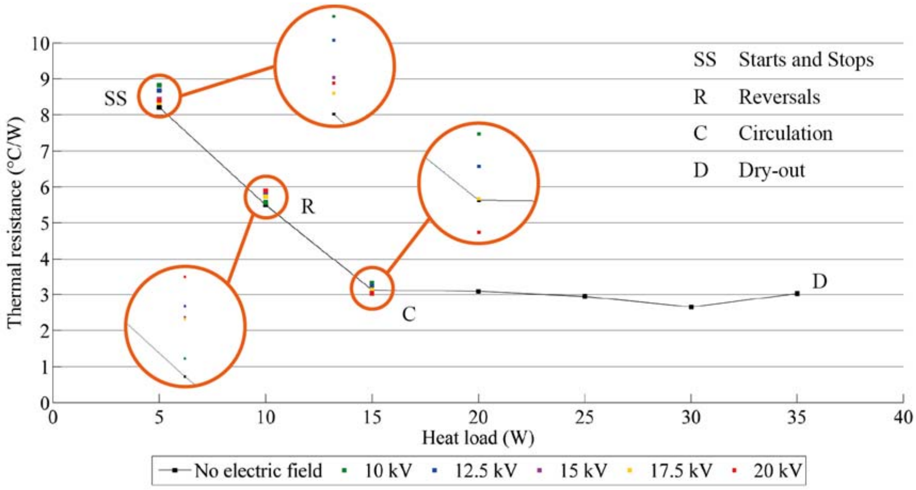


Figure 7. Effect of the electric field: equivalent thermal resistance.

5. Conclusions

In the present work, the behaviour of a single closed loop PHP tested without and with electric field is investigated. The device is made with an inner tube diameter of 2 mm and is partially filled with ethanol in order to provide comparison with the results already discussed in literature.

The results obtained without electric field clearly confirmed that the device operation is characterized by the occurrence of different flow regimes depending on the input heat power. On one hand, a low input heat power was not able to continuously sustain the working fluid motion thus resulting in unstable phenomena such as the "start and stop" fluid oscillations and the continuous flow reversals in the case of circulation. On the other, a high input heat power resulted in a stable circulation of the working fluid in a preferential direction.

The application of an electric field with the actual electrodes geometry and working fluid was not able to stabilize the device operation: the greater polarization of the working fluid than the surrounding glass tube significantly weakened the electric field intensity in the working fluid region and, accordingly, the resultant disturbance is not able to influence the working fluid motion. Nevertheless, the application of an electric field had a different effect on the equivalent thermal performance of the device depending on the input heat power and, therefore, on the related flow regime: for low input heat power, the application of an electric field worsened the thermal performance; for high input heat power, the application of an electric field is mainly traduced in an enhancement of the thermal performance at a high voltage supply (20 kV).

5.1. Future developments

The electric field intensity in the working fluid region could be enhanced by the use either of a couple of electrodes in direct contact with the working fluid or of a working fluid with a lower dielectric permittivity as compared with the glass tube. A working fluid that could be exploited to enhance the electric field intensity in the working fluid region is the refrigerant FC-72: having a dielectric permittivity of 1.6 at ambient temperature it polarizes less than the glass tube, thus resulting in a higher electric field intensity in the working fluid region.

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