Applied Thermal Engineering 129 (2018) 636–645

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Dynamic simulations of a honeycomb ceramic thermal energy storage in a solar thermal power plant using air as the heat transfer fluid

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HIGHLIGHTS

- A dynamic model was developed for honeycomb ceramic thermal energy storage.
- The model was validated by the experiment data of two honeycomb ceramic materials.
- The model can realize comprehensive thermal simulation at a low computational cost.
- The effects of the honeycomb ceramic structure parameters were studied.

ARTICLE INFO

Article history:
Received 22 November 2016
Revised 25 September 2017
Accepted 9 October 2017
Available online 16 October 2017

Keywords:
Solar thermal power plant
Thermal energy storage
Honeycomb ceramic
Dynamic simulations
Parametric analysis

ABSTRACT

Thermal energy storage is a key component for the marketability of solar thermal power plants (STPP). Thermal energy storage in a solar thermal power plant is essential for the system usefulness but has been rarely studied. This paper numerically investigates the heat storage in a honeycomb ceramic thermal energy storage in a solar thermal power plant using air as the heat transfer fluid using a one-dimensional thermal energy storage model in the object-oriented modeling language Modelica. This model can be used to easily study the thermal performance of the thermal energy storage system. The simulation results agree well with experimental data for two honeycomb ceramic materials for various charging and discharging processes. The model is then used to study the influences of the honeycomb geometric parameters on the thermal energy storage and the initial storage material cost. The results show that the total honeycomb ceramic length and the total cross-sectional area have the greatest effect on the initial thermal energy storage material cost.

1. Introduction

Solar thermal power plants are being developed as one option for future renewable energy systems [1–3]. The thermal energy storage (TES) is a crucial component in solar thermal power plants (STPP) that reduces the mismatch between the energy supply and the demand over the entire day and that mitigates the impact of intermittent solar radiation on the grid. The energy storage system also increases the availability and operational flexibility of the STPP, which is crucial to the market penetration of STPP systems [4–8].

Various media have been used as the heat transfer fluid in STPP systems [9–11], such as air, water/steam, thermal oils, and molten salts. Compared to other heat transfer fluids, air has economic, environmental and technical advantages [12,13]. Air is freely available in the atmosphere, non-toxic, produces no pollution, has no phase transition, does not degrade, has no upper temperature limitation, has no need for preheating, and allows higher efficiency thermodynamic cycles. Studies on the use of air as the heat transfer fluid began in Europe and Israel in the early 1990s with larger projects such as Phoebus-TSA in Spain, DIAPR in Israel and Julich in Germany [13].

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https://doi.org/10.1016/j.applthermaleng.2017.10.063
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Nomenclature

Latin symbols

a_{vs}	specific surface area per unit volume (m^{-1})
C_p	specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
d_h	single channel hydraulic diameter (m)
h	enthalpy ($J\,kg^{-1}$)
h_a	convection heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_v	volumetric convection heat transfer coefficient ($W\,m^{-3}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	length (m)
$\dot{m}$	mass flow rate per unit area ($kg\,s^{-1}\,m^{-2}$)
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
T	temperature (K)
t	time (s)
U	internal energy per unit volume ($J\,m^{-3}$)
v	velocity ($m\,s^{-1}$)
x	x-direction coordinate (m)

Greek symbols

ε	porosity
ρ	density ($kg\,m^{-3}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)

Abbreviations

HTF	heat transfer fluid
STPP	solar thermal power plants
TES	thermal energy storage

Subscripts

f	fluid
in	inlet
s	solid
v	volumetric
0	initial state

Several different TES concepts have been experimentally investigated for air system [14–16]. Among them, the honeycomb ceramic TES design stands out because of its excellent material characteristics, cost and practicality [7,17–19]. Honeycomb ceramics have been used as regenerative heat exchanger materials in industrial furnaces with high temperature air combustion [20]. Ceramics have 1.35 times the thermal conductivity and 1.2 times the storage capacity of concrete [19]. Ceramics have good thermal shock resistance and can withstand temperatures higher than 1000 °C. Honeycomb ceramics have a porous structure with many identical straight channels which ensures a small airflow resistance together with a large heat transfer surface area. The symmetrical honeycomb structure evenly distributes the airflow in each channel. In addition, the regular geometrical structure of the honeycomb ceramic block allows modular optimization the TES design. Thus, honeycomb ceramic TES systems have been successfully used for regenerator-type energy storage in the steel industry. Honeycomb ceramics were also used in the TES of the Julich STPP using air as the heat transfer fluid in Germany, which was put into operation in 2009 [12].

The classical mathematical models for simulating high temperature air combustion systems with honeycomb ceramics were developed by Rummel, Schumann, Hausen and other pioneers. Schumann [21] assumed that the heat transfer mechanism in the regenerator was only convection between the solid and the gas. Rummel also gave a simplified theory of the heat transfer in the honeycomb ceramic by fixing the convective heat transfer coefficient to an empirical value throughout the honeycomb ceramic and during all of the operating processes [22]. Bahnke and Howard [23] and Heggs et al. [24] reported the effects of the solid conduction in the flow direction on the overall heat transfer inside regenerator, which is not negligible. Hausen [25] presented differential equations assuming an overall heat transfer coefficient and a finite thermal conductivity. Ishii et al. [26] used the standard k-ε model and the P-1 radiation model to analyze the turbulence and radiation in a ceramic honeycomb regenerator for high temperature air combustion. Liu et al. [27] modeled the flow characteristics in honeycomb ceramics and the effects of the temperature difference and hole side length on the heat transfer and the flow resistance.

The flow rates in TES of a STPP system are much smaller than in high temperature air combustion systems and the flow in a TES is usually laminar. The TES charging and discharging periods are then often much longer than those in high temperature air combustion systems. In addition, the working fluid in a TES is air while in a regenerative heat exchanger the working fluid is flue gas containing carbon dioxide and nitrogen oxides.

There have been few reports of numerical or experimental research on honeycomb ceramic TES for STPP systems. Tests on the Jülich Solar Power Tower [12] experimentally verified the functionality and performance of the storage system. The test results indicate that the storage systems can be scaled up to large systems. Wang et al. [28] compared the thermal performances of six honeycomb ceramic TES for use in STPP systems using 3D CFD models to investigate the influences of porosities and hole pitches on the TES thermal storage time. However, experiments to evaluate the effects of all the different structural designs and working conditions would be very expensive. CFD simulations are very useful for numerical analyses, but are not very practical for in-situ dynamic performance predictions and analysis of the effects of various parameters due to the relatively long computing times.

This study developed a one-dimensional dynamic model of a honeycomb ceramic TES for use in a STPP system with air as heat transfer fluid using the modeling software Dymola, the object-oriented modeling language Modelica and spatial discretization [29,30]. The physical parameters of the solid and air and the heat transfer coefficients all varied with temperature unlike in previous models where they were assumed to be constant. The simulation results are compared with experimental data for different conditions. The model is used to investigate the influence of the honeycomb ceramic parameters such as the channel hydraulic diameter, porosity, length and total cross-sectional area on the TES performance and the initial material costs.

2. Honeycomb ceramic TES model

2.1. Physical model

The honeycomb ceramic TES is composed of a metal shell, thermal insulation, and the honeycomb ceramic blocks as shown in Fig. 1a. During charging, high temperature air flows through the TES and transfers heat to the packed honeycomb ceramic blocks