



## Experimental and theoretical analysis of an aluminum foam enhanced phase change thermal storage unit



Evan Fleming<sup>a</sup>, Shaoyi Wen<sup>a</sup>, Li Shi<sup>a</sup>, Alexandre K. da Silva<sup>b,\*</sup>

<sup>a</sup> Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX 78712, United States

<sup>b</sup> Federal University of Santa Catarina, Ararangua, SC 88906-072, Brazil

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### ABSTRACT

This paper investigates heat transfer enhancement of a shell-and-tube latent heat thermal storage unit, using water as the phase change material, by addition of open-cell aluminum foam. Two shell-and-tube thermal storage units were designed and fabricated such that they were identical except for the inclusion of aluminum foam in one unit. The experimental results indicated that the foam significantly increased the heat transfer during both solidification and melting, as characterized by the overall heat transfer coefficient. The relative enhancement was greater for melting than solidification due to the lower thermal conductivity of liquid water relative to ice. It was also observed that natural convection during melting was suppressed by the foam but that this suppression was still outweighed by the thermal conductance enhancement. Using a semi-analytical approach to model the coupled phase change and forced convection heat transfer, best-fit effective thermal conductivities for the water–foam composite were determined to be 1.8 W/m-K during melting and 5.1 W/m-K during solidification. The value obtained in this work for melting is significantly lower than predictions from existing effective thermal conductivity models for foam composites, and as is shown, the impact of this discrepancy on the overall thermal performance of the thermal storage unit is significant. The value obtained for solidification is also less than that predicted by the same thermal conductivity models; however, for solidification, the impact of this discrepancy is smaller. The discrepancies between values obtained in this work and effective thermal conductivity models is attributed to local thermal non-equilibrium, which is more severe during melting than solidification due to the lower thermal conductivity of liquid water relative to ice. This finding is further demonstrated by numerical investigation of phase change in a representative composite material containing a foam-like structure modeled on the well-known Kelvin cell.

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### 1. Introduction

Phase change materials (PCMs) are commonly implemented in thermal storage systems due to large storage energy density by latent heat of fusion, e.g., 333 kJ/kg for water [1]. Furthermore, the energy can be released and absorbed at a single temperature or across a small melting temperature range in contrast to sensible heat storage, which requires change in temperature and is thus energetically less favorable. Despite high energy density, achieving desired power density can be a significant engineering challenge due to the low thermal conductivity of common PCMs including water, paraffins, fatty acids, etc. A number of reviews have summarized PCMs and their applications as well as heat exchanger configurations [1–4]. Among the several options available, a shell-and-

tube heat exchanger has been a common choice for thermal storage owing to its relative simplicity and effective usage of surface area, which reduces the amount of heat exchanger volume necessary to achieve desired performance. This unit has been studied extensively, typically on a single tube basis [5–16] but also on a multi-tube scale [17,18].

For shell-and-tube thermal storage units, there are a number of approaches or strategies that may be adopted in order to increase power capacity. For instance, increasing the temperature difference between the heat transfer fluid (HTF) inlet and the PCM melting temperature will naturally lead to higher heat transfer, although there is often little room to vary this parameter in actual practice. Likewise, an increase in the heat transfer fluid velocity can increase both the flow convection coefficient as well as the flow heat capacity rate, but the consequent increase in pressure drop must also be considered. Furthermore, convection enhancement may have limited impact on overall performance if the

\* Corresponding author.

E-mail address: [a.kupka@ufsc.br](mailto:a.kupka@ufsc.br) (A.K. da Silva).

## Nomenclature

$A$	area ( $\text{m}^2$ )
$c$	specific heat capacity ( $\text{J kg}^{-1} \text{K}^{-1}$ )
$k$	thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ )
$\dot{Q}$	heat transfer rate (W)
$s$	phase change front location (m)
$t$	time (s)
$T$	temperature (K)
$U$	overall heat transfer coefficient ( $\text{W m}^{-2} \text{K}^{-1}$ )
$\dot{V}$	volumetric flow rate ( $\text{m}^3/\text{s}$ )

### Greek symbols

$\Delta h$	latent heat ( $\text{J kg}^{-1}$ )
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$\rho$	density ( $\text{kg m}^{-3}$ )
$\phi$	volume fraction (–)

### Subscripts

$Al$	aluminum
$eff$	effective
$in$	thermal storage unit inlet
$m$	melting point
$man$	manifold
PCM	phase change material
$out$	thermal storage unit outlet

PCM conduction resistance is dominant. HTF selection can also play an important role in design—higher thermal conductivity and higher heat capacity while lower viscosity are desirable. Lastly, the heat exchanger design itself of course plays a crucial role. Power capacity may be increased by decreasing the tubing pitch and increasing tube count, effectively increasing surface area and reducing the maximum PCM conduction length. However, doing so reduces the volume fraction occupied by the PCM compromising energy density, and there may be an undesired increase in HTF pressure drop.

Another approach to increasing power capacity of thermal storage systems is forming PCM composites with a filler material that increases the effective thermal conductance of the PCM. Various approaches have been investigated and have recently been summarized by Fan and Khodadadi [19]. The engineering goal of such composites is to maximize the increase in thermal conductivity while minimizing the amount of PCM volume that is replaced by the filler material. Wen et al. [20] have shown that for a shell-and-tube thermal storage unit, achieving an effective thermal conductivity of  $\sim 4 \text{ W/m-K}$  can greatly reduce the number of tubes needed and that beyond  $5 \text{ W/m-K}$ , the benefit is diminishing. Ji et al. [21] have found that a continuous matrix, e.g., a foam structure, can offer effective thermal conductivities exceeding those of discrete particles of the same material, and that a value of  $3.5 \text{ W/m-K}$  is obtainable at only 1.2% volume loading of graphite foam in erythritol. A few studies have achieved effective thermal conductivities in excess of  $10 \text{ W/m-K}$  with a graphite matrix [22–24], but at substantially higher volume fractions, which reduces the effective thermal storage energy density.

Thermal storage studies involving open-cell foams can be broken into three groups: steady state effective thermal conductivity enhancement [21,24–30], phase change enhancement [31–39], and thermal storage unit enhancement [40–43]. Steady state investigations, whether theoretical or experimental, all tend to find the same general conclusion that the effective thermal conductivity is primarily dependent on porosity and the respective material thermal conductivities but not the foam pore size [25–30]. These findings are consistent with effective medium theory if the interfacial resistances are negligible [44,45]. However, studies focused on phase change do find dependence on pore size [37–40]. For a given porosity, a smaller pore size results in higher pore density and will enhance heat transfer via higher specific surface area [36,39,40]. For melting, this effect may be somewhat mitigated by natural convection suppression, but nevertheless, there exists a pore dependence [37,38]. Aside from natural convection, the reason for the apparent conflict between steady state and phase change studies is due to local thermal non-equilibrium, i.e., the local (pore scale) temperature difference between the two composite constituents (PCM and foam) is comparable to the magnitude of the non-

local (bulk composite scale) temperature gradients [45]. To accommodate local thermal non-equilibrium, different two-temperature models have been reported [33,34,38,40,41,46]. However, such an approach does not lend readily to determination of effective thermal diffusivity or conductivity values that can be used for quick performance evaluation.

Although previous theoretical efforts have demonstrated heat transfer enhancement by foam in a shell-and-tube heat exchanger [40–43], experimental investigations have been lacking. In this paper, we report an experimental investigation of a full scale shell-and-tube heat exchanger to evaluate the benefits of low volume fraction (5.4%) aluminum foam during melting and solidification of water. We use a semi-analytical model [8,47] to analyze the coupled phase change conduction heat transfer in the PCM with the forced convection inside the heat exchanger tubing. The model performance was first benchmarked against melting and solidification experimental data for the heat exchanger without foam, i.e., when the thermal conductivity of the PCM is simply that of the pure liquid water or ice. Next, for the unit with foam, we used the effective thermal conductivity of the PCM–foam composite as a fit parameter in our model, i.e., we found the effective thermal conductivity values that yielded the least error between model predicted and experimental overall heat transfer coefficients. These best-fit values were then compared against predictions from various foam composite thermal conductivity models derived from steady state. Our results indicate that application of these foam composite models is not necessarily appropriate for a transient phase change problem due to the presence of thermal non-equilibrium. To more directly investigate the role of local thermal non-equilibrium in these phase change processes, a representative foam structure based on the Kelvin cell [26] was made to represent the aluminum foam used within the experiments. Using this representative PCM–foam composite, we were able to clearly show the presence of significant non-equilibrium for melting and that this non-equilibrium greatly impacted melting rates.

## 2. Materials and methods

### 2.1. Experimental

Two dual-pass shell-and-tube heat exchangers were designed and fabricated such that the designs were identical except for the inclusion of Duocel® aluminum foam (40 PPI and 5.4% relative density) acquired from ERG Aerospace. The heat exchangers with and without foam are shown in Fig. 1. The units were designed to meet specifications for an automotive cabin cooling application [47]. For each heat exchanger, there are a total of twenty seven 6061-T aluminum heat transfer tubes that are each 0.64 cm outer diameter, 0.090 cm wall thickness, and 47.0 cm length. All flow enters and

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