

Design and study of a Flat Plate Oscillating Heat Pipe. Flow Pattern analysis and Heat Transfer Performance

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Abstract. Recent and constant demands for greater power densities and smaller sizes of electronic systems have stimulated the growth of new designs of different passive heat transfer methods such as heat pipes. Particularly, Oscillating Heat Pipes (OHPs) are relatively novel devices, capable of removing high heat rates over long and short distances with not much temperature drop. Its heat transfer mechanism relies on a self-oscillating motion of a two-phase flow of a working fluid circulating through meandering channels. This study concentrates on the design, building and assembling a test rig in order to analyse the flow pattern of deionised water through a 5 turns Flat Plate Oscillating Hat Pipe under different heat inputs, which was made in the School of Engineering and Materials Science of the Queen Mary University of London by two PhD students. The filling ratio of the water is 40%. Furthermore an experimental study on the OHP thermal performance is carried out in order to examine the effects of different surface wet conditions: super hydrophilic, hydrophilic and cleaned brass. It is demonstrated the formation of liquid slugs and vapour plugs of the water along the channels. The experimental results showed that the hydrophilic surface tend to be more energy efficient. The heat transfer performance of the superhydrophilic and hydrophilic is higher than brass by 5-12% and 15-20% respectively

Keywords: Oscillating Heat Pipe, two-phase flow, liquid slugs, vapour plugs, heat transfer

1. Introduction.

Oscillating (or pulsating) heat pipes (OHP) are predicted to be a promising solution for the thermal management of compact cooling and have a wide variety of applications. 2013 Heat Transfer International Conference of American Society of Mechanical Engineers (ASME) [1] presented OHPs as an assuring novel technique for enhancing the energy efficiency throughout industry. It is a passive, innovative and efficient device introduced and registered in the nineties by Akachi [2].

OHPs consist of a serpentine channel of a tube of capillary dimensions, which has been partially filled with a working fluid as Figure 1 depicts. The heat input produces the evaporation and boiling of the working fluid, which increases the vapour pressure. This pushes the liquid slug towards the cooling part, where the bubbles begin condensing and the vapour pressure decreases. Thus, the liquid goes back to the heating section. The growth of the bubbles in both zones enables the self-excited oscillatory motion of liquid slugs and vapour plugs [3]. The process deals with a two-phase thermodynamic cycle and also entails a combination of different mechanisms: bubble nucleation, slug flow, condensation and pressure and temperature fluctuations. Heat pipes are non-equilibrium heat transfer devices and the phenomenon is complex to understand. It has still investigation shortage. For this reason much research on understanding the operating mechanism and the self-oscillating motion has been done until date.

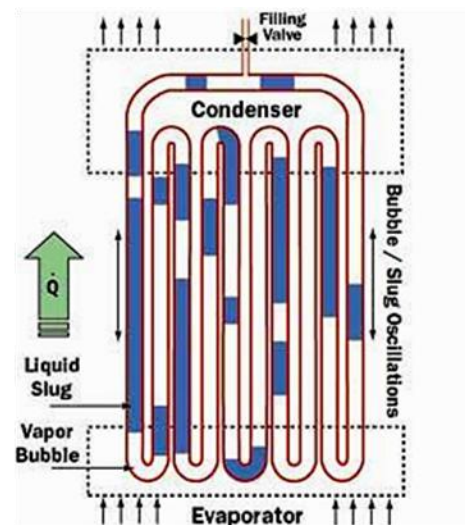


Figure 1. Schematic representation of closed-loop oscillating heat pipe (CLOHP) [4].

adiabatic section and 38 mm condensation section (Figure 3).

The evaporator zone of the OHP consists of a brass block attached in the rear lower side of the brass plate. A cartridge heater (RS, 400 W, 220 V ac) is inserted into this block to be connected to a power supply and then heating the water inside the channels. Cylindrical configuration instead of strip was selected due to the compactness of the cartridge heater and the small space available. The heat input is regulated by an autotransformer. The block is covered by a cork sheet in order to achieve minimum heat losses (Figure 4). Thus, the maximum heat transfer rate delivered by the cartridge heater is transferred to the evaporator zone. The maximum desired temperature in the meandering channels is 100°C. Hence, the evaporator zone is designed to reach 115°C at the wall of the block next to the OHP in 15 minutes.

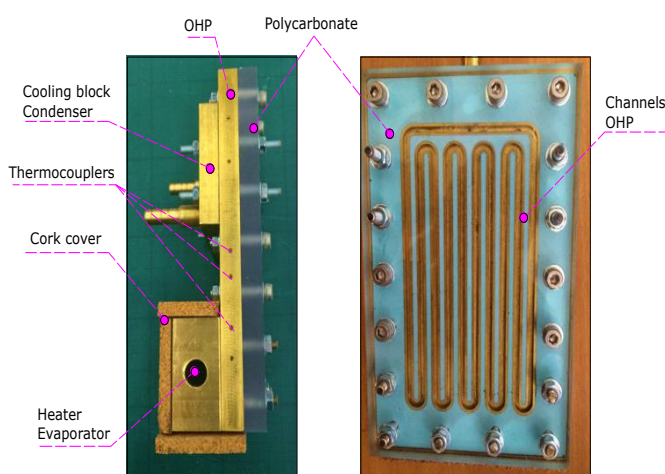


Figure 4. Assembly OHP

A cooling block is located at the top rear part of the OHP. This condenser part is cooled by water circulation at constant inlet temperature of 15 °C coming from a cold bath (Thermo Scientific, Phoenix II, ± 0.01 K) and range flow rate of 200 ccm to 3000 ccm. This flow rate is controlled by a flowmeter (Acrylic Flowmeter 200-3000 CCM, Instruments Direct, $\pm 3\%$). The cold bath unit supplies a pressure pump to flow the water. PVC flexible tubes of 6 mm inner diameter are used for the connexions cooling circuit-cold bath-flowmeter (RS PVC 25 m long transparent tube).

As far as temperature measurement concerns, twelve perforations of 0.8 mm diameter were drilled in the sideways of brass plate and located just 2 mm beneath the channels with the purpose of placing thermocouples connecting to a data logger. Two more thermocouples are placed in the inlet and outlet of cooling block to measure water temperature. The thermocouples were calibrated for the range maximum of ± 0.1 °C. For this study it is assumed an ambient temperature of 20°C.

A two-valve valve is placed on the copper tube at the top of our OHP as can be seen in Figure 5. A vacuum pump is connected to this valve aiming to fill the channels with the working fluid without increasing the pressure. The

working fluid was introduced by a syringe with the wanted filling ratio.

B. Preparation of different surfaces.

Before running the experiment, three surface wetting characteristics were prepared: the brass surface of the OHP was prepared to be cleaned brass, hydrophilic and superhydrophilic.

Firstly, the cleaned brass was achieved by washing the plate with sulphuric acid and deionised water. Then, in order to obtain a hydrophilic surface, a CuO coat layer was prepared. The brass plate was immersed in a solution of 2 mol/L KOH and 0.07 mol/L $K_2S_2O_8$ at 80°C for 30 min. Thus, the coat layer was created on the surface and the plate was dried at 120 °C for 45 min. Finally with the purpose of creating a hydrophilic surface, previous CuO layer was submerged in a diluted H_2SO_4 bath. Afterwards, the OHP base was introduced in a 0.0020 mol/L solution of n-octadecyl mercaptan and in ethanol for 30 min at 70 °C [11]

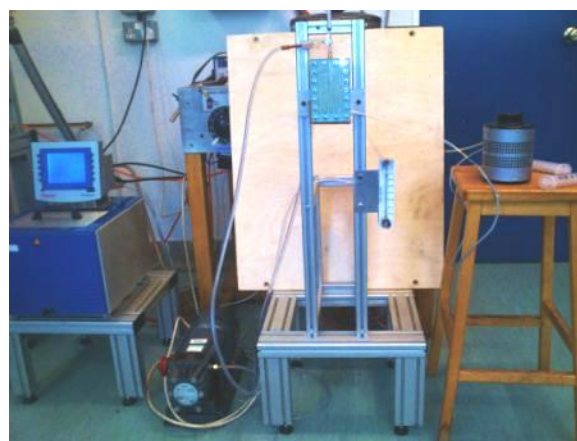


Figure 5. Test-rig configuration

3. Results

A. Flow Pattern

In total, 10 experimental runs at two different flow rates were performed with five different heat inputs: 400 W, 200 W, 100 W, 50 W and 25 W. The first set was run for a flow rate equals 200 ccm, which means laminar flow, and the other set for a flow rate equal to 1000 ccm. The filling ratio was 30% and the angle orientation was 90°C, vertical position and bottom heat mode.

As the heat input increased, the working fluid required a period of 15 min to get a new stable state. The system was considered to be in a stable condition when the temperature between the thermocouples was lower than 0.2°C.

First of all, it was observed the desirable effect: liquid slugs of water, as it is apparent from figure below. Hence, the design meets the requirements for the heat pipe operation. This phenomenon is because the surface tension forces are larger than gravitational forces.

The analysis and visualization indicate that by increasing the heat input from 25 W to 400 W, the frequency of the bubbles motion increases also, but the flow pattern is

essentially similar. A more powerful camera might appreciate this parameter change.

When the subcooled liquid reached the adequate temperature or in other words, when the wall temperature is higher than the saturated temperature (nucleate boiling), the regular flow pattern started with the relative quick growth of small bubbles in the evaporator zone. The velocity of bubbles growth depended on the heat input.

Due to convection and the consequent pressure increment, these small bubbles were dispersed until they coalescence and became vapour plugs which bring up the liquids slugs to the condenser, (Photo 1). This flow occurs at distinctly high velocity after ten seconds as maximum. The reason of these effects is fundamentally that when the water in the groove is heated and expands, its density is reduced and becomes more buoyant compared with the cooler water in the upper part.

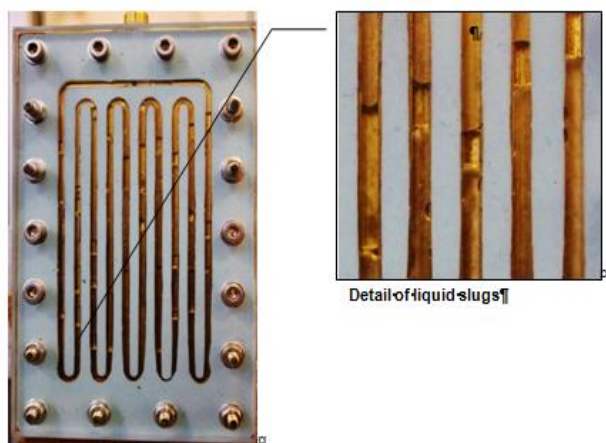


Photo 1. Expansion and contraction of the vapour plug. Start-up, evaporation section.

Because of inertia and gravity, the liquid slugs returned from the condensation to the evaporation zone and compressed the vapour plugs flowing up. It was also found that some small liquid droplets coming from the condenser emerged from the thin liquid film adjacent to the wall at high heat inputs. However, the dry out of the evaporator did not take place. Even though, it could occur for longer periods.

The previous phenomenon caused the bursting of some bubbles. Consequently and similarly to an elastic spring, the expansion and consequent contraction originated the oscillating movement expected:

Finally, since the flow was very unstable, it is difficult to assert a type of flow regime, but it can be said that it was a combination of slug flow along the condenser and the adiabatic part, and annular flow at the bottom of the device. Thus, forced convection boiling and nucleate boiling seem to coexist in the heat pipe

B. Surface effect on thermal performance

It's compared the thermal resistance, the evaporation heat transfer coefficient and the heat load of three wetting

surface conditions on the thermal performance of an OHP was studied.

It is clear from the graphs below that as the heat input increases, the thermal resistance decreases for all the cases.

Figure 6 illustrates the thermal resistance of the OHP for the three different surfaces at different heat input. The hydrophilic and superhydrophilic surfaces showed a better heat transfer performance than cleaned brass. The thermal resistance for the super hydrophilic surface was 10-20% higher thermal resistance than the hydrophilic one.

As is shown by Figure 7, both evaporation heat transfer coefficients in the superhydrophilic and hydrophilic OHP were higher than those for the cleaned brass.

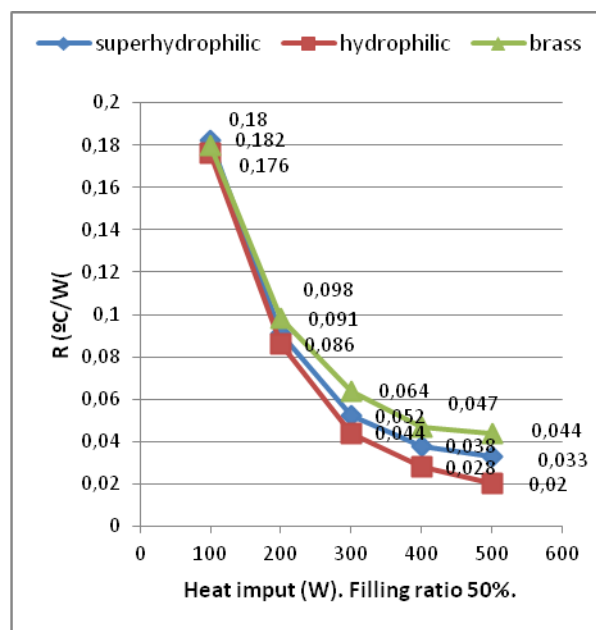


Figure 6. Thermal resistance of superhydrophilic, hydrophilic and cleaned brass at different heat inputs.

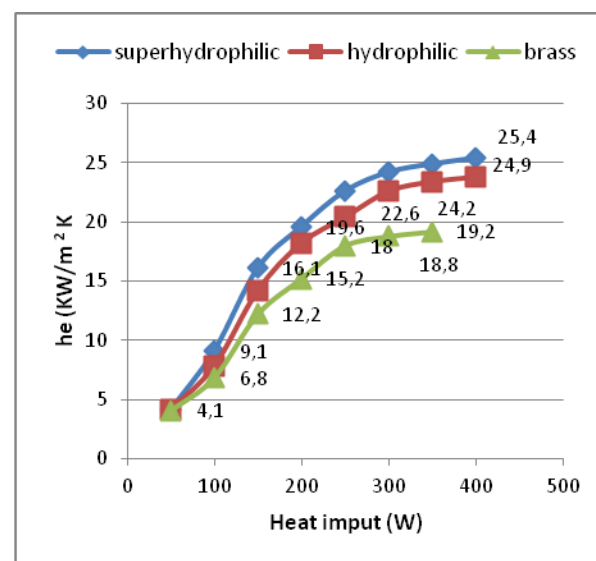


Figure 7. Evaporation Heat transfer coefficient of superhydrophilic, hydrophilic and cleaned brass at different heat inputs

As can be seen from Figure 6 the thermal resistance were notably bigger in the hydrophobic OHP due to the less movement of the liquid slug, and the heat coefficient of the hydrophilic OHP was upper than that of the brass surface as shown in Figure 7 account of to the decrease of evaporation section temperatures.

C. Filling Ratio effect on the thermal performance

The heat load, the start-up temperature and start-up power were evaluated at filling ratios of 30%, 50% and 75%. It's apparent from Figure 6 that there is a reduction in the heat transfer performance with the increment of the the filling ratio. The graph also shows that the hydrophilic surface presented the highest heat load in comparison with the superhydrophilic and cleaned brass.

Figure 9 and Figure 10 reveal that the hydrophilic surface displayed the lowest startup power and temperature while the brass showed the lowest ones. The startup temperature of the superhydrophilic, hydrophilic and brass OHP varied from 34 to 45°C, 33 to 49°C, and 30 to 40°C respectively.

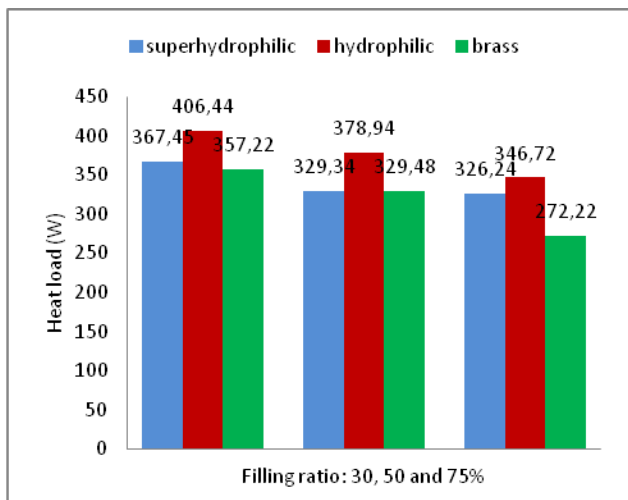


Figure 8. Heat load of the OHP.

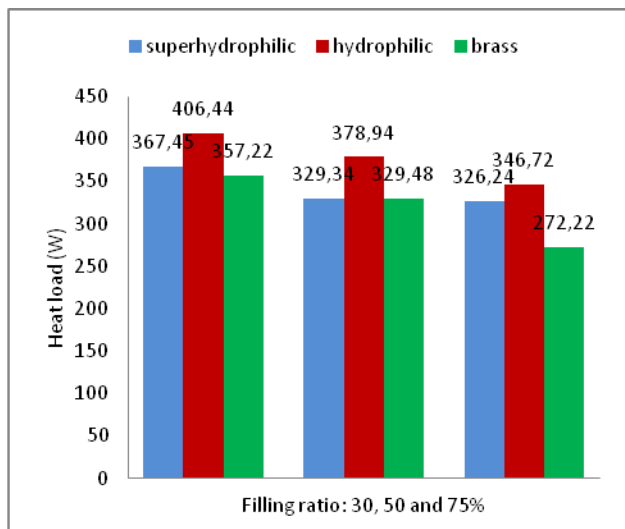


Figure 9. Startup power, superhydrophilic, hydrophilic and brass surface

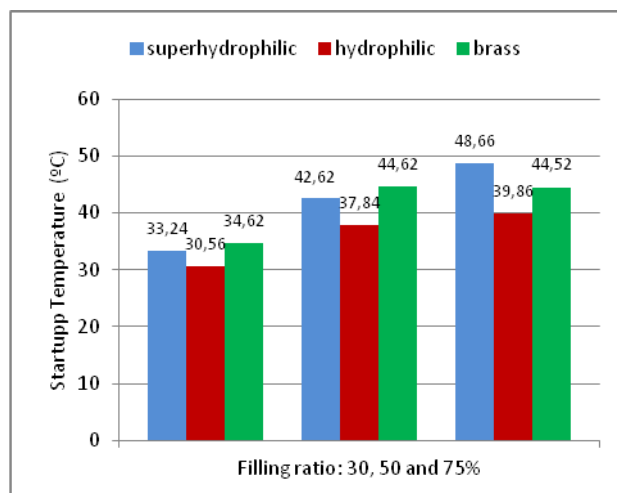


Figure 10. Startup Temperature, superhydrophilic, hydrophilic and brass.

4. Conclusions

From the test rig built and the research carried out the following points can be concluded:

- The design of the heat pipe meets the original conditions for its operation. Surface tension was higher than gravity forces.
- There must be sufficient liquid in the system to transfer sensible heat and create the flow featuring with vapour plugs and liquid slug
- The temperature difference between the liquid slug and the capillary wall was high enough at 25 W to cause the bubble growth
- Collapse and breakage of bubbles, coupled with nucleate boiling took place inside the engraved channels. All this phenomenons combined in the same system means a relatively complicate and unstable behaviour.

From the heat transfer performance, it's conclude the following,

- As expected, super hydrophilic and hydrophilic surface showed a higher thermal performance than cleaned brass. OHP.
- The hydrophilic surface reflected the lowest thermal resistance of the wet conditions analysed.
- The heat transfer coefficients in the superhydrophilic and hydrophilic OHP were approximately 20% higher than in brass OHP.
- In comparison with cleaned brass, the heat input required in the hydrophilic surface fall by 22 to 28% for the working fluid filling ratio of 30, 50 and 75%. A hydrophilic surface results in a better energy efficiency device.
- The startup temperature at which the self-oscillating process of OHP begins of the hydrophilic in contrast with

clean brass surface OHP is reduced about 12 to 16% according filling ratio of 30, 50 and 75%

- The heat transfer performance is reduced as the filling ratio is increased.

Despite the remarkable attempts in the last two decades, further investigation in OHPs is fundamentally needed. Refrigeration devices and heat sinks are usually substantially large and locations are limited for them. Hence, reducing the volume and weight of innovative cooling systems would lead to more efficient compact electronics and consequently, to energy and monetary savings.

In comparison with conventional heat pipes, oscillating heat pipes show prominent advantages such as: simple structure (no necessity of manufacturing complex and expensive wick structures), low cost and low weight.

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