International Journal of Heat and Mass Transfer 127 (2018) 535–543

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

On a theory for system-level cooling of close electronics enclosures by PCM-filled heat sinks—Exact solution and second law performance limits

C. Naaktgeboren [a,*], A.T. Franco [b], S.L.M. Junqueira [b]

[a] Federal University of Technology, Paraná, Guarapuava Campus, Research Center for Thermal Sciences, Av. Profa. Laura Pacheco Bastos, 800, Industrial, CEP 85053-525 Guarapuava, PR, Brazil

[b] Federal University of Technology, Paraná, Curitiba Campus, Ecoville Headquarters, CERNN – Research Center for Rheology and Non-Newtonian Fluids, Rua Dep. Heitor Alencar Furtado, 5000, Ecoville CEP 81280-340 Curitiba, PR, Brazil

ARTICLE INFO

Article history:
Received 15 May 2018
Received in revised form 3 July 2018
Accepted 4 July 2018

Keywords:
System-level electronics cooling
Stefan problem
Zero-phase modeling
Analytical solution
Second law of thermodynamics

ABSTRACT

This paper takes a fundamental approach on the simple, however widespread, application of closed electronics enclosures that are passively cooled by internally mounted heat sinks filled with phase change material (PCM) and exposed to periodic temperature environments. The regime of interest is that of periodic steady state (PSS). A model that allows for an analytical solution of the Stefan-like problem in the finite PCM domain and of the energy balance coupling of the closed enclosure is devised in dimensionless terms by using a lumped formulation for the enclosure and for the PCM domain, the later being known as zero-phase modeling (Naaktgeboren, 2007). The model is one that allows for internally reversible heat transfers in the PCM and in the enclosure domains, while retaining the finiteness (irreversibilities) of the heat interactions between the environment, the enclosure, and the PCM-filled heat sinks, as well as the heat sources irreversibilities, so as to allow for meaningful outcomes. Results include melting and freezing interface location history—conversely, melting and freezing times—and a design condition for perpetual occurence of phase change; hence, latent heat interactions. Moreover, a figure of merit for passive temperature regulation of real (irreversible) electronics enclosures is proposed as a temperature attenuation effectiveness. The limit imposed by the second law of thermodynamics on the temperature attenuation effectiveness is analytically derived and shown to depend on only two (out of the four) dimensionless parameters of the model. The original expression for the enclosure temperature attenuation effectiveness in the reversible limit, obtained herein, is of theoretical and practical significance.

1. Introduction

The problem of a closed enclosure with internal work-into-heat dissipations (heat sources) that exchanges heat with a periodic temperature environment finds application in system-level electronics cooling of outdoor systems [2,3] and on some types of buildings [4,5]. Electronics can be harmed by either internal temperature peaks or excessive temperature variations along the day-and-night cycle [6]—factors that also impact comfort on buildings.

The issue of passive temperature control of electronics by employing phase change materials (PCM)—as part of Latent Heat Thermal Storage (LHTS) systems—has been mainly addressed by means of local temperature management, i.e., on an electronic *component* level [7–10], on electronic or solar *module* level [11,6,12], and on portable *device* [13,14] treatments. Such local and mesoscale [14,15] thermal management approaches deal mostly with the mitigation of local temperature peaks.

In order to address the issue of temperature fluctuation along the day-and-night cycle of larger systems, a *system-level* temperature control may be used [3,5,16]. In periodic steady state (PSS) regime, the temperature of the enclosure (system) is expected to oscillate around a mean enclosure temperature. Therefore, reducing the enclosure thermal amplitude also means reducing its peaks of temperature, thus aiding all other local and mesoscale temperature control systems in place.

Electronics enclosure with PCM-filled heat sinks are complex systems from the point of view of transport phenomena. New technologies and specific systems are often studied both experimentally and numerically. Pertinent numerical studies include solution to the Stefan problem, recirculating flows in enclosures, phase change heat transfer, conjugate (coupled) heat transfer problems, and electronics cooling. An extensive compilation on such studies can be found on this [17] review.

* Corresponding author.
E-mail address: NaaktgeborenC.PhD@gmail.com (C. Naaktgeboren).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.012
0017-9310/

Nomenclature

$\mathbb{A}$	lumped enclosure dimensionless temperature amplitude, Eq. (22)
A	area, m^2, Eq. (2)
a	external ambient temperature amplitude, K, Eq. (1)
Bi	Biot number $(=\bar{h}_i\ell/k_L)$
$\mathcal{C}$	lumped enclosure incompressible substance specific heat, kJ/kg K, Eq. (2)
c	PCM incompressible substance specific heat, kJ/kg·K, Eq. (3)
$\bar{h}$	average convective heat transfer coefficient, kJ/kg ·K, Eq. (2)
k	PCM thermal conductivity, kW/m·K, Eq. (3)
L	PCM latent heat of fusion, kJ/kg, Eq. (5)
ℓ	PCM domain length, m, Eq. (10)
M	lumped enclosure mass, kg, Eq. (2)
m	external ambient mean temperature, K, Eq. (1)
n	a positive integer number, Eq. (31)
P	electronics enclosure steady power dissipation, kW, Eq. (2)
q''	heat flux, kW/m^2, Eq. (14)
T	temperature, K, Eq. (1)
t	time, s, Eq. (1)
X	sharp, planar phase change interface location in x, m, Eq. (5)
x	Cartesian coordinate, m, Eq. (3)
$\mathbb{Z}$	the integer number set, Eq. (31)

Greek symbols

β	complex temperature temporal parameter, Eq. (21)
γ	complex temperature free parameter, Eq. (21)
δ	dimensionless phase change interface penetration coefficient, Eq. (16b)
η	lumped enclosure temperature amplitude attenuation effectiveness, Eq. (34)
θ	dimensionless excess temperature, Eq. (14)
$\theta^\star$	complementary problem dimensionless excess temperature, Eq. (19)
κ_m	dimensionless time-average enclosure excess temperature in PSS, Eq. (16b)
μ	complex dimensionless excess temperature, $(=\theta_e + i\theta_e^\star)$
Ξ	dimensionless phase change interface location, Eq. (14)
ξ	dimensionless Cartesian coordinate, Eq. (14)
ρ	PCM density (same for solid and liquid phases), kg/m^3, Eq. (3)
Σ	dimensionless extent of a PCM phase in PSS, Eq. (17)
σ	dummy dimensionless time, Eq. (17)
τ	dimensionless time, Eq. (14)
Φ	lumped enclosure periodic temperature phase angle, rad, Eq. (21)
ϕ	lumped enclosure internal-to-external convective heat-power ratio Eq. (16a)
χ	lumped enclosure thermal inertia-power to external convective heat-power ratio, Eq. (16a)
ψ''	dimensionless heat flux, Eq. (14)
ω	external ambient periodic temperature angular velocity, rad/s, Eq. (1)

Subscripts

0	initial
a	periodic temperature external ambient
e	closed lumped electronics enclosure (system)
i	internal PCM-filled heat sinks
L	PCM liquid phase
m	melting
max	maximum
n	index
S	PCM solid phase
w	PCM-filled heat sinks wall $(x = 0)$

superscripts

$-$	near (closer to origin) side of
$+$	far (farther from origin) side of
$\star$	scale of
L	PCM liquid phase

In contrast, the present study takes a more fundamental approach on the subject, by proposing a model that (i) accounts for the most significant (global) enclosure and LHTS system design parameters in dimensionless form, (ii) provides an analytical solution, and (iii) allows for finding the theoretical *performance upper bound* for the technology of passive, system-level cooling of closed electronics enclosure using PCM, in terms of temperature amplitude attenuation, that stems from the second law of thermodynamics.

It is worth noting that fundamental studies exist on sensible and on latent heat thermal storage systems [18–20] that establish second law optima parameters for the storage system for the sake of *maximizing work production* by a coupled heat engine. The second law limit derived herein is conceptually different from these, in the sense that the goal here is to *minimize the enclosure temperature amplitude of oscillation*; or, conversely, *minimize peak enclosure temperature in the PSS regime*.

Despite the lack of conversion from heat into useful work by a heat engine, the second law is still applicable to the enclosure peak temperature minimization problem. The connection is immediately recognized when one contemplates the Clausius statement of the second law [21,22] while identifying that the closed enclosure, with internal work-into-heat dissipations, dynamically syncs heat into two surroundings: (i) the periodic temperature (external) environment, and (ii) the PCM-filled (internal) heat sinks. Since one can define an enclosure sub-system in which "*no other effect*" is present, in order to sync heat to a surrounding system, the Clausius statement of the second law requires that the enclosure temperature must be higher than the given surrounding. However, in the limit of reversible heat transfer, the temperature excess that causes heat to be transfered becomes negligible, giving rise to a lowest maximum enclosure temperature limit stemming from the second law of thermodynamics.

In the discipline of Heat Transfer, this equilibrium thermodynamic limit of internally reversible sensible heat exchange in single-phase systems corresponds to the model of *lumped capacitance*, and arises for asymptotically small values of the Biot number, i.e., whenever $Bi \to 0$.

The Stefan problem in this same Biot number limit is the *zero-phase Stefan problem* [1], which retains the moving boundary nature of the Stefan problem, while only allowing for internally reversible sensible and latent heat exchanges. The zero-phase Stefan problem can be thought of as a multiphase thermodynamic system in equilibrium at constant pressure (and also constant volume, if one takes the phases to be incompressible and having the same specific volume), in which heat interactions change the phase fraction between the phases, or, equivalently, the *quality* of the multiphase system in equilibrium, without changing its temperature.