Applied Energy 178 (2016) 281–293

Contents lists available at ScienceDirect

Applied Energy

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

Dynamic simulation and experimental validation of an open air receiver and a thermal energy storage system for solar thermal power plant

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HIGHLIGHTS

- Dynamic models are developed for an air receiver and a thermal energy storage.
- The models can provide comprehensive thermal simulation at low computational cost.
- Both of the models were validated by the experimental data.
- Three Nusselt number equations were compared in simulations of the receiver model.
- A receiver and thermal energy storage system model was developed.

ARTICLE INFO

Article history:
Received 9 August 2015
Received in revised form 29 May 2016
Accepted 14 June 2016

Keywords:
Solar thermal power plants
Dynamic simulations
Air receiver
Thermal energy storage
Modelica language
Experimental validation

ABSTRACT

The transient performance of solar thermal power plants is critical to the system design and optimization. This study numerically investigates the dynamic efficiencies of an open-loop air receiver and a thermal energy storage unit. One-dimensional dynamic models of the air receiver and thermal energy storage were developed using the Modelica language with a graphical user interface and the Dymola solver to provide comprehensive thermal simulation at low computational cost. An air receiver and thermal energy storage experimental platforms were built to validate the simulation models. The simulation results compare well with the experimental data, so the models can be used to predict the variations of air receiver and thermal energy storage efficiencies. The models were then combined into a receiver and thermal energy storage system model with control schemes. The schemes control the air receiver outlet air temperature at relatively stable values while the thermal energy storage automatically switches between charging, discharging and stand-by modes.

1. Introduction

As one of the main options for future new energy technologies, solar thermal power plants (STPP) have drawn much attention because STPP has high efficiency due to the high working temperatures. STPP can produce electric power from a renewable energy [1,2]. Several fluids have been used as the heat transfer fluid (HTF) in STPP systems [3–5]. Air has several technical and economic advantages over commonly used fluids such as water/steam, molten salts and thermal oils. Air is freely available in the atmosphere, creates no pollution, has no phase transition, does not degrade, has no upper temperature limit, and has no need for preheating [5,6]. In concentrated solar systems using air, the air receiver that converts the solar radiation energy into thermal energy in the air is the major component of the system [7,8]. The first air receiver was a tube type developed in the USA. Volumetric air receivers have been researched in Europe since the 1980s. In general, open volumetric air receiver is composed of an arrangement of absorber modules, connecting construction, supporting construction and insulation. Each absorber module includes a porous absorber and an absorber cup. The absorber is installed in the front of the cup to be fixed, and the neck in the rear of the cup is inserted into a steel casing for absorber modules connecting and supporting. During the operation, the porous absorbers absorb the solar irradiation and transfer the energy to the air flow. The hot air out

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http://dx.doi.org/10.1016/j.apenergy.2016.06.056
0306-2619/

Nomenclature

Latin symbols

A	area (m^2)
a_{vs}	specific surface area per unit volume (m^{-1})
B	volumetric thermal expansion coefficient
C	roughness coefficient
Cp	specific heat ($J\,kg^{-1}\,K^{-1}$)
d	mean cell diameter of the ceramic foam (m)
d_h	single channel hydraulic diameter of the honeycomb (m)
DNI	direct normal irradiance ($W\,m^{-2}$)
g	kinematic viscosity ($m^2\,s^{-1}$)
Gr	Grashof number
H	storage height (m)
h	enthalpy ($J\,kg^{-1}$)
h_n	free convection heat transfer coefficient ($W/m^2\,K^{-1}$)
h_v	mean volumetric heat transfer coefficient ($W\,m^{-3}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
K_1	permeability coefficient (m^2)
K_2	inertial coefficient (m^{-1})
L	thickness (m)
l	characteristic length (m)
$\dot{m}$	mass flow rate per unit area ($kg\,s^{-1}\,m^{-2}$)
Nu	Nusselt number
P	pressure (Pa)
p	perimeter (m)
Pr	Prandtl number
q	radiation flux ($W\,m^{-2}$)
R_1	heliostat reflectivity
R_2	parabolic mirror reflectivity
Ra	Prandtl number
Re	Reynolds number
S	solar radiation source ($W\,m^{-2}$)
T	temperatures (K)
t	time (s)
U	internal energy ($J\,m^{-3}$)
u	superficial velocity ($m\,s^{-1}$)
W	heat loss (W)
x	x-direction coordinate (m)
y	y-direction coordinate (m)

Greek symbols

α	thermal diffusivity (m^2/s)
β	Rosseland mean extinction coefficient (m^{-1})
ε	porosity
ρ	density ($kg\,m^{-3}$)
δ	Stefan–Boltzmann constant ($W\,m^{-2}\,K^{-4}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
υ	kinematic viscosity (m^2/s)

Abbreviations

CCD	charge coupled device
DNI	direct normal irradiance
HTF	heat transfer fluid
STPP	solar thermal power plants
TES	thermal energy storage

Subscripts

con	convective
f	fluid
in	inlet
l	based on characteristic length
r	reference
rad	radiative
s	solid
shell	storage shell
tot	total
v	volumetric
∞	ambient

of different absorbers will joint in the rear of the receiver. Using small absorber units overcomes the difficulty of big porous absorber manufacture and makes up-scaling to larger systems possible [9]. The absorber in the volumetric air receiver is normally made of porous material since the three-dimensional configuration of the porous material brings lower heat losses and better heat transfer between the absorber and the air. Ceramic material is wildly used in the absorber due to its good mechanical strength, high-temperature capability and potential for using smaller pieces to build the absorber. Chavez and Chaza [10] tested a ceramic absorber at the Plataforma Solar de Almeria with solar fluxes up to 824 kW/m^2 to show that the porous ceramic material has reasonable thermal efficiencies and excellent structural integrity in the high flux, high temperature solar environment. Becker et al. [11] conducted theoretical and numerical investigations of the flow stability in a volumetric solar receiver and concluded that the instabilities can be avoided by using a suitable absorber material with high thermal conductivity and a quadratic pressure drop correlation like ceramic foam. Fend et al. [12] compared experimental results for a variety of porous materials and showed that the most promising materials for volumetric air receivers are ceramic foams and ceramic fabrics.

The intermittent nature of solar radiation requires thermal energy storage for 24 h. electricity production to reduce the mismatch between the energy supply and demand, which is one of main differences between the STPP and other renewable energy systems [13]. The main advantages of integrating a STPP system with solar thermal storage include extended utilization of the power block and life expectancy of the system components due to the reduction of thermal transients [14,15]. Several different thermal energy storage concepts have been experimentally investigated with air as the HTF in the receiver [6,16–18]. Considering the economic and material characteristics, honeycomb ceramics are especially suitable as the thermal energy storage material due to their large specific surface areas, low flow resistance, small thermal inertia, and low cost [19].

Many numerical studies have investigated air receivers using silicon carbide ceramic foams as absorbers. Some studies were from a macro-perspective based on certain simplifying assumptions. Bai [20] investigated the heat transfer in ceramic foams in solar air receivers based on a one dimensional physical model. Wu et al. [21] and Xu et al. [22] analyzed the temperature distributions in the fluid and solid phases in ceramic foam air receivers for various porosities, average particle diameters, air inlet velocities, and absorber thicknesses using two dimensional numerical models. Other researchers have studied air absorbers from the microscopic point of view using a Representative Element Volume (REV) of the ceramic foam. Wu et al. chose idealized packed tetrakaidecahedrons to represent the detailed geometry of the porous ceramic foam in a three dimensional model to predict the local convective heat transfer coefficient [23] and develop a new pressure drop correlation [24] for the air flow in the porous ceramic foam. Wang and Pan [25] developed a random generation-growth method to reproduce the microstructures of open-cell