

Heat Transfer Performance of a Dual Latent Heat Sink for Pulsed Heat Loads

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ABSTRACT

This paper presents the concept of a dual latent heat sink for thermal management of pulse heat generating electronic systems. The focus of this work is to verify the effectiveness of the concept during charging through experimentation. Accordingly, custom components were built and a prototype version of the heat sink was fabricated. Experiments were performed to investigate the implementation feasibility and heat transfer performance. It is shown that this heat sink is practicable and helps in arresting the system temperature rise during charging (period of pulse heat load).

INTRODUCTION

Future electronic systems will involve small size, lightweight and compact components that release very high waste heat in a pulse. Miniaturization of such systems will generate large heat fluxes during the pulse time, which will require the development of an efficient thermal management system.

A key design issue is the need for fast charging so as not to overheat the pulse heat generating electronic device. In conventional passive latent heat sinks employing either thermal energy storage (TES) using solid-liquid phase change materials or using the heat pipe phenomenon, the heat transfer path comprising of heat absorption, storage and discharge each will have either high thermal resistance or a low rate of heat transfer. For instance, a latent solid-liquid phase change TES facility, if employed as a heat sink cannot provide for rapid heat absorption since most of the available solid-liquid phase change materials (PCMs) have extremely low thermal conductivities and since heat transfer occurs by diffusion. Inability of heat sink to quickly absorb heat from the heat source would result in rapid temperature rise of the heat source material and thus will eventually cease its functioning. This degradation of the performance of the heat source or

component being cooled will be even faster if the heat fluxes that it generates are very high. Hence, most of the latent TES devices employing phase change materials are designed as heat spreaders with a large size both at the heat absorption end and at the heat dissipation end. Low thermal conductivities of phase change materials also hamper the swiftness of heat storage in solid-liquid phase change heat storage facilities. Liquid-vapor latent phase change heat sinks like thermosyphons and heat pipes always have the limitations of critical heat flux of the working fluid and evaporator dry-out at high heat fluxes.

Suggestions were made by prior researchers to improve the rapidity of heat storage process in solid-liquid phase change heat sinks and successful attempts have been made along those lines. Some of them include using fins and metal [1] or graphite [2] foams along with a phase change material enclosed in a container or mixing thermal conductive metal particles or adding liquid metal in the phase change material to form a colloidal suspension [1]. Of these, employing porous graphite foam to enhance the heat transfer of a TES system proved very effective and successful [2]. Even on improving the thermal conductivity of PCMs, it is not possible to use them for high heat flux applications owing to their inherently low latent heat values compared to the liquid-vapor phase process, the latent heat of which is more suitable for absorbing high heat fluxes.

This work presents the concept of a dual latent heat sink intended for low thermal duty cycle, high heat flux electronic heat sink applications. This new heat sink design combines the features of a vapor chamber (VC) with rapid thermal energy storage employing graphite foam inside the heat storage facility along with phase change materials. A vapor chamber acting as a heat spreader enables for more uniform temperature distribution along the surface of the device being cooled while incorporating the rapid liquid-vapor phase change heat absorption feature at the heat source. Hence, the vapor chamber feature elevates the system thermal

conductivity by about hundred to thousand times that of pure metallic copper. This feature coupled with the rapid TES facility in the design makes this integrated system an interesting and useful one for multiple thermal management applications. The focus of this work is to use phase change materials as a temporary storage of waste heat for heat sink applications. The reason for storing the high heat fluxes temporarily is to be able to reject the heat at the average level when the heat source is off. If heat has to be rejected in real time, the condenser has to be very large. The current design incorporates all the attractive features like fast charging ability for moderate-to-high heat fluxes, compactness, reliability and lightweight.

Potential application areas include, but are not limited to, temperature control of IGBTs and MOSFETs, laser diode cooling, actuator and avionics cooling in aircraft, thermal management of electronics in directed-energy weapon (DEW) systems and their subsystems and battery thermal management for electric or hybrid vehicles, thus covering a wide gamut of heat flux applications.

There is no available open literature until date that focused on experimentation of a dual latent phase change system except for a similar work by Weislogel and Chung [3]. They experimentally studied the condensation phenomenon on packed bed of closely spaced spheres filled with a PCM. However, their work differs from the current effort in that their focus was not on observing the effect of having PCM in a vapor chamber with specific heat sink application as a heat spreader, which is the key focus of this work. Also, the flow effects of vapor on TES does not apply to the current concept, since vapor always occupies the chamber and does not flow through densely packed TES units unlike in Reference [3]. This will induce a different boundary condition for heat transfer to the TES. In addition, variety of improvements were made in the TES setup of this heat sink compared to the setup described in Reference [3] and have been detailed in Reference [4]. Therefore, it is interesting to perform experiments on an integrated vapor chamber thermal energy storage (VCTES) heat sink to verify the implementation feasibility and understand the major impediments to its efficient thermal performance. The focus of this work is to verify the effectiveness of the concept during charging through experimentation.

SETUP AND EXPERIMENTATION

For easy demonstration of the key objectives of this work, a prototype was built and the following sections focus on the design, component integration, setup and experimentation of this prototype version.

PROTOTYPE DESIGN – The focus was to design the best possible heat sink prototype with the available commercial components. This helped in simplifying the experiment setup process, still capturing the key features of the original design [4]. Figure 1 shows the

schematic of the prototype used for experiments. Table 1 shows the important design parameters. Other versions of the prototype designs considered for experimentation are mentioned in Reference [5]. The design shown in Figure 1 was chosen since it provides for a narrow operating temperature range compared to other configurations considered. The design tool as detailed in Reference [4] was used to optimize the prototype version using mostly off-the-shelf components for easy experimentation. In optimizing the prototype design given in Table 1, it was assumed that the PCM (details are discussed later) melts isothermally at 386 K and that all the latent heat of the PCM is available at this temperature. The total and latent storage capacities of the heat sink were calculated using this assumption.

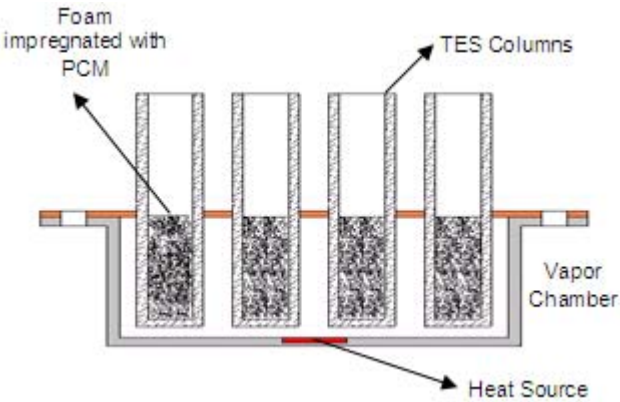


Figure 1. Schematic of the heat sink prototype designed for experimentation

Table 1. Key design parameters of the heat sink prototype

Parameter	Value
VC length (m)	0.14
VC breadth (m)	0.12
VC wall thickness (mm)	7.6
Number of columns	4
Column length (mm)	50.8
Column height (mm)	25.4
Column width (mm)	12.7
Column wall thickness (mm)	1.6
Pulse heat time (s)	16 or 32
Total mass of PCM (gm)	35
Total mass of VCTES (gm)	1600
p = Mass of (PCM / VCTES)%	2.2
Total latent heat storage (kJ)	4.7
Latent storage density (kJ/kg)	2.9

As can be seen in Figure 1, TES columns in the prototype design were extended as fins on the condenser surface to enable efficient discharging.

COMPONENTS – The vapor chamber and the plates of the heat sink were machined using CNC mill. The

machined parts are shown in Figures 2 and 3. A material with a high tensile strength, lightweight, easy-to-machine and compatible with the heat transfer fluid (HTF) would be an ideal choice for the vapor chamber and TES columns. For experiment purposes, an easy-to-machine, low thermal diffusivity glass-mica ceramic material, Macor®, was selected for making the vapor chamber along with its sidewalls to prevent parasitic heat loss in the experiments. For the top plate to the vapor chamber and for making custom TES containers, Copper was selected as the appropriate material as it is compatible with water. Copper also has high strength and so can withstand high internal pressures.

The TES columns were integrated as shown in Figures 4 and 5. PCM was filled in the TES units/columns by dipping them in an oil bath and raising the oil temperature above the PCM melting temperature. A high thermal conductive bond, PyroDuct 597A® [6] (thermal conductivity of 9.1 W/m.K), was used to bond foam pieces to the copper plates of the TES columns as shown in Figure 4. PyroDuct 597A® has a maximum operating temperature of 960 °C and so was not subjected to any damage during soldering of the column side and bottom plates. Pocofoam® was used to improve thermal conductivity of PCM in the experiments. The key properties of Pocofoam® could be found in Reference [7]. Typical properties include an effective in-plane thermal conductivity of 135 W/m.K and an out-of-plane value of 45 W/m.K, porosity of 0.75 with 96% open porosity and a density of 550 kg/m³. Foam samples were placed such that their out-of-plane direction coincided with the major heat transfer path to TES units. This enabled to use the high thermal conductivity value of the foam for heat transfer to PCM. Holes were drilled in the foam samples for inserting thermocouple wires. AWG 36, T-type thermocouple (TC) wires were used. Each column contained five thermocouples. Four thermocouples were placed inside the foam by drilling from the top (see Figure 5), two 0.225" deep, two 0.45" deep (Figure 6). The fifth thermocouple tip was placed at the center of the foam sample large face and was used for measurement of temperature in the heat transfer direction along with the one at the center of the sample.



Figure 2. Vapor chamber



Figure 3. Top plate

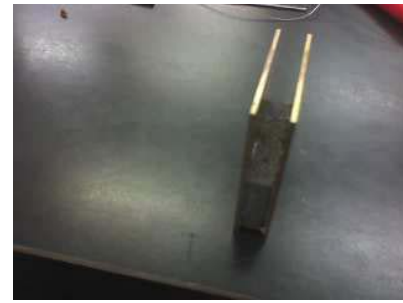


Figure 4. TES column with graphite foam sandwiched between copper plates



Figure 5. An integrated leak-proof TES column with side plates soldered and thermocouple wires instrumented

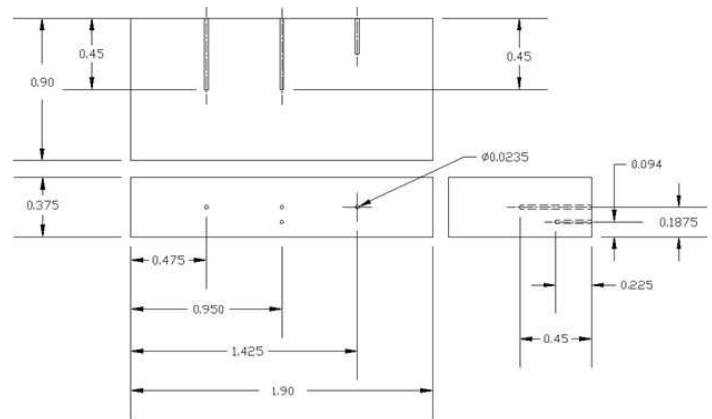


Figure 6. Thermocouple locations in graphite foam in a TES Column (dimensions in inches)

After assembling the TES columns, the condenser (top plate with TES columns) was assembled by attaching the sealed columns to the top plate and is shown in Figure 7. A special epoxy H74 from Epotek® [8] was used for this purpose.

While attaching the columns to the top plate, the entire setup and individual columns were all checked for horizontal orientation using a spirit level. Figure 8 shows the sealing mechanism employed at the inside/bottom junctions of the top plate assembly, wherein, RTV silicone was stuffed carefully in the very fine gaps between the TES columns and top plate grooves such that the entire condensation area for vapor remained clean.