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PULSATING HEAT STRIPES: A COMPOSITE POLYMER SHEET WITH ENHANCED THERMAL CONDUCTIVITY

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1. INTRODUCTION

The use of polymeric materials to replace metallic parts is the obvious choice to address weight and cost constraints in a large number of devices and applications, including space, aircraft and portable electronics applications. Whilst polymeric materials offer excellent features of mechanical flexibility, resistance to fatigue, low weight and low cost in comparison with metallic materials, they exhibit poor heat transfer performance due to their low thermal conductivity. Recently, there were several attempts to increase the thermal conductivity of polymers by means of high-thermal conductivity additives and fillers, such as minerals, fibres and metals [1]. Commonly used fillers include particles [2,3], fibres [4], metal powders or particles [5,6], and carbon nanotubes [7-9].

In the present work, it is proposed to enhance the thermal conductivity of polymer sheets by embedding a self-driven liquid-vapour mixture, which transfers heat from an evaporator to a condenser region of the material according to the well-known working principle of pulsating (or oscillating) heat pipes (PHP) [10]. The heat transfer fluid circulates in a closed-loop serpentine channel, which is cut out in a polypropylene sheet, and sandwiched between two transparent polypropylene sheets, bonded together by selective laser welding. The resulting channel has a rectangular cross-section characterized by a large aspect ratio, hence the denomination *pulsating heat stripes* (PHS).

The thermal performances of composite polypropylene sheets with different designs of the serpentine channel and containing FC-72 as heat transfer fluid were tested by applying to the evaporator an ascending/descending power ramp ranging between 2 W and 35 W, and measuring the temperatures on the sheet surface for different orientations (vertical, inclined at 45°, horizontal). At the maximum heat supply, the equivalent thermal conductance of the PHS in vertical position exhibits a five-fold increase with respect to the composite polypropylene sheet without working fluid.

2. METHDOLOGY

Prototype composite sheets consisted of one black polypropylene layer (0.7 mm thick) sandwiched between two transparent polypropylene layers (0.4 mm thick), all with a length of 250 mm and a width of 100 mm. The transparent polypropylene layers were bonded on the two sides of the channel by selective laser welding [11], as shown schematically in Figure 1a. A serpentine shaped channel was cut-out in the central black layer, and featured either five or seven turns, as illustrated in Figures 1b and 1c. The channel had a width of 5 mm, which was determined so that the hydraulic diameter, D_H = 1.1 mm, satisfies the design criterion given in Eq. (1), which ensures surface forces prevail on gravity [12]:

$$0.7\sqrt{\frac{\sigma}{g(\rho_L-\rho_G)}} \le D_H \le 1.8\sqrt{\frac{\sigma}{g(\rho_L-\rho_G)}} \tag{1}$$

According to Eq. (1) the hydraulic diameter depends on the fluid properties; in particular, for the refrigerant fluid FC-72 (ρ = 1680 kg/m3; σ = 10 mN/m) the criterion becomes 0.54 mm ≤ DH ≤ 1.4 mm. The five-turns channel (Figure 1b) had a total volume of 8.4 ml, while the seven-turns channel (Figure 1c) had a total volume of 11 ml. A polypropylene fitting was used to connect a pressure transducer and a micro-metering valve used for introducing the heat transfer fluid.

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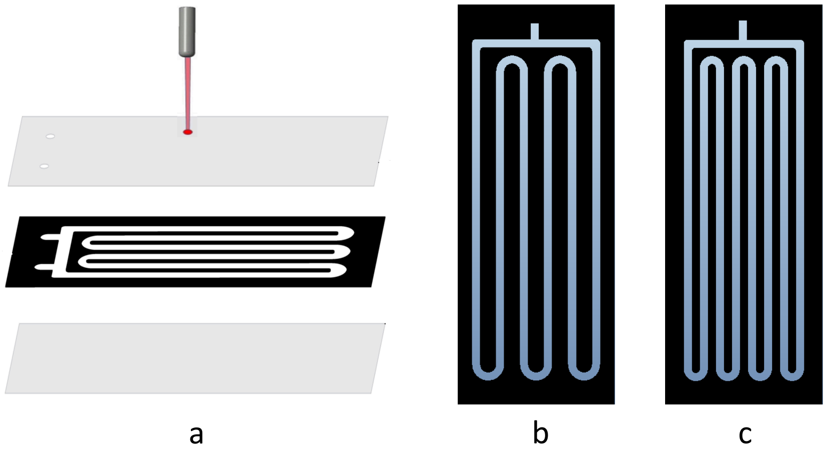

Fig. 1 Schematic of the manufacturing process (a) and top views of the PHS channels with five turns (b) and seven turns (c).

Experiments were conducted by applying to the evaporator section an ascending/descending stepped heating power ramp ranging approximately between 2 W and 35 W, and measuring the temperatures on the composite polymer sheet surface. For each power step, the heat supply was kept constant until a pseudo steady-state regime was attained. Tests were interrupted earlier in case any point of the material reached a temperature of 110°C.

The equivalent thermal resistance of the engineered composite polypropylene sheet in the longitudinal direction was calculated as:

$$R_{eq} = \frac{T_{ev} - T_{cond}}{\dot{Q}} \tag{2}$$

where T_{ev} and T_{cond} are the averages of the four thermocouples temperatures measurements of the evaporator and condenser sections, respectively, and $\dot{Q}$ is the heating power supply.

3. RESULTS

Temperatures measured in the evaporator and in the condenser zones of the composite polymer sheet during the ascending/descending heating power supply ramp are displayed in Figure 2. Due to the relatively small thermal conductivity of polypropylene, and to the intrinsically unstable gas-vapour flow, the composite sheet exhibits significant thermal inertia, and reaches a pseudo-steady state in about 40 minutes after each step change in the heating power supply. In all cases, the maximum performance is limited by the temperature of the composite sheet in the evaporator region, which is limited by the maximum continuous service temperature of the material used.

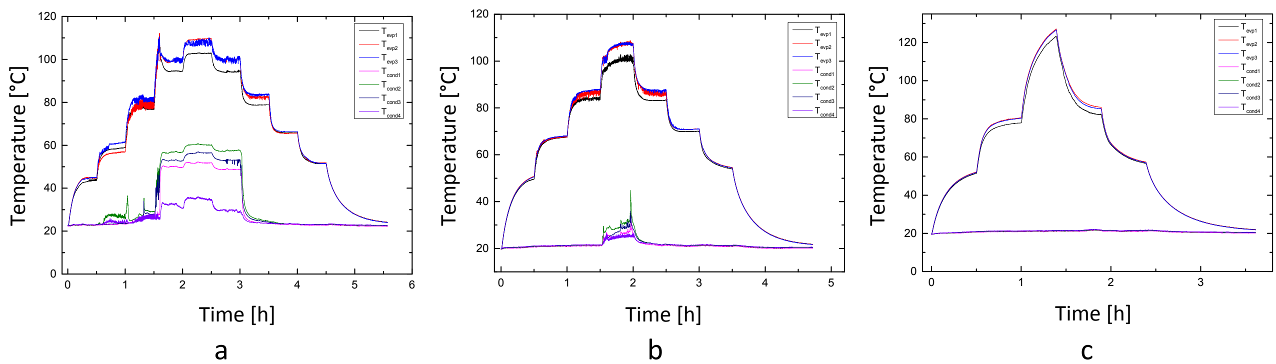

Fig. 2 Temperatures measured in the evaporator and condenser sections of the seven turns PHS in vertical position (a), with 45° inclination (b) and horizontal (c).

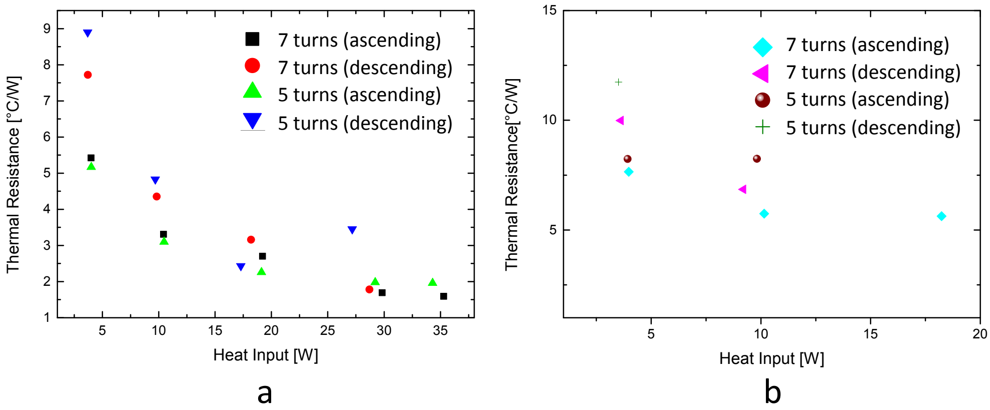

Fig. 3 Equivalent thermal resistances of the five-turns and seven-turns PHS in vertical position (a), and horizontal position (b).

The overall thermal performances of the composite polymer sheet in vertical and horizontal arrangement are shown, respectively, in Figures 3a and 3b, which display the equivalent thermal resistance of the material between a hot end and a cold end, calculated according to Eq. (2), as a function of the heating power supply.

4. CONCLUSIONS

A novel concept of engineered composite polymer sheet was designed and manufactured using three polypropylene sheets, bonded together by selective laser welding, where the central sheet contains a serpentine channel filled with a heat transfer fluid (FC-72). The thermal response was evaluated for two different geometries of the channel, for different values of the heat input at the evaporator. Preliminary results indicate a 500% increase of the equivalent thermal conductance for the seven-turn channel in vertical position, while the increase achieved in the horizontal position is significantly smaller. The proposed technology represents a promising route to produce composite polymeric materials with enhanced thermal characteristics.

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