Analysis of Heat Transfer of a Flat Plate Oscillating Heat Pipe, for Different Surfaces

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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, OHPs (Oscillating Heat Pipes) are relatively novel devices, capable of removing high heat rates over long and short distances with not much temperature drop. 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 heat 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 energy M.Sc. 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 tends to be more energy efficient. The heat transfer performance of the super-hydrophilic and hydrophilic is higher than brass by 5-12% and 15-20% respectively.

Key words: Oscillating heat pipe, heat transfer, flow pattern, thermal performance.

1. Introduction

OHPs (oscillating (or pulsating) heat pipes) are predicted to be a promising solution for the thermal management of compact cooling and have a wide variety of applications. In 2013 heat transfer international conference of ASME (American society of mechanical engineers) [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 Fig. 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, many researches on understanding the operating mechanism and the self-oscillating motion have been done until date.

Previous experimental works have focused on the heat transfer mechanism and on the visualizations of flow patterns.

It is generally agreed, QU, J. and WANG, Q. [5], Barua, H., et al. [6] that the thermal performance and the flow regime of OHP depend on the effects of the working fluid, FR (filling ratio), power input, operating

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

orientation and different geometries. The working fluid is commonly the most effective parameter to improve the thermal performance of heat pipes [7].

The difference between the power supplied in the evaporator zone and the heat released from the condenser part is usually less than 5% [8]. All the authors stated the same way of measuring the performance of the OHP by estimating the overall thermal resistance of the device as a simple steady state system, given by equation below:

$$R_{OHP} = \frac{(T_e - T_c)}{Q_{in}} \quad (1)$$

where, Q_{in} is the heat power input and, T_e and T_c are the mean temperature of the evaporator and condenser part.

The visualization of the fluid motion inside the heat pipe is strongly relevant for theoretical investigations on the fluid dynamics of the self-oscillating motion of the working fluid. LIU, X. D. and CHEN, Y. P. [9] studied the flow patterns of a flat plate OHP of a solar collector unit. Ethanol is used under different filling ratios and a numerical model explains the bubble behaviour. It is concluded an average deviation of

11.3% between the experimental study and the numerical results regarding the size of the bubbles. Furthermore, they determined that the higher evaporator temperature, the better thermal performance.

The results of HAO, T. et al. [10] and related references argued the relationship between the surface of the pipes, its working fluid oscillation and heat transfer performance. These authors studied two copper FP-OHPs with four and six turns respectively and the flow pattern. It was observed dissimilar liquid-vapour interface depending on the number of the turns and surface wetting characteristics: super-hydrophilic, hydrophilic, copper and hydrophobic. The authors concluded that the higher number of turns, higher thin film length and higher frequency oscillation. Hence, heat pipe with six turns showed better heat transfer performance. Also, a hydrophilic surface has a considerable positive effect on the slug motion and heat transfer performance in comparison with copper pipes. However, unlike OHP with four turns, the super-hydrophilic surface presented higher thermal performance for six turns OHP and the dry out of the evaporator occurs at some heat inputs.

2. Experimental Set-up

2.1 Test Rig Assembly

It is designed and built an experimental test rig consisting of three main parts: a five-turn OHP, a heating system at the bottom of the heat pipe and a cooling system at the top of it, Fig. 2 depicts this arrangement.

The OHP is made up of a brass plate (95% copper and 5% tin) ($140 \times 90 \times 10 \text{ mm}^3$) where five meandering channels ($2 \times 2 \text{ mm}^2$) were machined into the plate (Fig. 3). Since the OHP operates in vertical position, the brass plate is covered by a PC (polycarbonate) sheet to prevent water from coming out and to observe the flow pattern through the channels. PC is chosen

Fig. 4 Assembly OHP.

because of its convenient features including colourless and heat resistant up to around 130 °C. Both brass plate and PC sheet have been hermetically sealed with a built and designed shape of silicone (Flexil-S, J24 RTV) mixed with a catalyst to avoid working fluid leakage (Fig. 4). An own mould was fabricated by introducing the embossed drawing of the OHP on a numeric model milling machine. To fill the OHP with the working fluid, 1 mm diameter pipe and a valve were assembled on the top edge. Deionised water is used as working fluid.

The OHP's channels total length was 109 mm, distributed in 30 mm evaporation section, 41 mm adiabatic section and 38 mm condensation section (Fig. 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 (Fig. 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.

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 3,000 ccm. This flow rate is controlled by a flowmeter (acrylic flowmeter 200-3,000 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 Fig. 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.

2.2 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 super-hydrophilic.

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].

Fig. 5 Test-rig configuration.

3. Results

3.1 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 1,000 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 sub-cooled 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, (Fig. 6). This flow occurs at distinctly high velocity after ten seconds as maximum. The reason of these effects is

Fig. 6 Expansion and contraction of the vapour plug. Start-up, evaporation section.

fundamentally that when the water in the groove is heated and expanded, its density is reduced and becomes more buoyant compared with the cooler water in the upper part.

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.

3.2 Surface Effect on Thermal Performance

It is 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 were studied.

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

Fig. 7 illustrates the thermal resistance of the OHP for the three different surfaces at different heat input. The hydrophilic and super-hydrophilic 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 Fig. 8, both evaporation heat transfer coefficients in the super-hydrophilic and hydrophilic OHP were higher than those for the cleaned brass.

As can be seen from Fig. 7 the thermal resistance was 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 Fig. 8 account of to the decrease of evaporation section temperatures.

3.3 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 is apparent from Fig. 7 that there is a

Fig. 7 Thermal resistance of superhydrophilic, hydrophilic and cleaned brass at different heat inputs.

Fig. 8 Evaporation heat transfer coefficient of superhydrophilic, hydrophilic and cleaned brass at different heat inputs.

Fig. 10 Startup power, superhydrophilic, hydrophilic and brass surface.

Fig. 9 Heat load of the OHP.

reduction in the heat transfer performance with the increment of the filling ratio (Fig. 9). The graph also shows that the hydrophilic surface presented the highest heat load in comparison with the super-hydrophilic and cleaned brass.

Figs. 10 and 11 reveal that the hydrophilic surface displayed the lowest start-up power and temperature while the brass showed the lowest ones.

Fig. 11 Startup temperature, superhydrophilic, hydrophilic and brass.

The start-up temperature of the super-hydrophilic, hydrophilic and brass OHP varied from 34 to 45 °C, 33 to 49 °C, and 30 to 40 °C respectively.

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 these phenomena combined in the same system mean a relatively complicate and unstable behaviour.

From the heat transfer performance, it's concluded as 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 super-hydrophilic 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 start-up 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 to 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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