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INVESTIGATION OF A THIN LOOP HEAT PIPE WITH A NOVEL POROUS MEDIA

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Abstract. *Loop heat pipes (LHPs) are promising two-phase heat transfer technologies used in many applications, among them, the thermal control of electronics. To enhance their thermal performance, the wick structure must be carefully designed. In the present work, a flat thin loop heat pipe, specially designed for the thermal management of electronic gadgets, with a new wick structure, was thermally investigated. This novel porous media consisted of twisting several copper threads of a commercial electrical cable. To investigate the efficiency of the novel proposed wick structure, a loop thermosyphon, with the same external geometry but with no porous media inside, was developed for comparison of their thermal performances. The external dimensions of both devices were 76 x 60 mm² and 1.1 mm in thickness. Diffusion bonding was used as the major fabrication process. Both devices are tested in the gravity-assisted orientation for several heat fluxes. In conclusion, the novel wick structure of twisting several threads of copper wires, which is low cost and simple to fabricate, operated efficiently as a capillary structure for mini LHPs, improving their thermal performance and making it a suitable cooling alternative for flat electronic gadgets.*

Keywords: *loop heat pipe, diffusion bonding, thermal performance, electronics application, novel wick structure.*

1. INTRODUCTION

The use of smartphones has become a requirement of modern society, with several models of smartphones being released every year to supply the global demand. However, as the processing velocity of chip processors increases, the heat generation increases as well, which can jeopardize the device's operation and harm the user experience.

Loop heat pipes (LHPs) are two-phase passive devices that efficiently can remove the excess heat of electronic equipment, reducing their temperature. To remove heat from electronic components, the LHP needs to the very compact. In this context, several researchers over the world have extensively investigated compact LHPs for the thermal management of small electronic devices, such as smartphones. Mini LHPs developed for compact electronics must be miniaturized and flat to facilitate its thermal contact with the heat sources and sinks. However, to guarantee the thermal performance of miniaturized LHPs, their design and selection of the fabrication process are challenging (Domiciano et al., 2022; Tang et al., 2018).

One of the main parameters that impact the heat transfer capacity of an LHP is the wick structure, which provides the necessary capillary pressure to pump the working fluid and helps in liquid evaporation. Usually, most LHPs work with sintered metal powder porous media (Maydanik et al., 2014), though other types of wick structures can provide excellent capillarity as wires, screens, grooves, and non-metallic powder material (Krambeck et al., 2022; Mantelli, 2021; Maydanik et al., 2014). Different authors proposed other wick structures to improve the thermal performance of LHPs. Shioga et al. (2020) suggested a new wick for flat mini LHPs, composed of four copper sheets (0.1 mm thick each) with staggered holes of 0.2 in diameter, chemically etched. They showed that by controlling the pore size, the heat transfer capacity of the LHP was increased. Another novel wick structure, consisting of sintered copper fiber, was developed by Ling et al. (2018). They concluded that the proposed wick provided a nonlinear capillary pressure with porosity. Also, the maximum capillary was obtained for a porosity of 70%. Kumar et al. (2022) proposed the oxidation of a sintered copper powder wick inside an LHP to decrease the thermal conductivity, and so, to reduce the heat leakage from the evaporator to the compensation chamber from 18% to 7%, resulting in an increase of the heat transfer capacity from 100 W to 180 W.

Despite the recently published studies presenting new wick structures that could increase the thermal performance of LHPs, the manufacturing process can still be complex, usually involving one fabrication step dedicated only to the wick. In a previous study, Domiciano et al. (2023) proposed a novel wick structure, composed of twisting thin copper threads of electrical cables, for a mini LHP of 1.1 mm in thickness. The authors characterized the thermal behavior of the LHP with this new wick and compared it to an LHP with a conventional porous media (sintered copper powder), both having the same external geometry. The tests were only performed in the horizontal orientation. The novel wick structure could pump the working fluid efficiently and yield better thermal performance for the LHP than sintered powder wick, operating without gravity assistance. Despite these interesting results, a thermal performance study of the mini LHP operating in different other positions should also be explored.

In this research, the investigation of the heat transfer capacity of the novel porous media for thin loop heat pipes is extended. For this, the same LHP with a thickness of 1.1 mm proposed by Domiciano et al. (2023) was thermally tested with and without the assistance of gravity. Furthermore, a loop thermosyphon, with the same external geometry but without capillary structure was constructed and tested to produce data to be compared with the novel proposed wick structure. The main contribution of this work is to improve the knowledge of the thermal performance of the mini LHP with this new and efficient cheap wick structure, easily found in the market. This same wick certainly could be inserted in other two-phase heat transfer devices.

2. EXPERIMENT

2.1 Fabrication of the heat transfer devices

The proposed LHP of 70 x 67 x 1.1 mm was proposed to fulfill the requirement of electronic gadgets' compactness. A novel wick structure, consisting of twisting several electrical copper wires of 0.1 mm in thickness, was inserted in the evaporator and in the liquid line of the LHP to provide the necessary capillary pressure for the working fluid circulation (see Figure 1a).

Since the main objective of the present research is to investigate the thermal performance of the novel proposed wick structure, a second heat transfer device, called loop thermosyphon (LT), was manufactured, as illustrated in Figure 1b. Both devices have the same external geometry, however, instead of the twisted copper wires, in the LT, three solid support structures (around 1.5 mm in width) were used to provide the evaporator mechanical resistance necessary for the fabrication, avoiding deformations of the four vapor flow channels. Besides, a porous medium made of sintered copper powder was inserted in the evaporator inlet region to guarantee the unidirectional flow of the vapor in the vapor line direction, preventing the return of liquid in this line, which avoids the device operation failure.

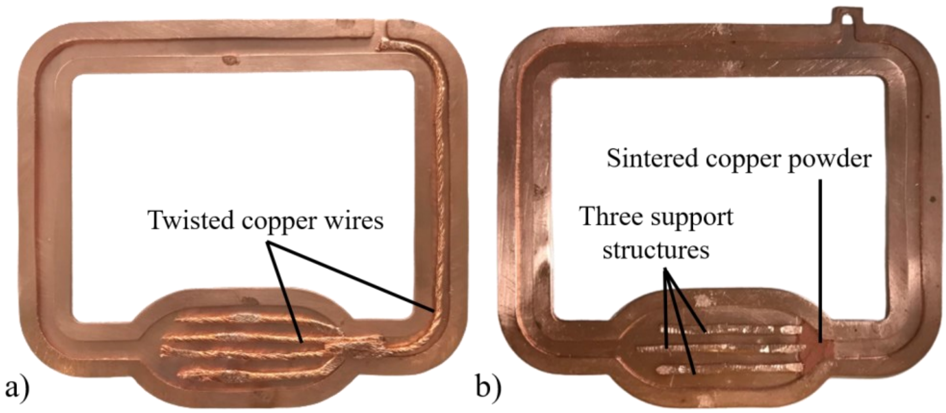

Figure 1. The prototype of the heat transfer devices: a) novel LHP and b) LT.

The manufacturing procedure of both heat transfer devices consisted of the diffusion bonding of three copper sheets in a sandwich arrangement, with two external (closing) plates with 0.3 mm in thickness and one internal of 0.5 mm thick. The plates were machined with a water jet machine. The wick structure manufacture for the LHP consisted of twisting several copper electrical wires and spot-welding them into the internal surface of one of the external sheets. For the LT, the copper powder barrier was sintered, and the three sheets were also spot welded. More details about the diffusion bonding, sintering process, and copper power properties can be found in Domiciano et al. (2022).

2.2 Experimental procedure

With the heat transfer device fully evacuated by means of a turbomolecular pumping station (*Edwards*™ T-Station 85), the LHP and LT were charged with the desired amount of distilled water, i.e., a volume that provided the best thermal performance in previous studies. A filling ratio (FR) of 35% (0.17 ml) and 50% (0.25 ml) were used for the LHP and LT, respectively. According to Ku (1999), the best FR that provides the best thermal performance in any device depends on its designs, therefore, the working fluid volume used in both LHP and LT were not the same. More specifically, the volumes for the evaporator and liquid lines were completely different for the LHP and LT, due to the presence of the wick structure in these sections. In this work, the FR is defined as the ratio between the working fluid and the total volume, i.e.:

$$FR = \frac{V_l}{V_t} \times 100\% \quad (1)$$

where V_l is the liquid volume inserted and V_t is the total void volume of each heat transfer device. After being charged, a forceps was used to seal the charging tube and to prevent the entrance of non-condensable gases.

Following the procedure, the device is coupled to the experimental setup, as shown in Figure 2. A special setup was manufactured to simulate a typical application of electronics, considering the following conditions: the heat was delivered to the evaporator by a copper block (electrical resistor inside) with a contact area of 100 mm² (usual condition for smartphones processor) and the heat was dissipated in the condenser by means of air natural convection. In the sequence, a purging process was carried out to remove any non-condensable gas that may have entered the heat transfer device during the working fluid charging. Finally, the purged device can be thermally tested.

As usual, the tested devices were composed of five main sections: evaporator, vapor line, condenser, liquid line, and compensation chamber. As seen in Figure 2, except for the evaporator, which was insulated, all the rest of the devices were submitted to air natural convection, and, for this reason, the vapor line, liquid line, and compensation chamber were considered as the condenser.

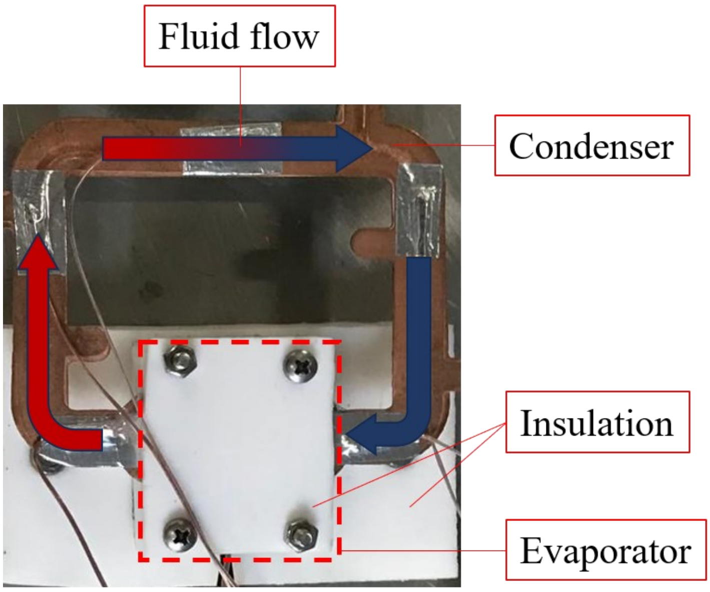

Figure 2. Experimental setup for the thermal tests.

Both devices were tested in the same experimental setup and apparatus, which is presented in Figure 3. Using *Labview*™ software and a computer, a sequence of heat loads was applied to the outer surface of the evaporator by an electrical resistor embedded in a heating copper block. The power increased in steps of 0.5 W or 1 W until it was forcibly stopped when the evaporator temperature reached 100 °C, which is the limit condition for a satisfactory operation of electronics. A power unit (*TDK-Lambda*™ GENH40-19) supplied energy to the electrical resistor. A data acquisition system (*DAQ-NI*™ SCXI-1000) with seven thermocouples (*Omega Engineering*™) was used to measure the outer surface temperature along the device. T_1 evaluated the temperature of the evaporator (close to where heat is applied), T_2 estimated the temperature of the evaporator outlet, T_3, T_4, and T_5 measured the inlet, middle, and outlet temperatures of the condenser, respectively, while T_6 quantified the temperature of the evaporator entrance and T_{amb} assessed the ambient temperature.

As the main objective of this research is to evaluate the thermal performance of the novel wick structure inserted into an LHP and compare it to a wickless LT, they were tested in the gravity-assisted (evaporator below the condenser) and horizontal (no assistance of gravity) orientations.

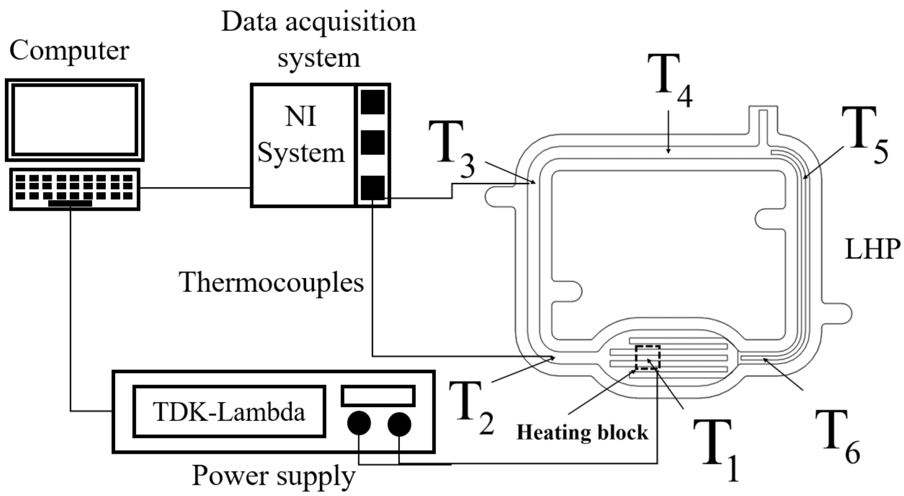

Figure 3. Schematic of the experimental apparatus.

The thermal resistance, R_t, was selected to evaluate the thermal performance of both heat transfer devices, i.e., its heat transfer capacity. This parameter can be determined by the following expression:

$$R_t = \frac{T_e - T_c}{q} \tag{2}$$

where q is the heat transfer rate, T_e is the evaporator temperature, given by T_1 measurement, and T_c is the condenser temperature, assessed by T_4. The thermal resistance uncertainty was calculated by the error propagation method described in Holman (2011), consisting of measurement error from the thermocouple, data acquisition system and power supply unit. All thermocouples were calibrated using the same experimental apparatus. The thermal resistance uncertainty, δR, can be estimated as:

$$\delta(R)^2 = \left[\frac{\partial R}{\partial T_e}\delta T_e\right]^2 + \left[\frac{\partial R}{\partial T_c}\delta T_c\right]^2 + \left[\frac{\partial R}{\partial q}\delta q\right]^2 \tag{3}$$

where δT_e and δT_c are the temperature uncertainty of the evaporator and condenser, respectively. The energy supplied by the power unit was the heat transfer rate, q, applied on the outer surface of the evaporator, defined as:

$$q = U \cdot I \tag{4}$$

where U is the voltage and I is the current output of the power unit. The standard uncertainty of voltage and current was provided by TDK-Lambda manufacturer, of 0.15 V and 34 mA.

3. RESULTS AND DISCUSSION

First, the thermal performance of the proposed novel wick structure was analyzed in terms of the transient temperatures of both the LHP and the LT operating in the gravity-assisted orientation, which attends to the operational requirements of the LT. Second, the thermal resistances of both devices are investigated and compared to each other.

3.1 Transient temperatures

The startup of an LHP or LT can be simply recognized when vapor reaches the condenser section, by the observation of the sharp increase of the condenser temperature (T_4) when the temperature difference between the evaporator (where heat is supplied) and the entrance of the evaporator is large enough. This unbalanced temperature raises a pressure variation that promotes the fluid motion along the LHP and LT, starting the operation as a two-phase device. The proper startup of the proposed LHP operating with the assistance of gravity was observed at 2 W (see transient temperatures of Figure 4). At this power level, the condenser temperature (T_4) increased, almost reaching the evaporator temperature (T_1) and suppressing the inlet evaporator temperature (T_6). The temperature difference (T_1 - T_6) for the startup at 2 W was 3.63

°C. Increasing the heat load, all the temperatures from T_1 to T_5 became closer to each other but departed from T_6, which means that the condenser all almost full of vapor. Also, it can be concluded that heat was transferred by the two-phase phenomenon instead of by heat conduction. During the test, no overshot temperature was noticed, i.e., the device could operate until 8 W without drying out when all working fluid would become vapor.

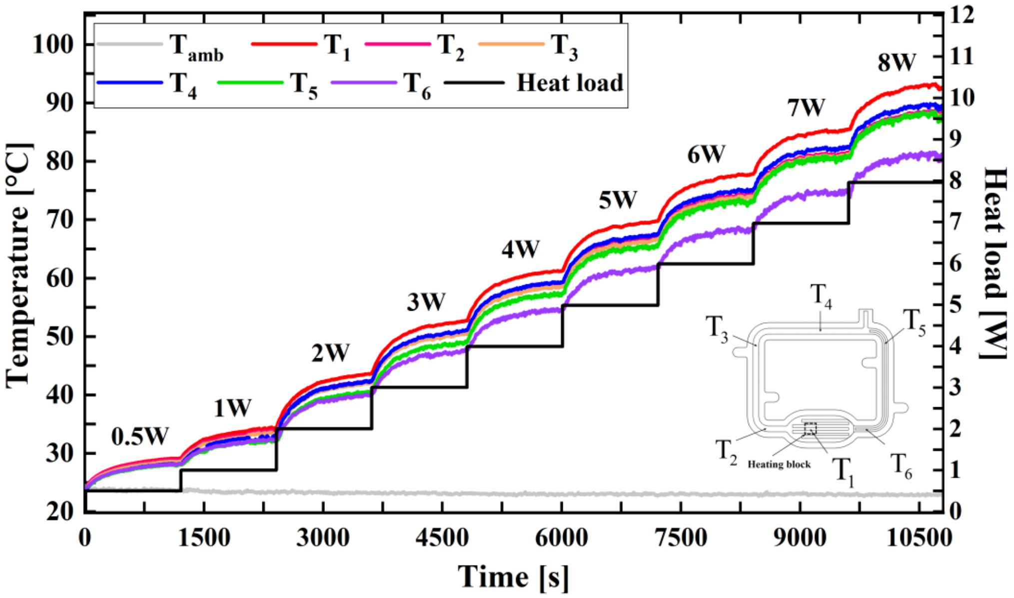

Figure 4. Transient temperatures of the LHP with water operating in the gravity-assisted orientation.

Figure 5 shows the transient temperatures of the LT operating in the gravity-assisted orientation. Below 2 W, the LT transported heat only with pure conduction. At 2 W, the LT started a proper fluid circulation using the two-phase change phenomenon with an unbalanced temperature (T_1 - T_6) of 5.09 °C. Like the LHP, the LT could work until 8 W before reaching the limit temperature of 100 °C, and no dry-out occurred.

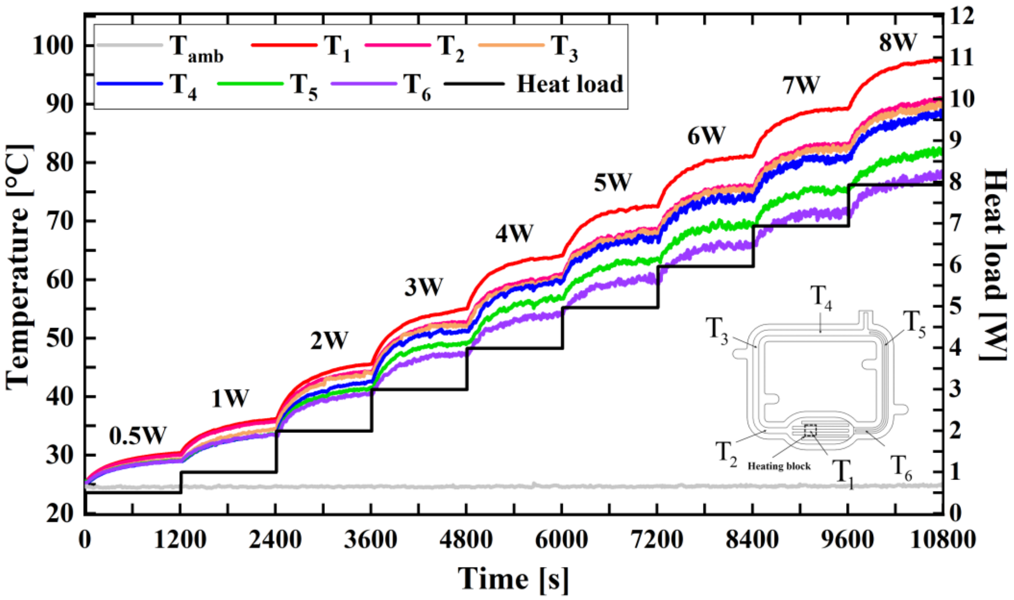

Figure 5. Transient temperatures of the LT with water operating in the gravity-assisted orientation.

At 2 W, when both devices started operating, they present similar behaviors, with the LT evaporator temperature around 2 °C higher than the LHP, which was 43.59 °C. With increasing heat load, the LHP became more effective, as the evaporator temperature of the LHP was lower than that of LT, while the temperature of the condenser inlet was higher. At 8 W, the evaporator temperature of the LT was 97.56 °C, 5 °C higher than that of the LHP, of 92.53 °C.

The condenser temperature distribution shows that the LT operated with only a fraction of the condenser filled with vapor, as the outlet condenser temperature was lower than other temperatures (T_2, T_3, and T_4), i.e., which means that the gravity force was not enough to overcome the pressure drop along the thermosyphon. On the other hand, as mentioned, the LHP worked with the condenser fulfilled with vapor, showing that the novel wick structure is really effective for thin heat transfer devices.

Comparing both graphs (Figure 4 and Figure 5), it can be noticed that the temperatures of the LHP are closer to each other when compared to those of the LT. Although the pressure drop along the LHP (presence of wick structure) is larger than the LT, the LHP showed a better performance, regarded to the capillary pressure provided by the wick structure. In this case, the working fluid pumping promoted by the wick structure was highly effective in overcoming the pressure drop of the LHP. Usually, for large-scale heat transfer devices, thermosyphons are more efficient than heat pipes when operating in gravity-assisted mode. In the present case, this hypnosis was not validated, possibly because the two-phase change phenomenon becomes more complex in highly confined volumes with large pressure drops, found in the very thin tested devices.

3.2 Thermal resistance comparison

The thermal resistance was the other comparison parameter used in this work. Figure 6 shows the thermal resistance of the novel LHP and LT in the gravity-assisted and horizontal orientations. Also, the thermal resistance of the LHP with no working fluid (operation with pure conduction) is presented, which was 3.65 ± 0.43 °C/W, almost the same as the LT, 3.71 ± 0.44 °C/W.

For the gravity-assisted orientation, as seen, both devices worked with a two-phase phenomenon. The lowest thermal resistance of the LHP and LT were 0.41 ± 0.05 °C/W and 1.06 ± 0.15 °C/W, respectively. Thus, it can be said that the novel wick structure improved the thermal performance of the heat transfer device by about 61% when compared with the LT.

Besides, for the horizontal orientation, the LT could not startup, showing a thermal resistance of 3.38 ± 0.39 °C/W, similar to that of the empty LHP. Concluding, the LT could not satisfactorily operate, even in the gravity-assisted orientation, presumably due to the large pressure drop along the device caused by the confinement.

However, the thermal resistance of the LHP in the horizontal orientation was reduced to 0.26 ± 0.04 °C/W, showing that the novel wick structure provided the necessary pumping force to promote the working fluid circulation along the device.

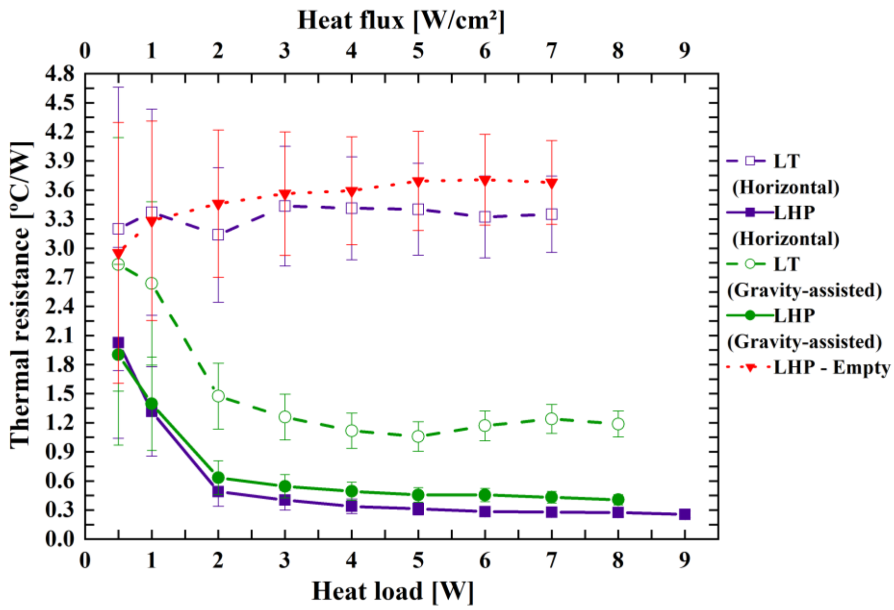

Figure 6. Thermal resistance of the novel LHP and LT in the gravity-assisted and horizontal orientation.

The proposed LHP with the novel wick structure was compared with another LHP in the literature, studied by Domiciano et al. (2022). The authors investigated an LHP with the same external geometry as the present research (Figure 1) and a wick structure, only inserted in the evaporator, composed of sintered copper powder (same teeth geometry proposed for the LHP in Figure 1a). The sintered copper power was the same used for the LHP (Figure 1b). However, the internal thickness of the LHP proposed by Domiciano et al. (2022) was 1 mm, higher than the proposed novel LHP in this work (0.5 mm thick). For this reason, to compare the thermal performance of both LHPs, the ratios between the best thermal resistance and the thermal resistance of the same but empty device, for the new and Domiciano´s et al. (2022), were taken comparison parameter, as shown in Table 1. The thermal resistance for the empty Domiciano´s device was 3.33 ± 0.37 °C/W, lower than the present LHP, as expected, due to the larger copper mass of the device. However, above 2 W, the new LHP showed lower thermal resistances (lower ratios R_{LHP}/R_{empty}), even considering their thinner geometry.

Table 1. Thermal resistance ratio comparison of the present work with the literature.

Heat load [W]	Ratio R_{LHP} / R_{empty} (Domiciano et al., 2022)	Ratio R_{LHP} / R_{empty}
0.5	0.770	0.644
1	0.369	0.425
2	0.157	0.183
3	0.152	0.153
4	0.148	0.137
5	0.152	0.123
6	0.146	0.123
7	0.157	0.117
8	0.149	0.110

To summarize, the novel wick structure, obtained by twisting several threads of copper wires, worked efficiently as a capillary structure for mini LHPs, improving their thermal performance. The proposed wick is gravity independent and easy to manufacture. Due to its advantages, this novel porous media enables the production of these wick structures of LHP on an industrial scale.

4. CONCLUSION

The thermal performance of a novel porous media for mini thin loop heat pipes for electronic gadgets, operating in gravity-assisted and horizontal orientations, was experimentally investigated in this research. The novel wick structure consists of twisting several electrical copper wires of 0.1 mm thickness inserted in the evaporator and the liquid line of the mini LHP. A loop thermosyphon with the same dimensions was experimentally analyzed in order to compare the thermal performances of both devices.

Despite both devices operating satisfactorily, the new porous media improved the thermal performance of the heat transfer device by about 61% when compared to the loop thermosyphon in the gravity-assisted orientation. For the horizontal orientation, the LT could not operate. Besides, the novel wick structure provided the necessary pumping force to promote the working fluid circulation along the device, resulting in excellent thermal behavior for the mini LHP.

In conclusion, the novel wick, consisting of twisting several threads of copper wires, operated efficiently as a capillary structure for mini LHPs, improving their thermal performance and making it a suitable cooling alternative for flat electronic gadgets.

5. ACKNOWLEDGEMENTS

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