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Simulation and experimental study on honeycomb-ceramic thermal energy storage for solar thermal systems

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HIGHLIGHTS

- A honeycomb-ceramic is proposed for thermal energy storage of concentrated solar energy.
- A verified numerical model was developed to simulate the thermal performances.
- A long discharging period can be obtained when the parameters are designed properly.

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ABSTRACT

A honeycomb-ceramic thermal energy storage (TES) was proposed for thermal utilization of concentrating solar energy. A numerical model was developed to simulate the thermal performances, and TES experiments were carried out to demonstrate and improve the model. The outlet temperature difference between simulation and experimental results was within 5% at the end of a charging period, indicating the simulation model was reasonable. The simulation model was applied to predict the effects of geometric, thermo-physical parameters and flow fluxes on TES performances. The temperature dropped more quickly and decreased to a lower temperature in discharging period when the conductivity was smaller. The storage capacity increased with the growth of volumetric heat capacity. As to a TES with big channels and thin walls, the outlet temperature increased quickly and greatly in a charging process and dropped sharply in a discharging process.

1. Introduction

Thermal applications of solar energy include power generation, hydrogen production and other thermo-chemical conversions. Solar thermal energy storage (TES) is very important to make a stable heat supplier, which can improve the reliability and reduce the operation cost [1] through storing and releasing thermal energy in need.

By now, three kinds of TES have been proposed or applied, including sensible thermal, latent thermal and chemical thermal energy storages. Sensible thermal energy storage works by temperature changing. Liquid materials of sensible TES, such as molten salt and synthetic oil, have been applied in the Solar One, Solar Two, and Solar Tres, etc, whose temperature do not exceed 600 °C [2]. Solid materials, such as concrete and ceramics, are regarded as potential choices in fields of high temperature TES application [3] for low price, high strength and high-temperature resistance. Plataforma Solar de America (by DLR) [4–6] built and tested a set of concrete storage modules in a trough solar thermal power system, where steel pipes served as tube heat exchangers between heat transfer fluid (HTF) and solid material. An experimental temperature of 325 °C had been demonstrated by almost 100-thermal-cycle, and it was forecasted to be of good thermal stability, well thermal shock resistance and low internal temperature difference [4]. Due to the limits of concrete and steel, the storage temperature could be hardly improved further.

A honeycomb ceramics storage, often applied in high temperature air combustion (HTAC) technologies [7], had a 1.2-times storage capacity and a 1.35-times thermal conductivity comparing to a concrete storage [2]. The cost of honeycomb ceramic is relatively low, and it's convenient to purchase. The ceramic is of high-temperature resistance above 1000 °C and of good thermal shock resistance. The gas flow in each channel of storage material can be well distributed because of the symmetric honeycomb structure. In addition, the TES system is easy to design due to modular geometric units [1].

As to numerical models, Rummel presented a simplified theory of a heat regenerator avoiding complicated computation in 1930's,

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where he assumed the heat transfer coefficient was an empirical constant at any position of the regenerator and over a whole operation cycle [8]. Schack developed an approximate solution in which empirical expressions of time-dependent gas and solid temperatures were built and other important coefficients should be provided by experiments [8]. Nusselt presented classic differential-equations of heat transfer in thermal regenerators [9,10]. Hausen developed a differential equations by introducing a finite thermal conductivity and an overall heat transfer coefficient [8,11], and these equations had been extended for cylindrical- and spherical storage materials. Rafidi and Blasiak [12] brought forward a two-dimensional simulation model to forecast temperature profiles of gas and solid materials in a honeycomb regenerator and HTAC experiments were used to validate the model.

Different from HTAC, the charging and discharging periods of TES are always several hours or even days, which is much longer than that of HTAC (several seconds). By now less experimental and numerical studies have been reported on temperature dynamic changes for solar thermal applications.

An improved model of TES was proposed here, where heat transfer coefficients and other parameters varied with temperatures, while the previous models always neglected the changes, and TES experiments were carried out to demonstrate the model. The simulation model was applied to predict the effects of geometric, thermo-physical parameters and flow fluxes on TES performances. A long effective discharging period could be obtained when the parameters were designed properly.

2. Simulation model

A physical model is shown in Fig. 1. Air flows into small channels of honeycomb ceramic. The heat transfer includes conductivity of solid material and convection between air and solid surfaces. The direction of air flowing is named as x and the perpendicular direction is y.

In order to analyze heat transfer performances between fluid and solid materials where hot and cold fluids pass alternately, assumptions are given by.

(1) The thermal conductivity of solid material in y axis is infinite;
(2) The initial temperature distribution of solid material is uniform;
(3) The boundary of y direction of every channel is adiabatic;
(4) The inlet mass flow rate of fluid is constant in charging and discharging processes.

Firstly, the temperature difference of solid material in the y direction is ignored in the model. It is because that the wall of solid material is very thin, ~0.001 m, comparing to the length of the channel, 0.4 m, in the experiments, and the convective thermal resistance ($R_{\text{conv}} = 1/h_c A$) between gas and solid wall in the y axis is dozens of times of the conductive thermal resistance of solid material ($R_{\text{cond}} = \delta/\lambda A$) when the solid wall is thin enough. In addition, this assumption has also been adopted in the classic Hausen and Nusselt theories. Therefore the thermal conductivity of solid material in the y axis is assumed to be infinite. Secondly, the initial temperature of solid material is uniform when the TES system starts to work. Thirdly, each channel is an independent cell in the model, and the boundary of each channel is adiabatic. Thus, there is no heat transfer between channels, i.e. there is no heat loss in the y direction of every channel. Finally, the inlet mass flow rate is constant for each channel in charging and discharging process when the pump works stably.

One-dimensional equations of energy conservation are given by Refs. [9,10],

$$\text{Solid material}: \quad \rho c_p \frac{\partial T_s}{\partial \tau} - \lambda \frac{\partial^2 T_s}{\partial x^2} = h(T_g - T_s) \tag{1}$$

$$\text{Fluid}: \quad \rho c_p \left(\frac{\partial T_g}{\partial \tau} + u \frac{\partial T_g}{\partial x} \right) = h(T_s - T_g) \tag{2}$$

Heat transfer coefficient changes with local temperatures; while in the previous models, it was considered to be a constant, neglecting the changes of temperature. In this paper, the model supposed the heat transfer coefficient is a variable, as well as fluid density and velocity, changing with temperature.

According to Reynolds number ($\text{Re}_g = ud/\nu_g < 2200$), air flow is in a laminar state, and the empirical equation of convective heat transfer in porous materials [13]is expressed by:

$$\text{Nu}_g = 3.66 + \frac{0.0668 \text{Re}_g \text{Pr}_g \frac{d}{l}}{1 + 0.04 \left(\text{Re}_g \text{Pr}_g \frac{d}{l} \right)^{2/3}} \left(\frac{\eta_g}{\eta_s} \right)^{0.14} \tag{3}$$

where $\text{Re}_g \text{Pr}_g d/L < 10$. The initial and boundary conditions are as follows,

$$\tau = 0 \quad T_s = T_0 \tag{4}$$

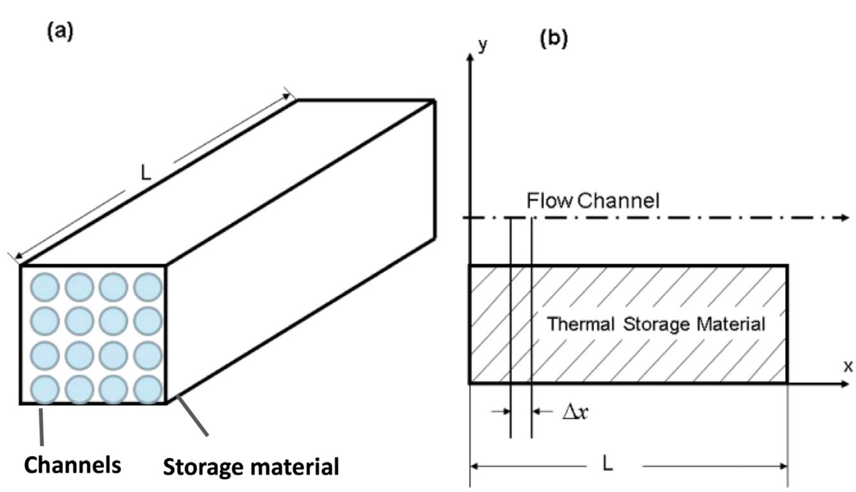

Fig. 1. Schematic of numerical model (a) storage outline; (b) cross section of unit.