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Geometry optimization of a heat storage system for concentrated solar power plants (CSP)

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ABSTRACT

In the present study, geometry optimization of a phase change material (PCM) heat storage system is presented. The existing PCM-fins heat exchanger system works at the back side of a solar receiver in order to minimize the effect of the solar radiation fluctuations inside the cavity. As initially designed, the system does not accomplish the expected design purposes and thus optimization is needed. Optimization is usually time-consuming and some algorithms need a starting point, therefore one suitable method is geometrical optimization which aims to find the optimal shape of a system for a given criteria and providing a rough optimal geometry. Here, constructal theory, 'point to volume', is applied to find the optimum shape factor of the elemental volume of the presented PCM-heat exchanger. With this methodology, an optimum ratio of the PCM and fin width and length is found and beyond that the method is extended to 'surface to volume' problem. Results have been numerically validated using a CFD software and demonstrate that it gives a very good approximation of the real optimum which can be used as initial configuration for further optimization through CFD simulation or other optimization methods that require a starting point.

1. Introduction

Electricity consumption is growing rapidly in many countries; its global use increased by 54% between 1990 and 2005. Nowadays, electricity is the second major energy commodity in OECD countries with a share of 22%, after oil products with a 47% [1]. To move towards depletion of fossil fuels consumption to achieve the worldwide goals of climate change and CO_2 mitigations, the use of renewable energies is essential.

One feasible way to produce electricity from renewable energy is concentrated solar power (CSP) plants [2,3]. By 2050, with appropriate support, CSP could provide 11.3% of global electricity, with 9.6% from solar power and 1.7% from backup fuels (fossil fuels or biomass) [2]. Nowadays, four CSP technologies are represented at pilot and commercial scale: parabolic-trough collectors (PTCs), linear Fresnel reflector (LFR) systems, power towers or central receiver systems (CRS), and dish/engine systems (DE) [4]. According to Lovegrove et al. [5] tower systems or central receiver systems represent the next generation of CSP plants as they can achieve higher efficiency and lower cost.

To compensate the intermittency of solar resource and to protect the solar receiver of a central receiver system, thermal energy storage technologies can be employed. Among these technologies, phase change materials (PCM) tanks can either be implemented for continuous electricity production, by supplying required heat when sun is not available [6,7], or to protect the receivers in tower system [8,9]. In parallel, other more mature technologies, mainly based on solar salts, for CSP applications are being tested at pilot plant scale [10] and on the other hand first demonstrations at pilot plant scale of more recent technologies, based on thermochemical materials, are growing [11,12].

In the literature, publications regarding design and optimization of PCM heat exchanger for storage in CSP applications can be found [13,14]. Several technologies have been investigated: encapsulated PCM for thermocline systems [15–17], shell and tube heat exchangers [18–20] implementing finned tubes [21,22], heat pipes [23] or metallic foam [24] for heat transfer enhancement. All these studies make extensively use of CFD tools, permitting accurate performance evaluation through 2D or 3D modelling. However,

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Nomenclature

c	heat capacity J kg-1K-1
d	height of the conductive material m
$e\dot{x}d$	total exergy destruction W
f	shape factor
H	height of the system m
jq	heat flux density W m-2
k	thermal conductivity W m-1 K-1
$\tilde{k}$	conductivities ratio
L	length of the system m
Lm	latent heat J kg-1
$\dot{Q}$	total heat power W
$\bar{q}X$	average heat flux to reach x W
S	total entropy production W K-1
T	temperature K
$\bar{T}$	average temperature K
tX	time to reach x s
W	width of the system m
X	conversion degree
Z	exergy impedance W-1
z	dimensionless exergy impedance

Greek symbols

β	kinetics constant K^{-1} s^{-1}
θ	Carnot factor
ρ	density kg. m^{-3}
σ_q	Heat source W m^{-3}
φ	liquid fraction
φ	Conductive to total volume ratio

Subscript

0	elemental (geometry) or reference (temperature)
1	construct 1
a	active material
c	conductive material
Cu	copper
irr	irreversible
m	melting
PCM	phase change material
ptv	point to volume
stv	surface to volume

Superscript

*	optimal

such tools could be time consuming when optimizing. The geometry needs to be drawn at a first step before generating a mesh. Therefore, simplified tools to approach the optimized geometry could be very interesting. Optimization methods giving valuable results with relatively simple calculations and less time consuming are aimed for studying the plausibility of new systems. One method is geometrical optimization which aims to find the optimal shape of a system for a given criteria. Bejan proposed in 2000 [25], a general method devoted to this objective: the constructal theory [25]. Since then, several studies have been published proving the viability of this theory in a huge variety of fields, being one of them heat transfer and fluid flow systems [26]. In addition, and focusing on thermal energy storage designs, the constructal method has been extended to coupled heat and mass transfer by Azoumah et al. [27], or to thermochemical reactors, taking the total entropy production as minimization criteria [28]. Tescari et al. [29] revisited the so–called ‘point to volume’ problem (ptv) studied by Bejan in his original work [30], using the thermodynamic of irreversible processes. It was shown that global optimization gives better results than the step by step optimization usually used in the constructal theory. Moreover, this work defined the entropy and exergy impedances, which have to be minimised to facilitate heat transfer. Neveu et al. [31] successfully applied the impedance minimization method to thermochemical reactor.

The aim of the present study is to prove the fact that the impedance minimization gives a good approximation of the optimal shape of a defined geometry, and therefore it is an appropriate method to obtain a starting point for an accurate further optimization of TES systems predesign. Furthermore, this study introduces and solves an original problem, named ‘surface to volume’ (stv) problem, which represents a more realistic structure than the ptv problem for TES systems optimization.

2. Background

2.1. Protection storage for high temperature solar receiver

To smooth the variation of temperatures of a pressurized air solar receiver of a concentrated solar plant (CSP) a PCM heat exchanger working between 873 K and 1173 K was designed and published by Verdier et al. [8,9]. The main idea of this PCM tank is to stabilize the outlet air temperature in case of cloud covering, as represented in Fig. 1 left, thus protecting the solar receiver and other critical downstream components. Fig. 1 right, shows the location of the PCM tank in the entire system being integrated at the back of the receiver.

The PCM used is lithium carbonate (Li_2CO_3) since its melting temperature is close to the working temperatures, being 996 K. The fins are made of copper, being a highly conductive metal. Pictures and a scheme of the current heat exchanger can be seen in Fig. 2. After tests, it was concluded that this heat exchanger needed to be optimized to achieve better results [9].

This study also provided a 2D model using CFD software. The PCM model is based on Calvet et al. study [32] in which the local liquid fraction (φ) evolution is evaluated through a 1st order heterogeneous kinetic law (Eqs. (1) and (2)):

$$\frac{d\phi}{dt} = \beta(T - T_m)\phi \text{ if } T < T_m \text{(solification conditions)} \qquad (1)$$

$$\frac{d\phi}{dt} = \beta(T - T_m)(1 - \phi) \text{if } T > T_m \text{(melting conditions)} \qquad (2)$$

The kinetic constant β, fitted by comparison between model and experiments, was found to be 0.001 K^{-1} s^{-1}. Verdier [33] also remarks that the value of β can have a big impact on computing time; however its effect to the TES evolution remains weak, showing that the behaviour of the PCM TES is controlled by heat transfer.

2.2. Geometrical optimization

Constructal theory initiated by Bejan [25] aims at optimizing the geometry of systems in which heat or matter is flowing. This method consists in finding the optimal geometrical shape that minimizes the global transfer resistance. Cooling of electronic devices was first investigated by Bejan [30] where also the ‘point to volume’ (ptv) problem was defined.