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Thermal energy storages analysis for high temperature in air solar systems

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HIGHLIGHTS

- HTTES in a honeycomb solid matrix is numerically investigated.
- The numerical analysis is carried out assuming the honeycomb as a porous medium.
- The Brinkman–Forchheimer–extended Darcy model is used in the governing equations.
- Results are carried out for different mass flow rates and porosity values.
- The main effect is due to the porosity which set the thermal energy storage value.

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ABSTRACT

In this paper a high temperature thermal storage in a honeycomb solid matrix is numerically investigated and a parametric analysis is accomplished. In the formulation of the model it is assumed that the system geometry is cylindrical, the fluid and the solid thermo physical properties are temperature independent and radiative heat transfer is taken into account whereas the effect of gravity is neglected. Air is employed as working fluid and the solid material is cordierite. The evaluation of the fluid dynamic and thermal behaviors is accomplished assuming the honeycomb as a porous medium. The Brinkman–Forchheimer–extended Darcy model is used in the governing equations and the local thermal non equilibrium is assumed. The commercial CFD Fluent code is used to solve the governing equations in transient regime. Numerical simulations are carried out with storage medium for different mass flow rates of the working fluid and different porosity values. Results in terms of temperature profiles, temperatures fields and stored thermal energy as function of time are presented. The effects of storage medium, different porosity values and mass flow rate on stored thermal energy and storage time are shown.

1. Introduction

Energy storage technologies are strategic and necessary components for the efficient utilization of renewable energy sources and energy conservation. Energy conservation and management are needed in several industrial and commercial applications in order to supply thermal energy. Various devices are employed to satisfy the energy demand in commercial, industrial and utility sectors which can vary on daily, weekly and seasonal bases. Thermal Energy Storage (TES) is useful for energy conservation and allows to align energy production with consumer demand. TES is an expanding field within the subject of renewable energy technologies. In fact, the use of TES for thermal applications, such as space and water heating, cooling, air-conditioning heat sinks, has recently received much attention [1–7].

TES in concentrated solar power (CSP) technology is very important to deliver high-temperature heat in the form of sensible heat storage in a packed bed of rocks or other ceramic materials and it is especially suitable when a gas is used as the heat transfer fluid

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in the solar receiver [8–12]. However, some other types of porous media such as ceramic foams or honeycomb could be employed as material for High Temperature Thermal Energy Storage (HTTES) unit to realize a different sensible heat storage system with lower thermal capacity and pressure drop [4,8,12].

A sensible heat storage system consists of porous solid material through which the fluid circulates. Heated fluid (usually air) flows from solar collectors into a bed of graded particles or foams or parallel channels (honeycomb system) from top to bottom in which thermal energy is transferred during the charging phase. During the charging mode, solar heated gas is forced into the top of the container, i.e. upper plenum and then passes evenly down through the porous medium heating the storage and passes out through the lower plenum. Gas is drawn off at the bottom and returned to the collectors. When energy is needed from storage, the gas flow is reversed. Several studies describe numerical models for sensible heat storage in porous media [12]. Coutier and Farber [13] mentioned that packed bed generally represents the most suitable energy storage unit for air based solar systems.

It should be underlined that heat transfer to and from a flowing fluid to a packed bed has been the subject of many theoretical and experimental investigations since Schumann's original work [14]. In that study one-dimensional two-phase model for packed bed system was assumed by ignoring the thermal capacity of the fluid, axial conduction in the fluid and axial conduction in the bed material. The extraction of numerical information from the solutions by providing monograms, extensive graphs and tabulations were carried out in Refs. [15–17]. Numerical simulations were carried out to solve the governing equations for the packed bed by finite difference methods [18–20]. The dynamic response of a packed column was studied by a mathematical model and an arbitrary time dependent inlet air temperature was accomplished in Ref. [21]. Different aspects of sensible heat storage systems were analyzed in Ref. [22]. A study on different energy storage techniques and materials used in sensible heat storage systems was presented in Ref. [23]. A comparative numerical investigation on packed bed thermal models suitable for sensible and latent heat thermal storage systems was reported in Ref. [24]. A method of preserving the stratification by segmenting the storage bed was numerically studied in Ref. [25]. An experimental investigation on heat transfer and pressure drop characteristics of packed bed solar energy storage system with large sized elements of storage material was presented in Ref. [26]. An extensive literature review of research work on packed bed systems was presented in Ref. [27]. The effect of multiple charge and discharge cycles was studied in detail in Ref. [28]. A high temperature TES was numerically parametrically analyzed by using CFD code to solve the governing equations in porous media in transient regime [29]. High temperature TES in a packed bed of rocks was studied by Hänchen et al. [9] for air-based concentrated solar power plants. A comparison between numerical results and their experimental data was accomplished for a packed bed of crushed steatite (magnesium silicate rock) at 800 K. Recently, a HTTES with ceramic foams was numerically studied in Ref. [30] in order to evaluate the thermal and fluid dynamic behaviors of these systems in terms of porosity. The results showed the effects of the porosity and working fluid mass flow rate on the stored thermal energy and storage time.

The honeycomb structure is used in many applications such as heat storage, heat regenerators, drying and cooling of electronic equipment [8,10,12,31–40]. The efficiency of micro-cell aluminum honeycombs in augmenting heat transfer in compact heat exchangers using analytical models was evaluated in Ref. [31]. For convective cooling, the overall heat transfer rate was found to be elevated by about two orders of magnitude when an open channel was designed with an aluminum honeycomb core. A two-dimensional numerical model to determine the dynamic temperature and velocity profiles of gases and solid heat-storing materials in a composite honeycomb regenerator was developed in Ref. [32]. The energy storage was calculated and thermal performance of honeycomb heat regenerator was evaluated at different switching times and loading. A honeycomb reactor obtained by the assembling of several cavities, in order to optimize a thermo chemical reactor for hydrogen production or high temperature heat storage, was examined in Ref. [33]. A simplified method to optimize the geometry of a solar thermo chemical reactor considering radiation in the cavity and conduction inside the reactive material was performed. A honeycomb porous microchannel cooling system for electronics cooling was proposed in Ref. [35]. Preliminary experimental investigation was conducted to understand the characteristics of heat transfer and cooling performance under steady single-phase flow. The experimental results allowed to conclude that the considered cooling system is able to perform heat dissipation well. A two-dimensional model for predicting heat and mass transfer in an alanate hydride reactor with metallic honeycomb structure heat exchanger was developed in Ref. [36]. A numerical investigation on honeycomb ceramics' heat transfer process to estimate the effects of temperature difference and hole side length on heat transfer and the resistance losses was presented in Ref. [37]. The design and characterization of monolithic heat sinks was reported in Ref. [38]. It was showed that the proposed heat sink geometries presented a performance enhancement relative to a conventional longitudinally finned heat sink. Multiphase transport model to simulate drying of honeycomb ceramic substrates in a conventional (hot air) drier was developed in Ref. [40]. Heat and moisture transport in the honeycomb walls as well as channels was modeled.

In this paper high temperature thermal energy storage with a honeycomb as a solid matrix is numerically analyzed. The investigation refers to the Elioslab project on high temperature concentrated solar energy systems which has developed a solar system with a 30 kW high temperature solar receiver [41] but with a different porous medium structure and gas. The commercial CFD Fluent code is used to solve the governing equations in transient regime, in local thermal non-equilibrium (LTNE) and in the generalized flow Brinkman–Forchheimer–extended Darcy model. The interfacial heat transfer coefficient between solid matrix and fluid is evaluated with a three dimensional steady state numerical analysis on a single channel. Moreover, also the effect of radiative heat transfer is taken into account. Numerical transient simulations are carried out at different mass flow rates. The results are carried out for mass flow per unit cross section of the same order of magnitude given in Ref. [9] and allow to evaluate the effects of the porosity and the working fluid mass flow rate on the stored thermal energy and storage time related to charge and discharge cycles.

2. Mathematical description

The geometry under investigation is shown in Fig. 1. It consists of a cylinder whose diameter D is equal to 0.60 m and height L is 1.0 m. The fluid and the solid thermo physical properties are assumed temperature independent. In all cases a ceramic material is considered and the porous medium is constituted by a honeycomb structure. The solid material is made of cordierite, whose properties are summarized in Table 1, and the working fluid is air. The radiation heat transfer mechanism is taken into account for all configurations. Two charging–discharging cycles are considered. In the charging phase air enters at 1473.15 K whereas in discharging