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Constructal design of latent thermal energy storage with vertical spiral heaters

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ABSTRACT

This paper reports a numerical and analytical study of time dependent storage of energy by melting a phase change material in a cylindrical tank. In the first part of the study the heater was a vertical spiral tube positioned coaxially with the tank. In the second part, the heater consisted of two coaxial spirals positioned on the same axis as the cylinder. In accord with the philosophy of constructal design, the heat and fluid flow configuration was endowed with degrees of freedom in order to morph toward better overall performance for a fixed amount of heating material. The paper documents the effect of the geometrical features such as helix diameter and pitch on the overall performance.

1. Introduction

The constructal law is the view that in flow systems in nature the architecture evolves freely in time in order to facilitate access to the currents flowing through it. In other words, the resistances of a flow system become reduced and rearranged over space and time, leading to the occurrence of progressively efficient flow configurations globally. Applications of this view are numerous especially in the domain of heat transfer [1–5]: from the cooling of electronics to energy storage and tree-shaped designs for heat transfer.

Heating Ventilation and Air Conditioning systems account today for more than half the energy consumption in buildings [6]. This drives the need to add a renewable energy component to the energy sources while solving the problem posed by the mismatch between energy supply and energy demand. Recently latent thermal energy storage systems focused the attention of the research community as a mitigation solution dedicated to building applications [7–15]. A high storage capacity is reached by means of materials that undergo phase change from solid to liquid (or liquid to gas). Among the many existing applications, solar collectors coupled with Phase Change Materials (PCM) tanks are a promising technique: the energy provided by the solar collectors is stored during day time by melting the PCM contained in the tank, while at night the solidification of the PCM released the stored energy [16–25].

The objective of the present paper is to determine the best configuration of the thermal energy storage system such that two objectives are met: (i) the lowest volumetric ratio of heated tube and tank, and (ii) the complete melting of the phase change material during a fixed time of 8 h. The volume of the storage tank and the tube diameter are fixed. The liquid inside the tube is heated to the temperature T_w by the solar panel. The time scale of heat transfer inside the tube is much shorter than the time necessary to melt the entire volume. Therefore the tube is considered to be isothermal, and its walls are at the temperature T_w. More details on this assumption can be found in [26,27].

2. Model

The tank is modeled as a vertical cylinder with adiabatic walls. Let $D = 0.60$ m be the cylinder diameter, and $H = 1$ m the tank height. The spiral tube is heated by a solar panel and connects the top and bottom surfaces of the tank. It is shaped as a vertical helix centered along the vertical axis of the tank. The tube diameter is d and it is fixed at a value of 2 cm. The tube volume is a degree of freedom, which means that the inner helix radius (R_H) and the pitch (p) can vary (Fig. 1). The tube volume is calculated as $n\pi^2 d^2 R_H/2$, where n is the number of turns, and where it was assumed that $p < 2\pi R_H$. The rest of the tank volume is filled with PCM, for which the properties are given in Table 1.

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Nomenclature

C	constant
c_P	specific heat at constant pressure (kJ/kg K)
d	diameter of tube (m)
D	diameter of tank (m)
g	gravity (m^2/s)
H	height of tank (m)
k	thermal conductivity (W/m K)
L_f	latent heat of fusion (kJ/kg)
n	number of turns
Nu	Nusselt number
p	helix pitch (m)
P	pressure (Pa)
Pr	Prandtl number
$\dot{Q}$	heat transfer rate (W)
q''	heat flux (W/m^2)
r	radius (m)
R_T	radius of tank (m)
R_H	internal radius of helix (m)
Ra	Rayleigh number
t	time (s)
T	temperature (K)
$V\,(V_r, V_\theta, V_z)$	velocity vector (m/s)
z	axial coordinate (m)

Greek letters

β	thermal expansion coefficient (K^{-1})
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
τ	temperature interval (K)

Subscripts

w	wall
0	reference

The PCM is considered to be in solid state at $t = 0$. The initial temperature, uniform over the entire volume, is $T_{init} < T_w$. In time, the material melts by conduction and natural convection. Assuming that the melted PCM is an incompressible liquid, the heat transfer and the fluid flow are described by the laws of conservation of mass, momentum and energy,

$$\nabla V = 0 \quad (1)$$

$$\rho \frac{DV}{Dt} = -\nabla P + \mu \nabla^2 V + \rho g \quad (2)$$

$$\rho c_P \frac{DT}{Dt} = k \nabla^2 T \quad (3)$$

where V is the velocity vector of components in cylindrical coordinates (V_r, V_θ, V_z), g is the gravitational acceleration, and k is constant. The model accounts for the natural convection effects through the Boussinesq approximation, namely $\rho = \rho_0\,[1 - \beta(T - T_{init})]$. The heat capacity method [29] is chosen to model the phase change of the material. Assuming that the change of phase occurs between T_0 and $T_0 + \tau$, we write that the specific heat is

$$c_P^* = c_P + \frac{L_f}{\tau}, \quad \text{when } T \in (T_0, T_0 + \tau) \quad (4)$$

where L_f is the material latent heat of fusion. When $T \leqslant T_0$ and $T \geqslant T_0 + \tau$, the specific heat value corresponds to the one given in Table 1 (the same value for solid and liquid).

Finally we implemented in the model a step function for viscosity: when the PCM is in the solid state, its viscosity is 4 orders of magnitude higher than the viscosity corresponding to the liquid state and presented in Table 1. The boundary conditions are:

$$\frac{\partial T}{\partial n} = 0, \quad \text{along the tank walls} \quad (5)$$

where n is the normal vector to the wall.

$$T = T_w, \quad \text{along the tube wall} \quad (6)$$

The non-slip velocity condition is applied along all the solid surfaces, tank and spiral tube.

The computations were performed by using a finite element package [30]. In order to confirm that the solution is independent of the size of the mesh, the solution was performed with a coarse mesh and then was calculated again increasing the number of elements by a factor of 3 until the changes in the peak temperature became of order of 2%. In accord with constructal design [2–5], the peak temperature was chosen because it is a global feature of the flow system, not a local one.

3. One helix

The first set of simulations concerns the case when the tube of diameter d is coiled into a single helix. In order to determine the volume of tube necessary to melt the PCM, and hence the geometrical characteristics of the helix (pitch, number of turns, diameter) we first considered the extreme case corresponding to the limit

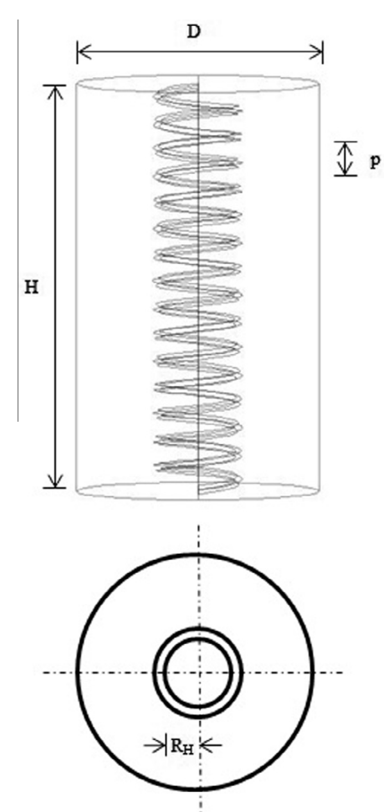

Fig. 1. Tank with phase change material (PCM) and spiral heater.