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Topology optimization for heat transfer enhancement in Latent Heat Thermal Energy Storage

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ABSTRACT

Performance of a Latent Heat Thermal Energy Storage depends strongly on the spatial layout of high conductive material and phase change material. Previous design studies have explored a limited design space and have rarely taken advantage of any formal optimization approach. This paper presents a topology optimization framework of a Thermal Energy Storage system involving phase change. We solve the Stefan problem for solidification with a fixed grid finite element method based on the apparent heat capacity technique, while the topology optimization problem is formulated using a density-based method. This approach allows to identify design trends that have been rarely investigated in the past. Firstly, we explore the inherent trade-off between discharged energy and required time for complete discharge. We obtain very different designs and highly varying performances at selected Pareto points. Secondly, by comparing results obtained in two and three dimensions we observe that 3D designs allow superior performances by presenting features that are not apparent in 2D. Thirdly, we propose a formulation of the design problem that yields a nearly constant thermal power output during the entire discharge process. If the maximum discharge time is sufficiently large, the optimized design presents fins that are disconnected from the internal tube.

1. Introduction

Thermal Energy Storage (TES) plays a crucial role in modern energy systems. It allows reducing the temporal mismatch between energy supply and demand, resulting in a more rational use of resources. Among the available options, Latent Heat Thermal Energy Storage (LHTES) systems comprised of phase change materials (PCMs) show two of the most desirable properties for heat storage systems: *high energy density*, which allows the construction of compact designs well-suited for distributed applications [1], and *minimal operating temperature variation*, which yields a nearly constant efficiency of the heat transfer device during the entire charge/discharge process. These properties make PCM ideal also for other applications, e.g. space heating and cooling [2–4], solar energy technology [5], thermal management in Li-Ion batteries [6] and electronics cooling [7,8]. For further information on thermal energy storage with phase change materials the reader is referred to state-of-the-art reviews such as those by Zalba et al. [9], Sharma et al. [10] and Kalnaes et al. [11].

Despite the aforementioned advantages, the use of LHTES is still hampered by its poor heat transfer properties. Most of the PCMs suffer from very low thermal conductivity, which limits the achievable heat transfer rate and reduces the spectrum of feasible applications [12]. To resolve this issue, the engineering community has followed different approaches, for instance addition of carbon additives [13], dispersion of high conductivity nanoparticles [14,15], utilization of steel lessing rings [16] or high-porosity metal matrices [17], microencapsulation in partially melting/solidifying slurries [18], adoption of multi-tubes configurations [19–21], and increase of heat transfer surface area with highly conductive fins. The latter approach is the most widely adopted because of its simplicity, low construction cost, and ease of fabrication and maintenance [22].

One of the first numerical studies concerning heat transfer surfaces embedded in PCM was conducted by Smith et al. [23], who used the finite difference method to solve the solidification problem adjacent to a cold fin and analyzed the effect of fin dimensions. Lacroix [24] developed a more accurate model based on the enthalpy formulation that also accounts for convective heat transfer from the Heat Transfer Fluid (HTF) and conducted a parametric analysis to investigate the effect of design and control variables

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Nomenclature

$H^{(0)}$	initial total enthalpy
N_s	number of design variables
T	temperature
T^h	approximated temperature field
Z	storage unit height
$\mathbf{J}$	Jacobian matrix
$\mathbf{R}$	residual vector
$\tilde{s}$	filtered design variable
c_p	specific heat
f	liquid fraction
f^*	liquid fraction defined with dimensionless temperature
h	specific enthalpy
k	thermal conductivity
l	characteristic length
p	material interpolation exponent
q_v	volumetric heat generation
r_1	internal tube radius
r_2	external shell radius
r_f	filter radius
s	design variable
t	time
v^h	admissible test function
z	objective function

Dimensionless groups

Fo	Fourier number
Ste	Stefan number

Greek symbols

α	thermal diffusivity
β	projection steepness parameter
$\boldsymbol{\lambda}$	adjoint vector
η	projection threshold
Γ	boundary
Ω	domain
ω	filter weight
Φ	desired volume fraction
Ψ	desired fraction of initial energy
ρ	density
ρ_s	projected design variable
ξ	logistic function constant

Superscripts

$*$	dimensionless

Subscripts

d	Dirichlet
I	initial
id	ideal
m	melting
max	maximum
min	minimum
N	Neumann

such as the external envelope size and the HTF mass flow rate. The increasing availability of computational resources allowed researchers to progressively explore the influence of a greater number of parameters. For instance, Ismail et al. [25] studied the influence of the number of fins, their length and thickness on the time of complete phase change. In [26] the authors proposed the utilization of Artificial Neural Network (ANN) trained with experimental data to quickly conduct heat transfer analysis for different heat transfer areas and HTF operative conditions. More recently, Tay et al. [27] compared heat transfer enhancement in solidification through radial fins and pins in multiple configurations. They found that the complete solidification time is roughly 25% lower in the case of radial fins. Hosseini et al. [28] conducted a numerical and experimental investigation on longitudinally finned shell-and-tube LHTES, studying the relative effect of fin height and Stefan number. Their results showed that increasing the fin height leads to higher rate of heat absorption especially at the beginning of the charging process and for low Stefan numbers.

From the great amount of literature devoted to the analysis of finned surfaces for phase change materials it is hard to extract fundamental design guidelines. Most of the reviewed works are characterized by high physics complexity and low design freedom. The literature lacks a thorough and computationally affordable design optimization procedure for LHTES systems. A first study in this direction was conducted by Sciacovelli et al. [29] through a combination of a 2D transient finite volume physical model and response surface optimization method[30]. It was found that the discharge efficiency can be increased by 24% if optimal fins with two bifurcations are chosen. In a more recent development, a heuristic pseudo-optimization procedure based on the analysis of the entropy generation maps was used [31]. With this approach they were able to obtain an optimized fin tilt angle along the longitudinal direction which allows to halve the solidification time. Despite the importance of these studies for the development of optimization procedures for LHTES systems, they are still restricted to a low-dimensional design space [29]. This paper aims towards filling this gap in the literature.

Topology optimization allows for dramatic design changes during the optimization process and does not require a close to optimal design to start with. The method originated in the structural community with the pioneering work of Bendsoe [32], Zhou and Rozvany [33] who suggested the SIMP (Solid Isotropic Material with Penalization) or power-law approach. They introduced a fictitious porous material with normalized density ρ to define a continuous transition between two or more phases. This normalized density interpolates the material properties and is used as an optimization variable. The interpolation is formulated to penalize intermediate densities and converge to designs with well-distinct phases. Besides this "density" approach, topology optimization developed in alternative directions, e.g. level set [34,35], evolutionary approaches [36,37] and several others [38]. The method gained maturity in the structural community and quickly extended to many other fields such as fluid-dynamics [39–41], acoustics [42], bending waves propagation [43], aero-elasticity [44], electromagnetics [45] and meta-materials design [46]. Early interests in the field of heat transfer come from the fact that the problem of optimal design of heat dissipators undergoing steady-state conduction is a trivial extension of the typical compliance minimization problem for structural design [47]. Later on, more complicated heat transfer mechanisms were studied e.g. forced convection [48,49], natural convection [50,51] and radiation [52].

Although steady-state heat conduction problems has been tackled extensively, few studies [53,54] have considered transient effects. To date, only one work [55] has exploited topology optimization to enhance heat transfer during phase change. The authors presented novel and nonintuitive designs of PCM-based