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A LOW COST, FLEXIBLE PULSATING HEAT PIPE TECHNOLOGY

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ABSTRACT

A novel flexible pulsating heat pipe technology (FPHP) is presented, which enables fabrication of flexible, lightweight and low cost heat transfer devices using thermoplastic materials (polypropylene). A flexible and lightweight PHP is advantageous for space, aircraft and portable electronic applications where the device weight is crucial. Although the thermal performance of thermoplastics is usually poor, this technology enables the creation of composite thermoplastic materials having a significantly enhanced thermal conductivity. The basic concept is to sandwich a serpentine channel, which is cut out in a polypropylene sheet and contains a self-propelled gas-vapour mixture, between two transparent polypropylene sheets, bonded together by selective laser welding. This results into a heat transfer device with a large surface and very small thickness (approximately 1.5 mm), which makes it suitable for many existing and future applications where thermal management is not possible using existing technologies. The thermal performance of FPHPs was characterised for different heat input levels; local heat transfer coefficients were estimated by measurement of the heat fluxes and the wall temperatures at different positions in the FPHP. Results showed that the effective thermal conductance of the FPHP was nearly three times higher than that of the material constituting its envelope.

KEY WORDS: Pulsating Heat Pipe, Thermoplastic Material, Selective Laser Welding

1. INTRODUCTION

Pulsating heat pipes (PHPs) are becoming a popular technology to address passive thermal management of nuclear, defence and space applications [5–7]. The PHP design variants proposed and studied to date, have the potential to meet many of the present and future specific requirements from electronics cooling [8, 10], heat recovery [2, 15] and passive cooling of reactor containments, to name a few. However, certain characteristics of state-of-the-art PHPs (their mechanical rigidity, their weight, and their cost) make their use technically and/or economically challenging in several cases. This often prevents potential applications to a range of novel consumer technologies, where mechanical flexibility, weight and cost are critical design and/or marketing constraints. For example, flexible devices can be applied in multiple potential configurations, where the heat sink is out of plane with the heat source [3]. Early studies focusing mainly on space applications, proposed to obtain local flexibility in the adiabatic region using bellowed (corrugated) tubes [16, 17]. More recently, there was an increasing interest in the development of flexible HP devices built using thin metal foils, sintered metals [11], polymeric materials [9, 12, 18] and micro-machined liquid crystals [13].

However, the approaches proposed so far suffer from several technical issues. Firstly, the fabrication of flexible

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metallic components is possible only using thin-walled tubes and/or thin metal foils, with severe reduction of their mechanical resistance, in particular to fatigue; this has obvious consequence on the system reliability and operational lifetime. Secondly, these flexible heat pipes are not based on the wickless PHP concept, but the liquid phase circulation is promoted by a micro-manufactured wick structure, such as sintered copper woven mesh [12]; this results into high manufacturing cost and poor mechanical strength. Other technical issues encountered were liquid and gas diffusion through the polymer and billowing of the flexible material due to pressure differentials.

The flexible, lightweight, low-cost heat pipe technology proposed in the present work overcomes the above issues. The use of polymeric composite materials for structural components instead of thin metal foils removes the issues of mechanical strength and ensures adequate resistance to fatigue. In addition, the proposed FPHP concept does not require fabrication of micro-manufactured wicks, with a significant simplification of the manufacturing process and a multi-fold increase of the operational lifetime.

The proposed FPHP technology has three main novel advances in comparison with conventional PHPs. Firstly, the proposed flexible, lightweight, low-cost heat transfer device has no equivalent among state-of-the-art commercial or research heat transfer devices, both in terms of thermo-mechanical properties and potential applications. Secondly, the proposed device can be seen as a novel type of composite polymeric material with enhanced heat transfer characteristics, and significantly higher equivalent thermal conductivity in comparison with the individual component materials. Thirdly, the proposed device enables effective thermal management of passive nature in entirely new devices and materials, such as fabrics equipped with microelectronic devices, whose thermal management is severely hindered at present by mechanical, size, or weight constraints.

2. EXPERIMENTAL

2.1 Design and Manufacturing

The pulsating heat pipe consists of a closed loop serpentine channel, embedded in a multi-layer, rectangular polypropylene sheet (250 mm length, 90 mm width, 1.5 mm thickness), as shown in Figure 1a. The serpentine has four passes, and the channel cross-section is 10 mm x 0.7 mm, resulting into a hydraulic diameter $D_H =$

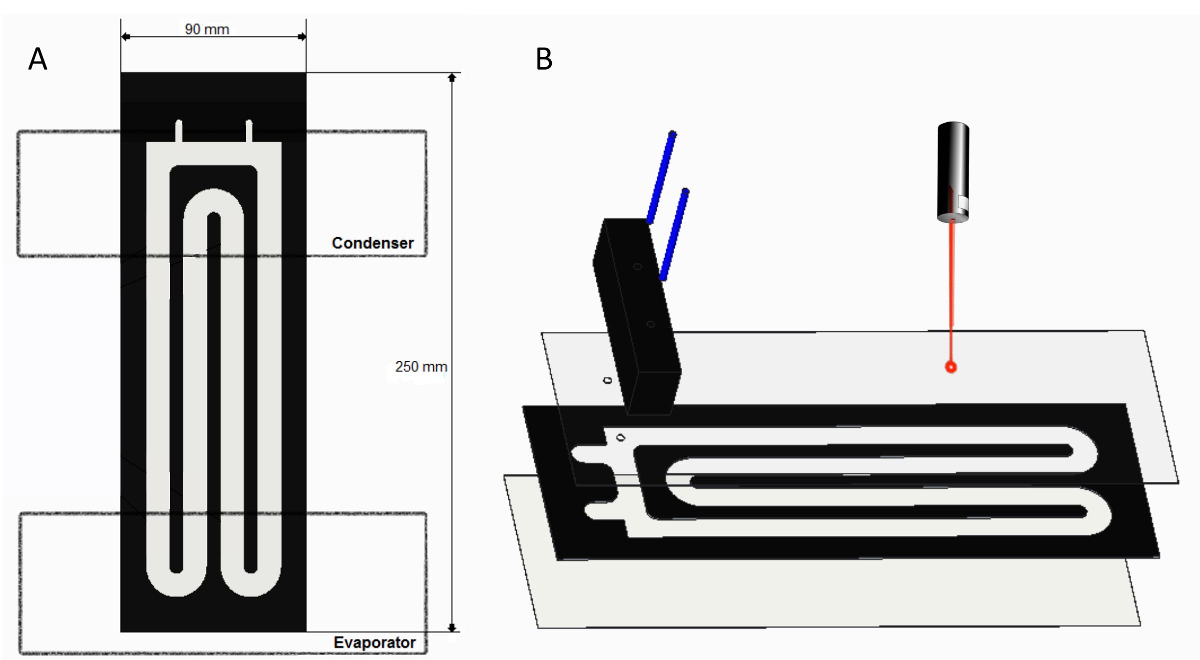

Fig. 1 Front view of the FPHP (a) and schematic of the FPHP assembly and laser welding process (b).

1.31 mm. This value satisfies the design criterion given in Equation 1 to ensure surface forces prevail on gravity [14], assuming the working fluid is ethanol and the operating temperature range is between 0°C and 100°C.

$$0.7 \times \sqrt{\frac{\sigma}{g \times (\rho_l - \rho_g)}} \leq D_H \leq 1.8 \times \sqrt{\frac{\sigma}{g \times (\rho_l - \rho_g)}} \tag{1}$$

The manufacturing process, schematically illustrated in Figure 1b, consists in cutting out a serpentine channel into a black polymer sheet (0.7 mm thickness), which is placed between two transparent sheets of the same material (0.4 mm thickness). The three polymer sheets are then bonded together by selective laser welding to create a strong and seamless joint among the three sheets; The external sheets are transparent to the laser wavelength, while the central layer absorbs the same wavelength, to enable polymer bonding exactly at the interface, without affecting the rest of the material [1, 4]. The polymer sheets material (polypropylene) was selected based on: (i) mechanical properties (elastic modulus, yield stress, resistance to fatigue); (ii) compatibility with a range of organic heat transfer fluids (ethanol, acetone, refrigerant fluids); (iii) suitability to laser welding; the maximum continuous service temperature is 130°C. After assembling the three sheets, two nylon connectors (4 mm i.d.) were glued in correspondence of two holes in the top transparent sheet, to enable connection of a pressure transducer and of a micro-metering valve used for vacuuming and filling.

2.2 Experimental Setup and Procedure

The experimental setup is schematically shown in Figure 2. The FPHP was mounted on a vertical support, with the evaporator zone at the bottom and the condenser at the top. Two ceramic heaters (100 W each) were applied to both sides of the FPHP in the evaporator region; heat sink paste was used to minimise the contact resistance. The heaters were connected to a regulated DC power supply (Circuit Specialists CSI 12001X) to enable a fine control of the power input. The condenser was cooled by two fan-assisted heat sinks (Malico). The heat pipe was connected to a pressure transducer (Lutron Electronic) and to a micro-metering valve (upchurch Scientific). Eight surface thermocouples (Omega Engineering) were distributed on the heat pipe surface (three

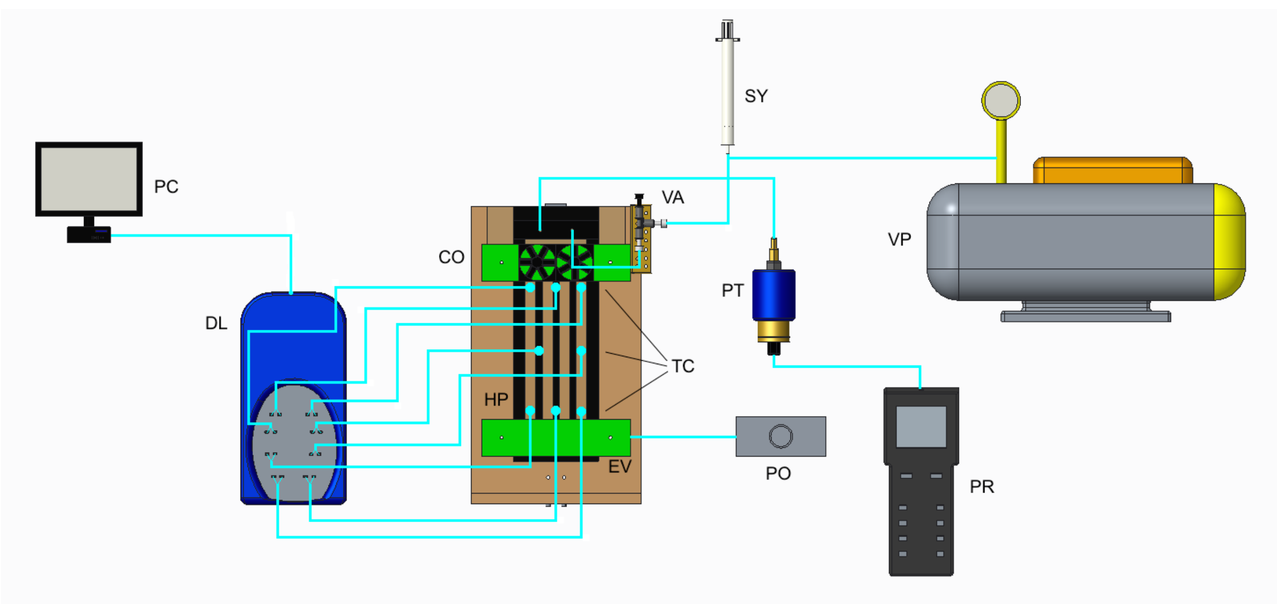

Fig. 2 Schematic of the experimental setup, composed of the heat pipe (HP), electric heaters (EV), cooling fans (CO), power supply (PO), micrometric valve (VA), vacuum pump (VP), syringe (SY), pressure transducer (PT) and reader (PR), 8 thermocouples (TC), data logger (DL) and computer (PC).

in the evaporator zone, three in the condenser zone, and two on the adiabatic zone), and connected to a data acquisition system. The locations of the eight thermocouples, labeled T1-T8, were chosen to obtain temperatures of the serpentine channel and of the solid material between two adjacent passes of the channel; in particular, T1 and T3 correspond to evaporator channels, T6 and T8 to condenser channels, and T5 to an adiabatic section channel.

To introduce the working fluid (ethanol), the FPHP was vacuumed to a pressure of 6 kPa (abs) using a two-stage vacuum pump (Bacoeng); then, the fluid contained in an external reservoir was slowly driven by the atmospheric pressure into the FPHP once the micro-metering valve was gently opened. The amount of working fluid used in the present experiments was 3 mL, i.e. 60% of the FPHP volume.

Experiments were conducted by applying a constant power to the evaporator section, and measuring the temperatures on the FPHP surface for 3000 s with a sampling rate of 1 Hz, to reach the steady-state regime; tests were interrupted earlier in case any point of the FPHP reached a temperature of 110°C. The evaporator power input was changed between a minimum of 2.6 W and a maximum of 13.2 W; to ensure a uniform initial condition, each test started from ambient temperature. For the sake of comparison, tests were also carried out without the working fluid, however in this case it was not possible to cover the entire range of heating power values because the evaporator temperature would exceed 110°C at steady state.

3. RESULTS

The effects of the two-phase heat transfer in the FPHP are shown in Figure 3, which compares the temperatures measured on the FPHP envelope (i.e. without working fluid, but not vacuumed) with those measured on the FPHP filled with ethanol, for the same heat input of 4.9 W in the evaporator section. In the heat pipe envelope (Figure 3a), the dominant heat transfer mode is conduction in a low-thermal conductivity material (k = 0.15 W/mK), therefore heating is strongly localised in the evaporator area, and the adiabatic and condenser zones are not affected significantly; the transient is smooth and considerably long, since it takes about 50 minutes to approach a steady state. As expected, the highest temperature was measured in the solid region separating two channels; the temperature difference of about 10°C between the evaporator channels (T1 and T3) indicates natural circulation of air occurs, with T1 being the ascending channel and T3 the descending channel.

In the presence of the working fluid (Figure 3b), the transient is much faster, and steady state is reached after

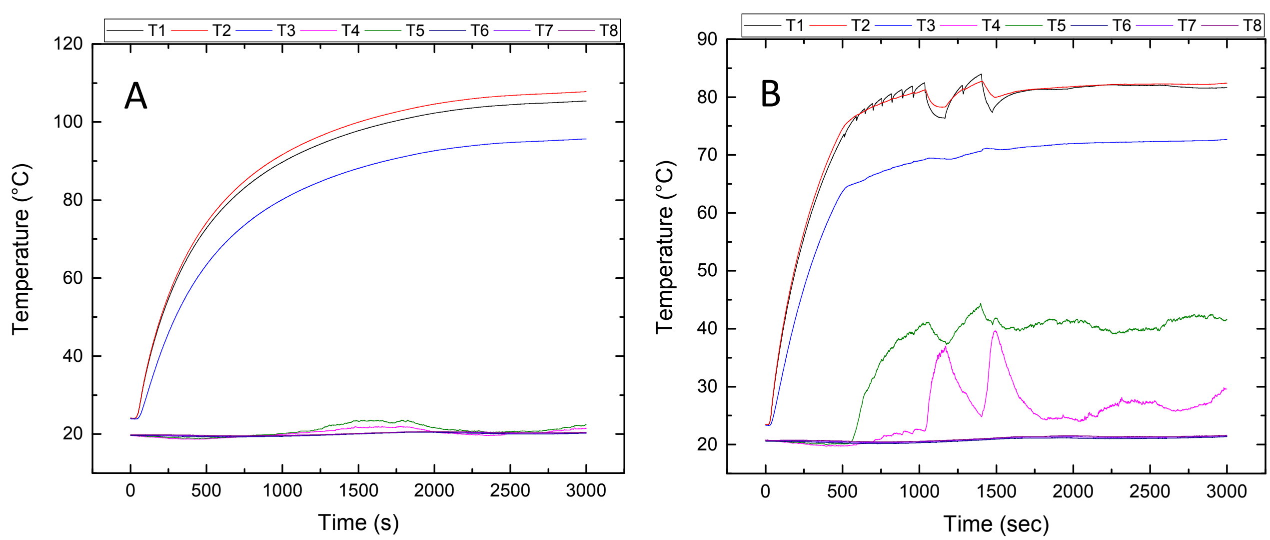

Fig. 3 Surface temperatures of the FPHP at different locations for a heat input of 4.9 W, without working fluid (a) and with working fluid (b), with no forced cooling at the condenser.

about 30 minutes; the onset of boiling is indicated by a deviation from the exponential trend, and occurs after less than 10 minutes. The evaporator temperature is significantly lower than in the absence of working fluid, due to the effective cooling of the boiling ethanol. Temperature oscillations in the channels (T1 and T5) indicate the transit of superheated vapor pockets.

Figure 4 displays temperatures measured for a heat input of 13.2 W, comparing the case without forced cooling of the condenser (Figure 4a) and that with forced cooling (Figure 4b). Without forced cooling, one can observe that the evaporator almost reaches a steady-state at the end of the sampling period of 50 minutes, however the condenser temperature is clearly growing. On the contrary, steady-state is attained in about 10 minutes when forced cooling is switched on (Figure 4b).

Finally, Figure 5 displays the measured values of the equivalent thermal resistance of the FPHP, defined as

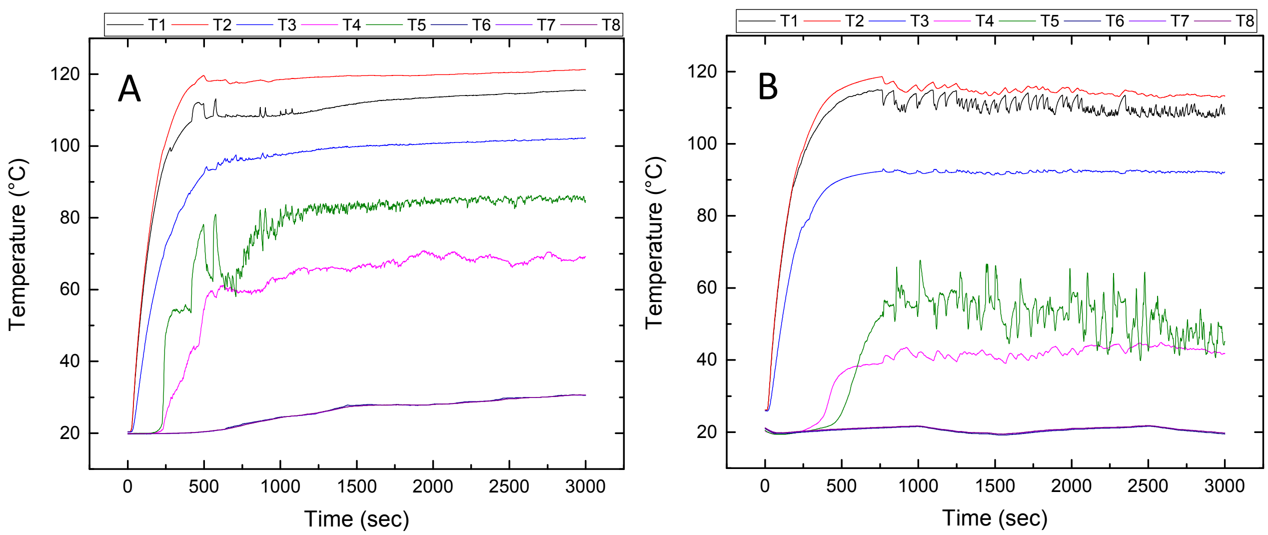

Fig. 4 Surface temperatures of the FPHP at different locations for a heat input of 13.2 W, without forced cooling (a) and with forced cooling (b) at the condenser.

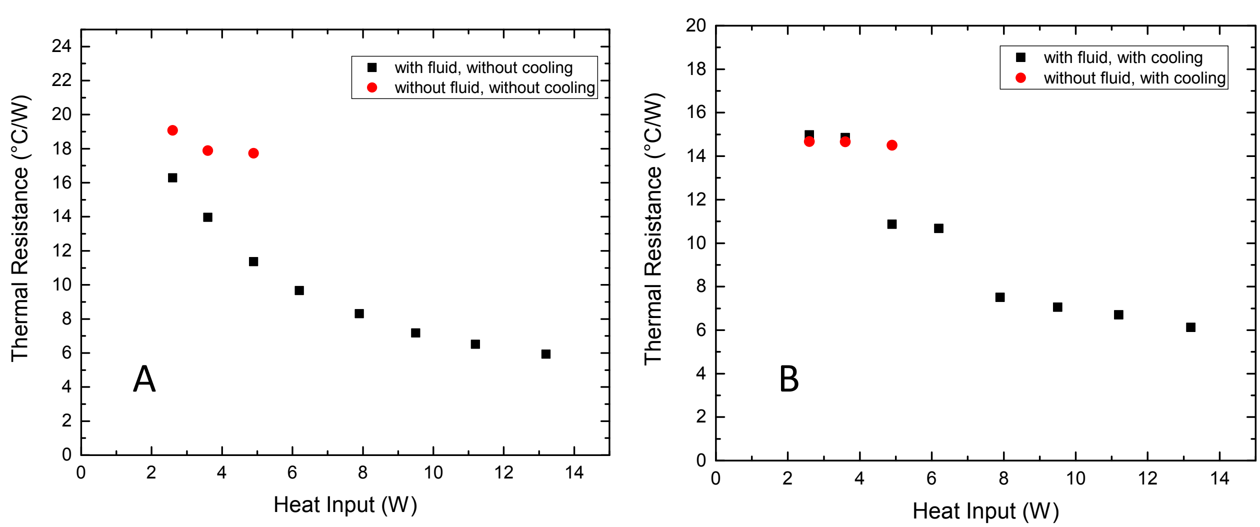

Fig. 5 Comparison of the equivalent thermal resistances of the FPHP and of its envelope, without forced cooling (a) and with forced cooling (b) at the condenser.

$R = \Delta T/\dot{Q}$, where ΔT is the difference between the average temperatures of the evaporator and the condenser, measured at steady-state, and $\dot{Q}$ is the heat transfer rate at the evaporator. The evaporator and condenser temperatures were calculated as the arithmetic average of the channel wall temperatures. Irrespective of the presence of forced cooling at the condenser, the equivalent thermal resistance of the FPHP tends to an asymptotic value of about 6 °C/W, whereas the thermal resistance of the bare composite material of the envelope is around 18 °C/W. This represents an increase of 300% in terms of the equivalent thermal conductance.

4. CONCLUSIONS

A flexible pulsating heat pipe was manufactured using polypropylene sheets bonded together by selective laser welding. The device was tested using ethanol as working fluid, and its thermal response evaluated for different values of the heat input at the evaporator and of the cooling rate at the condenser. Initial results indicate a three-fold increase of the equivalent thermal conductance in comparison with that of the composite polymer constituting the heat pipe envelope. This suggests the proposed technology represents a promising route to produce composite polymeric materials with enhanced thermal performances.

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NOMENCLATURE

D_H	hydraulic diameter	(m)	R	equivalent thermal resistance	(K/W)
g	gravity	(m/s^2)	ΔT	temperature difference	(K)
k	thermal conductivity	(W/mK)	ρ	density	(kg/m^3)
$\dot{Q}$	heat transfer rate	(W)	σ	surface tension	(N/m)

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