INFLUENCE OF INCLINATION ON THE PERFORMANCE OF A WICKLESS HEAT PIPE FOR SOLAR APPLICATIONS

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ABSTRACT

The paper describes an experimental study on the heat transfer inside a wickless heat pipe. In a previous paper [1, 2] an experimental campaign was conducted to ascertain the influence of different filling ratio on the heat transfer. The experiment was made with tubes inclined at 45°. To evaluate the influence of the inclination respect to the horizontal on heat transfer, a new campaign was conducted with the tubes inclined at 30°, to compare the result with those ones obtained with the different inclination. For this purpose the same filling ratio used in the previous campaign was used. The heat pipe is made of copper, the length is 1420 mm, internal diameter is 6 mm, and the vacuum inside is 10^{-5} bar.
The experimental campaign was conducted on the experimental facility named T.O.S.C.A. (Thermal-fluid dynamics Of Solar Cooling Apparatus), which has been designed and constructed to test the influence of various geometrical an thermo-hydraulic parameter on the performance of the wickless heat pipe. The facility was built in the "Thermal-Fluid Dynamics Applied to Energy Systems" laboratory of ENEA-Casaccia Research Centre (Rome),

The cooling loop is constituted of a collector coupled with a pump, a dumper and a heat exchanger. Pressurized water flows inside the collector cooling the heat pipe. The condenser section of the heat pipe is immersed in the free stream of the water. The heat pipe is heated by a heater made with an electrical wire wrapped on a length of 85% of the total length. We apply an electrical power, of 70W and 155W, values that simulate the solar power. Flow rate and pressure of the cooling water are constant. We measured the wall temperature of the heat pipe in the three different zone of the heat pipe: evaporator, adiabatic part and condenser; two other thermocouple are inserted in the collector to measure the heat transfer using a power balance.

INTRODUCTION

The recourse to the technologies able to employ the solar radiation profitably has become now a very common and advantageous practice in the industrial field as well as in the civil one. Solar cooling is the production of cold from solar heat, it allows to obtain considerable energy conservation compared to conventional plants. The solar cooling technology suggests to use the heat absorbed by "*evacuated tube solar panels*" to produce cold air or water to be used for summer air-conditioning or industrial refrigeration. The heat pipe is coupled with an adsorbing heat pump. The main feature of this configuration is that the greatest demand of energy for the air conditioning coincides with the maximum availability of solar radiation. A thermodynamic cycle is activated by the solar energy to product cold water or to treat air that can be used for room conditioning or refrigeration processes. For this purpose a wickless heat pipe is used as main component of the solar panel to use the high efficiency in heat transfer and its ability to transfer a great amount of heat over large distances with small temperature difference between the evaporation zone (heat input) and the condenser one (heat release).

In particular, this investigation has focused on the analysis related to the behaviour of wickless heat pipes used for the production of the abovementioned solar panels to be coupled to the adsorbing heat pumps for specific solar cooling systems. Heat pipe, meant as thermal duct, is a heat transfer device, characterized by high thermal conductivity which is based on the principle of evaporation and condensation of a working fluid introduced into a metal container. In its simplest configuration, the so-called wickless, the heat pipe consists of a closed tube of thermally conductive metal, such as copper or aluminium, in which the vacuum has been made and then filled with a small amount of working fluid. The rest of the tube is filled by the vapour of liquid so that there are no other gases

In a wickless heat pipe it is possible to identify three sections (Figure 1): a) at one end there is the evaporation section where the working fluid evaporates by absorbing the heat; b) at the other end, the condenser section, where the vapour condenses by releasing the heat; c) in the middle of these two ends, there is the adiabatic section where the vapour and liquid phases of the working fluid move in opposite directions without important heat transfer to the surrounding environment. Inside the device, the liquid and the vapour are in saturation conditions. When the evaporation section is very close to a heat source or is in a hot environment, the heat input causes the vaporization of the saturated liquid. This increases the pressure in the evaporation section which pushes the vapour towards the condenser section. Since the latter is in contact with a cool environment, the vapour condenses and releases the heat of vaporization which is transferred to the surrounding environment. Therefore, the condensed liquid can return to the evaporation section along the inner wall of the heat pipe due to the gravity force. Inside the pipe there is an endless heat transfer between the evaporation section and the condenser one where the working fluid transfers the heat. The heat pipe technology, originally used in space and nuclear applications, is now widely used in the computer industry for the cooling of microprocessors and electronic equipment. In particular, beside of the realization of solar panels, the wickless heat pipe is also used for the cooling of gas turbine blades, the realization of air-air or air-water heat exchangers and the extraction of geothermal energy [3].

A considerable amount of both theoretical and experimental studies has been conducted on the heat transfer performance of a wickless heat pipe in several applications. Such studies attempted to determine the effects that the variation of a series of quantities which are peculiar of a heat pipe has on the heat transfer performance.

Nguyen-Chi et al. [4] experimentally investigated the performance of a vertical wickless heat pipe using water as working fluid. Their study focused on the influence of operating parameters on the maximum performance either by dry-out or burn-out limits. Li et al. [5] experimentally investigated the steady-state heat transfer characteristics of a vertical two-phase closed thermosyphon at low temperature differences with water, R11 and R22 as working fluids. Shiraishi et al. [6] made an experimental study on the critical heat transfer rate in thermosyphons by taking into account the aspect ratio, filling ratio, working fluid property and operating pressure. Noie [7] experimentally analysed, among the various parameters that can affect the performance of a heat pipe, the effects linked to variations in input heat rate ($100 < Q < 900$ W), in the working fluid filling ratio ($30\% \leq FR \leq 90\%$) and in the evaporator length. Amornkitbumrung et al. [8] studied the effect of the inclination angle on the heat transfer rate of a copper thermosyphon filled with water. They concluded that the highest heat transfer rate occurs at 22.5° with a filling ratio of 30%. Wang et al. [9] studied condensation heat transfer inside vertical and inclined thermosyphons. They found that the inclination angle of a thermosyphon has an important influence on the condensation coefficient, and the optimum inclination angle varies with liquid filling from 20° to 50°. Negishi and Sawada [10] made an experimental study on the heat transfer performance of an inclined two-phase closed thermosyphon using water and ethanol as working fluids. Lee and Mital [11] performed an experimental study on the heat transfer performance of a two-phase closed thermosyphon while also developing a relatively simple theoretical analysis for its maximum heat transfer capacity. The study investigated the effects of parameters such as the amount of working fluid, the ratio of heated length to cooled length, the operating pressure, the input heat flux and working fluid were investigated.

The wickless heat pipes reported in literature have larger diameters than those examined in the present study. In this regard, the study conducted by Jouhara et al. [12] – which used a copper thermosyphon with 200 mm length, 6 mm inner diameter and 12 mm outer diameter - proves to be interesting.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental facility called T.O.S.C.A. (Thermal fluid dynamics Of Solar Cooling Apparatus) has been designed and built in the Laboratory of Thermal Fluid Dynamics applied to Energy Systems of C.R. Casaccia ENEA to test wickless heat pipes containing different amounts of working fluid. To characterize the thermosyphon, the experimental facility has been realized in the following way: a known and variable power is provided to the heat pipe by an electrical thread spread along the evaporation section of the device. The condenser section is inserted in a collector by which the cooling water flows. The inlet temperature and mass flow rate of water are note. Heat is removed from the condenser section and it is possible to quantify the heat transferred to the cooling water by measuring the outlet temperature from the collector. The Figure 1 shows the functional scheme of the apparatus: a valve allows water to flow to the test loop and then to set the pressure. After passing a filter, able to remove any solid particles, the cooling water is pumped by a eccentric pump, the water mass flow rate is in the range of 2.5 to 10 l/h. After the pump a damper (pressurized by azote) has been installed to further reduce pressure oscillations while maintaining stable flow conditions, the damper is also used as pressurizer. The capacity of the damper is of 2 litres, while the relief valve set pressure is equal to 6 bar. The cooling water pressure is measured by two pressure transmitters placed immediately upstream and downstream of the collector. Both transmitters have an accuracy equal to ±0.08% FS (full scale). After removing the heat from the condenser section of the heat-pipe, the cooling water flows inside a plate heat exchanger. A valve allows the cold water to enter into the exchanger to cool the water in the secondary loop. However, during the tests, this valve has never been opened. A Coriolis flow meter is used to measure the cooling water flow rate. The mass flow measuring range of the instrument is equal to 0÷65 kg/h. With regards to the temperature measurement, nine C_r-A_l thermocouples (K type) have been used: T_1, T_2, T_3 and T_4 temperatures have been acquired by four thermocouples (diameter 0.5 mm) installed inside the cooling water pipes of the test loop. The measurement of T_1 and T_2 temperatures, together with the measurement of p_1 and p_2 pressures, plays an important role in the apparatus because it allows to know the enthalpies (i_1 and i_2) of the cooling water and, consequently, the heat removed from the condenser section. The wall temperatures of the heat pipe have been acquired by three thermocouples welded directly on the outer surface of the device (T_5, T_6 and T_8). The first two thermocouples (diameter 0.5 mm) are placed 30 mm from the ends of the evaporation section, while the third one (diameter 0.25 mm) is situated 4 mm from the end of the condenser section. Finally, the T_{amb} and T_7 temperatures are acquired by two thermocouples (diameter 0.5 mm) which respectively measure the temperature of the test environment and the outer layer of thermal insulation of the heat pipe. In this way it is possible to know the heat losses from the heat pipe. All thermocouples mentioned before have an accuracy of ± 0.5 °C. The connecting pipes of the loop components are made of AISI 316 stainless steel. Several ball valves are installed on some pipes of the loop to allow or impede that the water flows. A release valve located directly on the collector has been installed to allow the air discharge from the loop. The demineralized water is used as coolant for its availability and compatibility with the materials used. The duration of each test is about 8000 seconds assuring that during the last 500 seconds the system is in steady state condition.

Test rig

Wickless heat pipes used in these experimental tests consist of copper tubes. Eight heat pipes are available for the analysis and each one contains a mass of working fluid (mwf) variable in the range of 3 to 20 grams. The filling ratio is defined as follows:

$$FR_{\%} = V_{vf}/V_e \bullet 100 \quad (1)$$

All the heat pipes, exactly alike geometrically, consist of a 1424 mm long copper tube having an inside diameter of 6 mm and outside diameter of 8 mm. The thermosyphon is inserted into a copper jacket warmed by a resistance heating wire consisting of a nickel-chrome alloy (80% Nickel and 20%

Chromium). This alloy is insulated from a sheath made of AISI 304L stainless steel. The copper jacket is the best mode to warm the heat pipe because it ensures a uniform warming of the device wall and greatly increases the flexibility of the facility as it allows to test the various thermosyphons in a very easy way. The length of the jacket, and consequently the length of the evaporation section, is equal to 1240 mm, while the adiabatic and condenser sections have a length of 94.3 and 55.7 mm respectively. The thickness of the jacket wall is equal to 1.2 mm.

The heater supply is conveyed through a VARIAC that allows to modulate the supplied power and to simulate the variation of the solar radiation during the entire span of the solar cycle. Two different level of power input are chosen 70W and 155W: These two value are similar to those really occurred in a solar heat-pipe with and without a reflective shield underneath.

To prevent heat loss, the heat pipe and the collector have been insulated by high temperature insulation glass fibres (thickness of 30 mm), a layer of polyurethane (thickness of 15 mm) and a layer of aluminium reinforced with glass fibres.

The inclination angle is 30° respect to the horizontal. This value allows a comparison with the previous data obtained with an inclination of 45°

The normal degree of vacuum created inside the pipe before the filling is 10^{-5} bar. For some specific tests also two different degree of vacuum of 10^{-6} and 10^{-3} bar are used. This to ascertain the influence of the vacuum degree on the behaviour of the heat pipe.

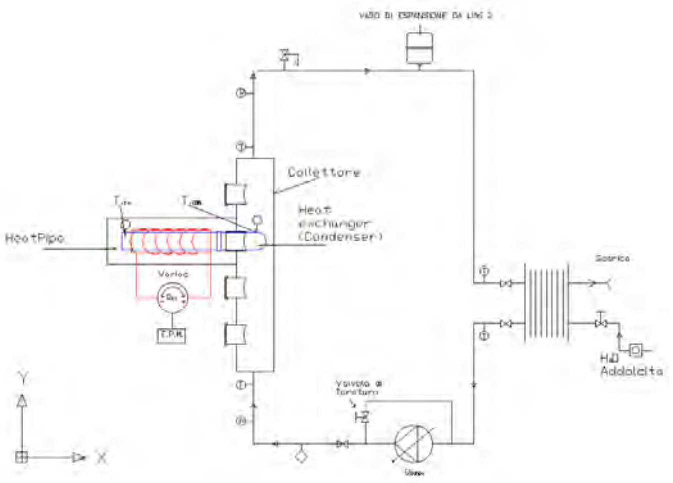

Figure 1 – Schematic diagram of the experimental apparatus

EXPERIMENTAL RESULTS

Several experimental campaigns have been carried out in order to characterize better the behaviour of the heat-pipe by varying its inclination and its vacuum with the main purpose of improving the heat pipe's performances for its application in solar cooling. The inclination was varied from 45° to 30° and the vacuum pressure from 10^{-3} mbar to 1 mbar. These tests were conducted by keeping fixed the flow rate and the pressure of the water in the secondary circuit respectively at 7,5 kg/h and at 3 bar. Furthermore these considerations were repeated for two levels of heat power, that are 70 W and 155 W, to simulate respectively the solar radiation upon the tubes both in natural conditions and considering the presence of solar concentrators.

Data were calculated as the average of the last 500 measure points collected by the acquisition system in order to get a representative numerical value of the stationary conditions. The last ones are reached with a certain degree of reliability in every test. This is due to the choice of an observation time of 8000 seconds, really more respect to the time constant of a common heat-pipe which is about 1000 seconds.

Inclination effect

The effect of the inclination on the heat-pipe's performances had been investigated by varying the filling ratios of the heat-pipes in the configuration of 30°.

In the figure 2 we observe the effect of a FR's change on the temperature T_5. This temperature has been measured at the bottom of the heat-pipe, immediately at the end of the heater with a thermocouple appropriately modified. The value of the temperature measured in this way provide information about the evaporator section, that is the section of the tube in which water change its phase conditions from liquid to the vapour state.

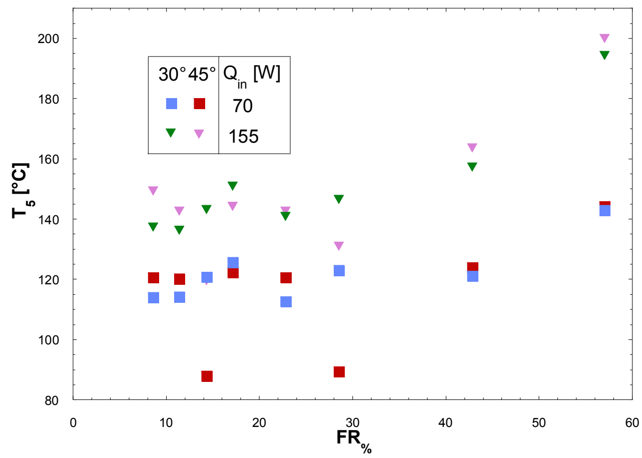

Figure 2 - Effect of the inclination on T_5 for different FR

Another investigation was conducted on the temperature T_6 which is the temperature of the adiabatic section of the heat-pipe, and it is measured just above the heater. We call it adiabatic because it lays between the heater and the junction with the secondary circuit, protected with a coat of mineral wool and polyurethane respectively of 3 cm and 1,5 cm, figure 3.

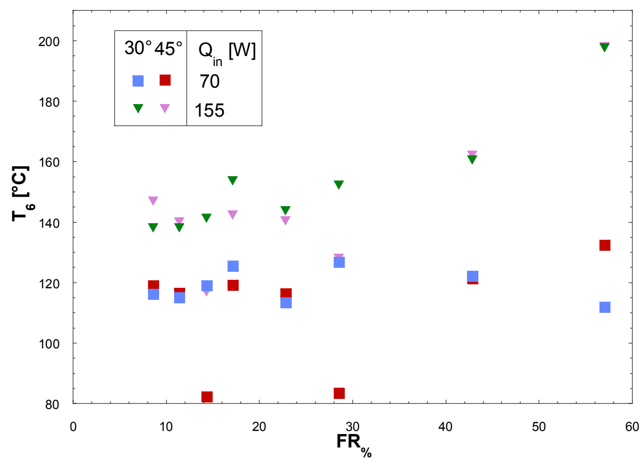

Figure 3 - Effect of the inclination on T_6 for different FR

This result means that there isn't a preferential inclination, in a certain range, which maximize the temperatures

This could be an advantage in terms of adaptability of the heat-pipe, as a component of a solar-cooling system to different latitudes. In fact, depending on the latitude there is an inclination which maximize the radiation upon the tubes.

We can deduce other important conclusions by observing both the power input and the power output in figure 4. They are respectively the power we provide through the electric wire with a variac and the power we remove through the cooling circuit.

The heat-power output has been calculated with the expression $Q_{out} = G_W (i_1-i_2)$, were G_W is the water mass flow and i_2 and i_1 are the enthalpies evaluated in correspondence to the temperatures T_2 and T_1, measured respectively before and after the condenser section.

Data could be easily fitted and equations are shown in the chart. These equations would provide an helpful device in projecting solar cooling plants: in fact they permit to evaluate the amount of heat power released to the secondary circuit once we know the heat power input.

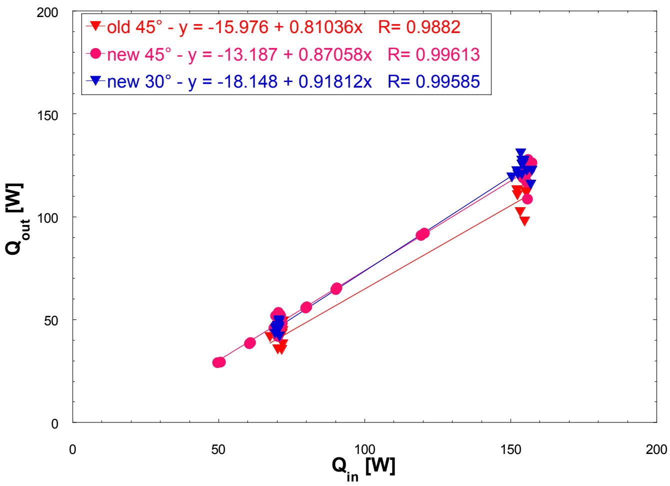

Figure 4 - Heat released in function of the heat input

The differences between the old heater and the new one is that the first was long 1220 mm and the new is long 1240 mm. Another difference is that the first had a diameter of 8,5 mm and the new one has a diameter of 9 mm. This fact, in addition to a difference in thickness caused several difficulties in phase of experimentation so the heater was substituted with the new one.

Figure 5 represents the heat released from the heat-pipe in function of the filling ratio both for an input power of 70 W and for an input power of 155 W for the two inclination of 30° and 45°. As already resulted from the observation of the temperature behaviour, the Q_{out} shows a substantial indifference to the inclination.

It is also interesting to investigate the behaviour in function of the time also in order to better understand the dynamical effects of the filling ratio and of the inclination.

As it concerns the effect of the FR, it is evident from the figure 6 that the time constant of different heat-pipes with different filling ratios remain approximately the same, that is about 1000 seconds. The only exception is the heat-pipe with a FR = 11,4% (m = 4g), but this difference seems more caused by accidental conditions occurring in measurements rather than by a constant behaviour. In fact, the other tests conducted with the same FR don't present the same pattern.

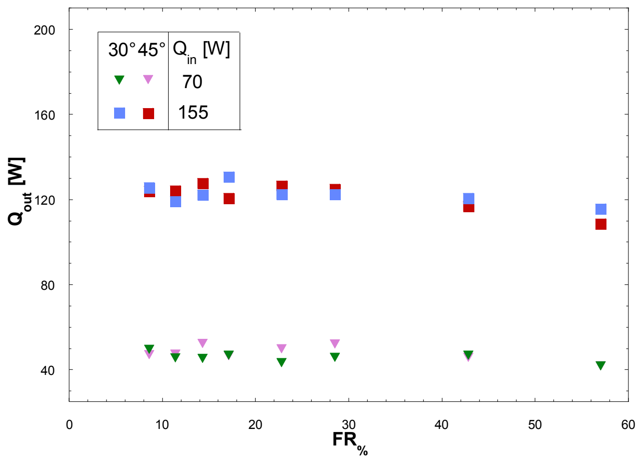

Figure 5 - Heat released in function of the FR for different inclinations

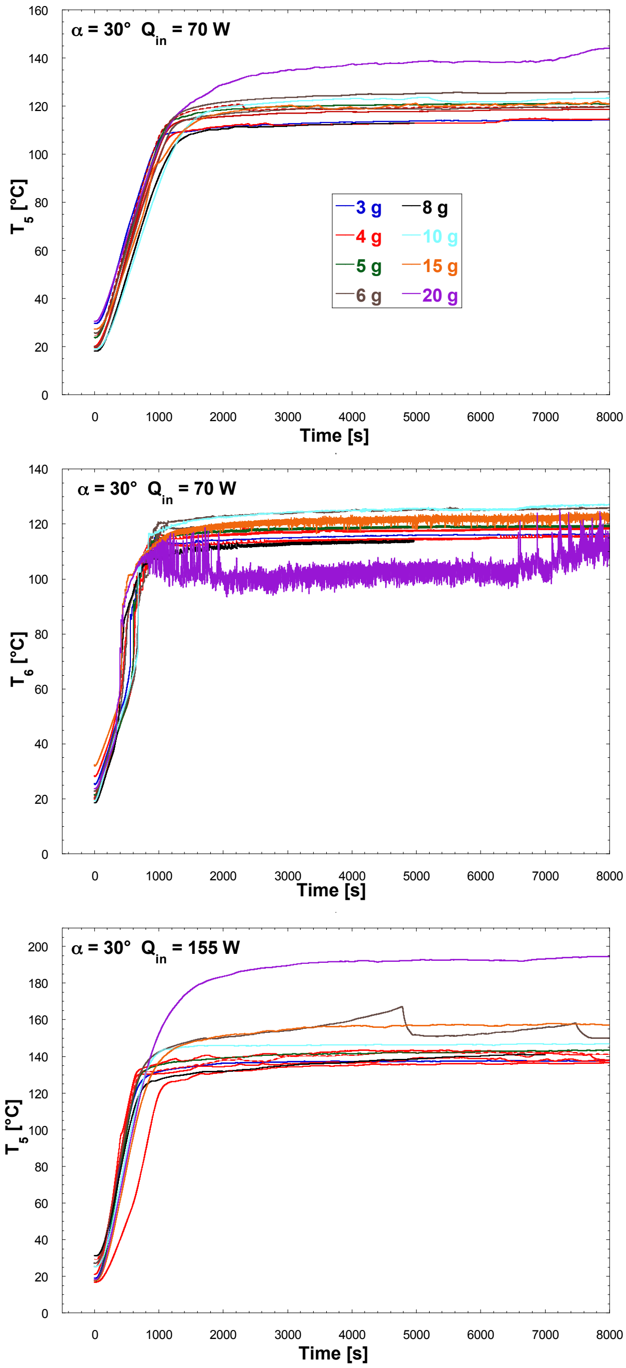

Figure 6 - Effects of the FR on temperatures T_5 and T_6 (continued)

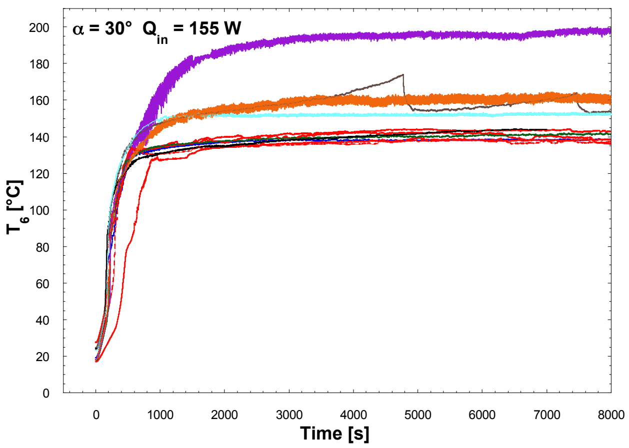

Figure 6 - Effects of the FR on temperatures T_5 and T_6

We can see from the figure 6 that the temperature T_6 undergoes various oscillations. This probably derives from the position of the thermocouple very close to the evaporator section. In fact these oscillations are clearly caused by the process of boiling. For frequencies lower than 0,1 Hz we refer to the process as low frequency nucleation. In our case the temperature oscillations vary from 0,5 Hz of the 15g to the 0,05 Hz of the 4g.

The temperature T_5 instead, doesn't present any meaningful oscillation, this is also because it is positioned at the base of the heat-pipe so probably it measures the temperature of the pure liquid phase in the evaporator section, without perceiving any important non-stationary effect.

It is important to outline that the data acquisition-system used for the experiments has a cutoff frequency of 2 Hz. Therefore it is possible that temperatures investigated have higher frequencies of oscillation invisible in charts. In fact the fully-developed boiling mechanism could also reach frequencies higher than 10 Hz.

Figure 7 shows the effect of the inclination on the time constant and we can recognize that there is no meaningful difference in terms of temperature evolution in time between the inclination of 30° and 45°.

For representations we considered an observation time of 2000 seconds, admitting that this time is sufficiently representative of the initial transitory for each kind of heat-pipe examined.

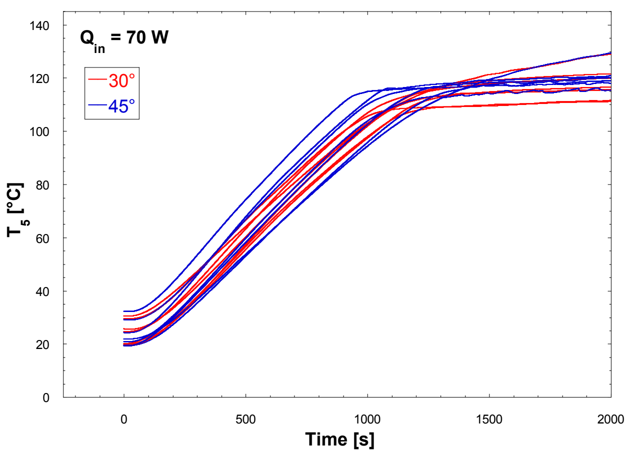

Figure 7 - Effect of the inclination on the time transitory

Vacuum effect

Different experimental data were obtained by varying the vacuum of the tubes. These tests were conducted in correspondence to an inclination of 30° and with the same conditions of the secondary circuit as already specified for the previous case.

For this new campaign only two different filling ratios have been tested: the 5 g and the 10 g corresponding to a FR respectively of 14,3 % and 28,6 %. This choice had been done in order to better understand the behavior of two particular heat-pipes.

These ones were tested in the last experimental campaign and showed lower temperatures respect to the other filling ratios. The following chart provides a possible explanation of this fact by admitting that an accident in the manufacturing process would have implied a reduction of the inner vacuum with a consequent reduction of the temperatures measured.

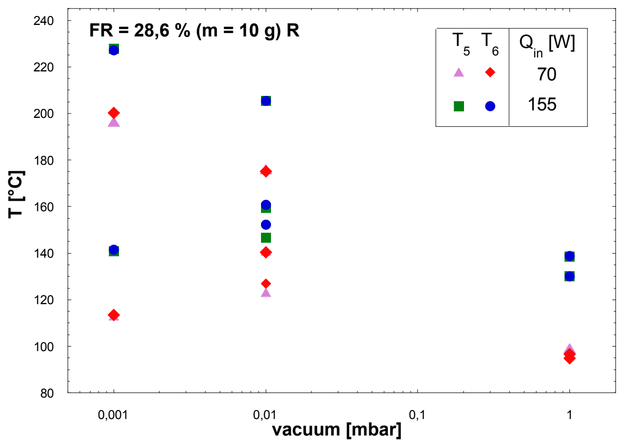

Figure 8 -Temperatures T_5 and T_6 in function of vacuum for FR=28,6%

As we can see from the figure 8, for the two power inputs of 70 W and 155 W, there is no evidence of an influence of this parameter on the temperatures value reached in steady state.

Repeating these considerations for the other filling ratio of 14,3 % we have obtained the following pattern represented in figure 9.

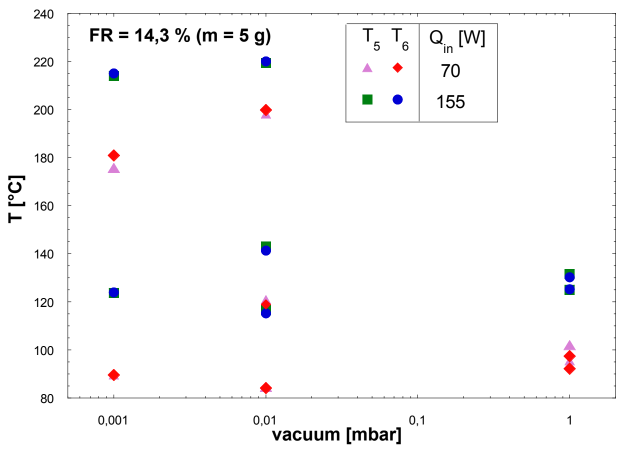

Figure 9 - Temperatures T_5 and T_6 in function of vacuum for FR=14,3%

Also in this case we are not able to find any evidence of the influence of the vacuum on the temperatures. The great scatter of the data, especially for the lowest value of the vacuum, indicate that some others parameters influence the phenomenon, or indicate the difficulties to realize a vacuum degree with good approximation.

To better understand the vacuum effects we have investigated the heat-pipes with 5g and the 10g for each level of heat power, first for 70 W and after for 155 W.

As evidenced from the figure 10, the time constant of the heat-pipes don't vary significantly with the inner vacuum.

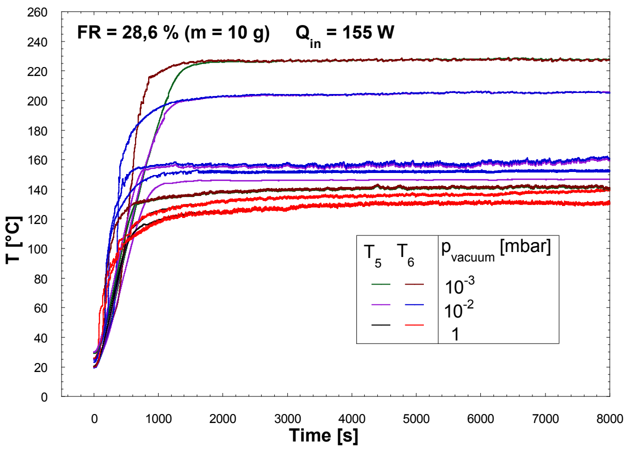

Figure 10 - Evolution in time of T_5 and T_6 for FR = 28.6%

It has been investigated also the heat released from the heat-pipe to the secondary loop when varying the vacuum of the heat-pipe. We can see from the figure 11 that the maximum power exchanged is not influenced from the vacuum, instead at lower vacuum the data show a great scatter.

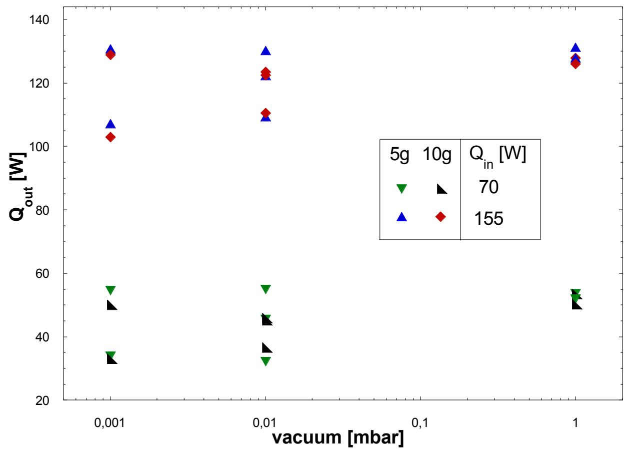

Figure 11 - Effect of vacuum on Q_{out} for different FRs and powers

CONCLUSION

A new experimental campaign was done to ascertain the influence of inclination respect to the horizontal plane. This in order to characterize better the thermal behaviour of an evacuated heat-pipe in steady-state conditions and in transitory times.

All others parameters being constant, the inclination was set to 30° instead of 45° of the previous works; the choice of 30° has been done in order to provide information about a working condition that is a common project solution. Results have evidenced that these effects are negligible allowing us to use the best inclination for the heat-pipe, when used in a solar collector. The only noticeable difference is a grater uniformity of the heat-pipe temperatures in the case of the inclination of 30° respect to the 45° one.

In this paper we studied also the influence of the vacuum created inside the heat-pipe before water insertion. Data do not permit to allow any conclusion, so we need new test runs which would ascertain the fluid-dynamic effect of the presence of incondensable gases on the heat exchange mechanism.

In the future we want to investigate the behaviour of the heat-pipe by simulating the presence of absorbing chillers with an electric resistance in order to estimate more accurately the solar cooling potentialities of the heat-pipe.

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