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Experimental thermal analysis of an innovative heat sink coupled to a nanoemulsion

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Abstract. This work presents some new experimental measurements collected on a very innovative system proposed for electronic cooling. This setup combines a classical heat sink with a latent thermal storage. The storage material is a phase change nanoemulsion made of water and 5 wt% of a commercial RT40HC paraffin wax with 1-octadecanol as nucleating agent (weight fraction 1:10 with respect to PCM), while the heat sink is made of copper via 3D printing. The integration between the two components does not interfere with the external air convective heat transfer, as the emulsion is embedded inside the heat sink, which has an internal cavity. The tests analyse the temperature of the component and the emulsion in different locations during the charging and discharging phases at several heat fluxes.

1. Introduction

There is an ever growing trend in increasing the computational power of electronic devices coupled with a reduction in sizes. This led to an urgent demand in enhancing the thermal management techniques to guarantee the reliable operation of these devices while preventing thermal-related failures. [1]. Phase Change Materials (PCMs) are now widely recognized for their significant advantages in energy storage, thanks to their latent heat contribution to heat transfer [2].Unfortunately, their low thermal conductivity is equally acknowledged [3,4]. In the literature, there have been numerous attempts to integrate Latent Thermal Energy Storage (LTES) systems based on PCMs with air cooled systems, such as heat sinks. However, most of these attempts obstruct or limit the airflow, affecting its efficiency, as the PCM blocks or constrains the air passage [5,6]. Alternatively, other hybrid heat sinks are composed by a PCM base layer plus some fins on top [7] or a PCM based plus PCM volumes between the fins [8,9] In this particular case, an innovative geometry was proposed, enabled by 3D printing technology, ensuring that convective heat transfer remains uncompromised. Additionally, a nanoemulsion was utilised to enhance the thermal conductivity of the PCM.

2. Experimental set up and materials

The experimental test rig consists of a wind tunnel having a rectangular section (width 100 mm, height 40 mm, length 2500 mm) in which the test sample is housed. At its entrance there is a filter that homogenised the air flow, then the air passes through the test sample, and at the exit there is a variable speed fan which regulates the flow rate. The volumetric air flow rate is measured by a Proline Prowirl R200 vortex flow metre with a measurement range from 20 $m^3 h^{-1}$ to 130 $m^3 h^{-1}$ and a declared uncertainty equal to ± 1% of the full scale. The temperature was measured by calibrated T-type thermocouples (uncertainty ±0.1 K). The air temperature was measured in 4 locations at the inlet and 4 at the outlet of the sample. The sample is placed on a 10 mm thick copper plate, necessary for homogenising the heat transfer. The copper plate temperature was monitored by a thermocouple, placed in a hole drilled in its centre. This temperature is of great interest as it corresponds to the junction temperature of a potential electronic component that must be cooled down by the heat sink. Below the copper plate, 12 resistances plugged to a variable power supply unit were used to generate the heat flux. Finally, below the resistance a 40 mm fiberglass insulation layer was added to limit the heat losses to the environment. The heat sink employed in the experiment, represented in figure 1, is completely hollow to host the emulsion. It was manufactured by FFF (Fused Filament Fabrication) 3D printing technology (Markforged MetalX) using Markforged copper filament (1.75 mm with a ~~measured~~ declared thermal conductivity of 350 W/mK after sintering, from manufacturer technical datasheet). The component was printed on an Al_2O_3 support with a nozzle temperature of 210°C. Chemical de-binding was performed for 24 h in Opteon SF-79 preheated bath. Sintering was run in a Sinter-2 oven (Markforged) under Ar/5%H_2 flow, using the thermal cycle for copper (Markforged property). This heat sink consists of two components welded together after sintering: a base and a cover, equipped with 25 fins. The base is squared with dimensions 100 x 100 mm, and a wall thickness of 1 mm. The base's height stands at 6 mm, while the fins measure 19 mm in height, 5 mm in width, and 23 mm in length. The sample temperature was measured in several locations by means of T-type thermocouples: 4 in the basement, 8 placed on the fin wall, and 6 inside the emulsions at different heights and locations.

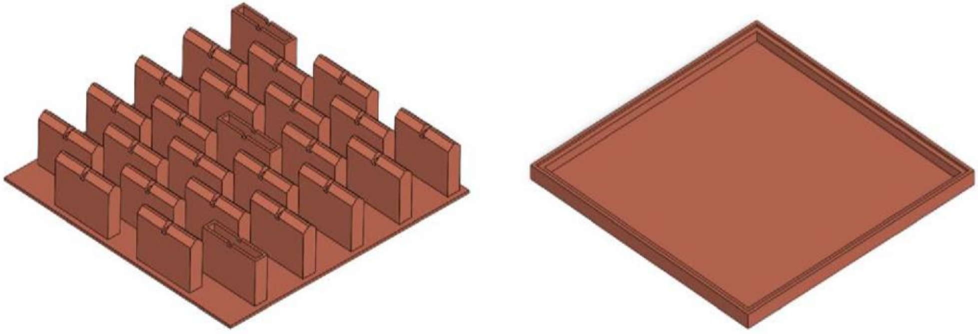

Figure 1. 3D drawing of the two parts of the sample before the welding process: cover with fins (left) and base (right).

2.1. *Nanoemulsion*

A colloidal dispersion of RT40 paraffin wax, characterized by a melting point of approximately 40 °C, with a concentration of 5 wt.% in water was used as nanoemulsion. The stabilization of the nanoemulsion was achieved through the use of 1:8 weight ratio of sodium dodecyl sulphate (SDS):PCM. Additionally, 1-Octadecanol served as the nucleating agent (NA), applied at a weight fraction ratio 1:10, aiming to mitigate the supercooling effect [10]. The PCM droplet size distribution and the colloidal stability were analysed using the dynamic light scattering (DLS) technique, employing a Zetasizer Nano ZS instrument from Malvern Instruments Ltd. The average value is around 200 nm at 25°C. These results, obtained in the presence of the nucleating agent (NA), indicate robust stability with minimal alterations in the size distribution following the thermal cycling process. Additionally, phase change transition temperatures of nanoemulsion with and without NA were characterized using the differential scanning calorimetry (DSC) technique with a DSC3 instrument from Mettler Toledo. The phase transition of the nanoemulsion with NA was observed to peak at a temperature of 38.9°C during the melting process. While, the solidification peak was observed to take place at 31.2°C. Finally, the total thermal energy storage density, calculated by summing the sensible heat of the nanoemulsion (in temperature increments of 15 °C) and the latent heat stored by the paraffin exhibited an 11% increase compared to water.

2.2. *Test campaign*

The set up was located in a climate room set at 25 ±0.2 °C for all the test duration. Each test was composed of a charging phase, where a constant heat flux was applied and a discharging phase in which the resistance was turned off and the sample was cooled down by means of the constant air flow rate. The whole test campaign included tests collected at different air velocities and different electric heat fluxes. For space reasons, only the last set of tests are here presented. In detail, the heating power ranged from 25 W to 100 W while the air flow rate was fixed at 100 m^3 h^{-1}.

3. Experimental results

Some of the data collected during the experimental campaign are presented below.

Figure 2 presents the emulsion temperature during the charging and discharging for the investigated flow rates. As the heat flux increases, the temperature at the junction experiences a gradual but consistent rise. The value of the plateau reached at the end of the charging is about 18 °C higher when 100 W is applied instead of 25 W. In a similar manner, during the discharging phase, if a higher heat flux is maintained, the emulsion temperature remains more elevated, indicating a significant influence of electric power on junction temperature. For instance, after 5 minutes the junction temperature is at 36 °C with 100 W and at 30 °C with 28 W. A noteworthy observation is that the emulsion did not reach the phase change conditions in all the tests. In fact, the melting temperature peak is at 39.1°C, whereas under the 25 W and 50 W test conditions the maximum temperature reached remains lower than 38 °C.

To try to highlight the phase change contribution, it was performed a direct comparison between the emulsion results and some other results obtained using pure water under identical working conditions (75 W and 100 m^3 h^{-1}). This comparative analysis is illustrated in figure 3 in terms of emulsion (or water) average temperature during charging and discharging. The emulsion temperature is higher during charging and colder during discharging than the water one. Likely, this is attributed to the emulsion lower specific heat capacity. However, in contrast to water, which exclusively exchanges sensible heat, the emulsion exhibits a subtle plateau in both the charging and discharging phases, indicating the contribution of the phase change material contained in it.

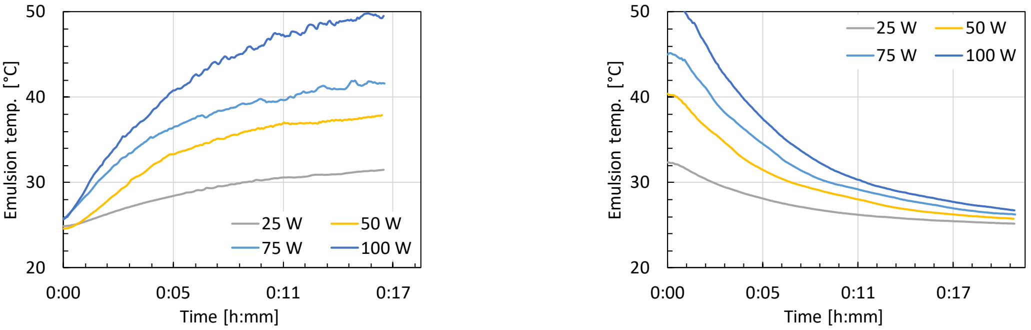

Figure 2. Average emulsion temperature during charging (left) and discharging (right) at 100 m^3 h^{-1} and several electric powers.

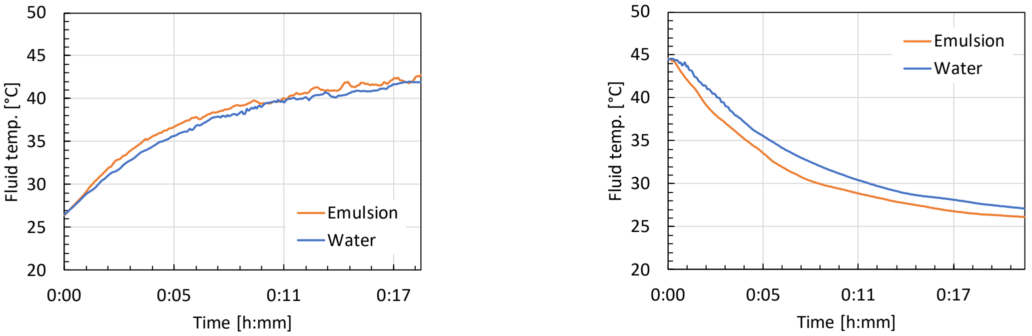

Figure 3. Average water and emulsion temperature during charging (left) and discharging (right) at 75 W and 100 m^3 h^{-1}.

4. Conclusions

This study proposed new experimental data obtained from an innovative electronic cooling system that combines a conventional heat sink with a latent thermal storage unit. The storage material employed is a phase-change nanoemulsion, and it has been embedded in a hollow heat sink manufactured by 3D printing. During the tests obtained at constant flow rate and 4 electric powers, the heat sink temperature field was monitored. As expected, as the electric heat flux increases, the emulsion temperature steadily rises. During discharging, a higher power also maintains a higher junction temperature during all the test duration. Interestingly, not all the tested conditions induced a phase change. To emphasise the PCM's role, a direct comparison was made with tests using pure water under identical conditions. The emulsion temperature is higher during charging and colder during discharging, likely due to its lower specific heat capacity. Based on these preliminary findings, there is a clear need to utilise a larger quantity of PCM to better exploit the latent thermal storage capabilities. In upcoming studies, it is requested that the heat sink's geometry should be modified to host a larger LTES. Additionally, nanoemulsion should have a higher concentration of PCM.

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