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Fully coupled transient modeling of ceramic foam volumetric solar air receiver

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Abstract

Ceramic foam is a promising material for the absorber of volumetric solar air receiver in concentrated solar thermal power (CSP) plant. The transient behaviors of volumetric solar air receiver are crucial to the receiver's controllability, and to some extent, the plant's safety. This study numerically analyzes the transient behaviors of volumetric solar air receiver under various working conditions. A fully coupled transient model of the volumetric solar air receiver is developed in this paper. The pressure drop of the absorber, the interfacial heat transfer between the flowing fluid and solid, and the radiative heat transfer due to concentrated solar radiation absorption by ceramic foam and the radiation transport inside the media were included together in this transient model. In addition, the temperature fields of the fluid and solid phases were obtained by using the local thermal non-equilibrium model. A comparison of the computed results with experimental data shows that this coupled transient model can be used to predict the performance of volumetric solar air receiver. Based on this model, the transient behaviors of the solar air receiver under a sudden heat flux, a sudden loss of heat flux, and a step change of heat flux were studied. The results of this study are very helpful in designing and controlling volumetric solar air receivers.

Keywords: Volumetric solar air receiver; Transient modeling; Local thermal non-equilibrium model; P_1 radiation model; CFD

1. Introduction

Across all the concentrated solar power (CSP) technologies, the central receiver power plant with the volumetric solar air receiver and a gas turbine has three advantages (Casals, 1999): (1) This technology requires less water to generate electricity than other technologies; (2) the high temperature of the thermodynamic cycles, results in a high efficiency for generating electricity; (3) the air is inherently a non-problematic heat transfer fluid due to its inert nature within the temperature ranges used. The first point is particularly advantageous as most solar energy abundant regions are located in arid, semi-arid zones and are therefore lack water. Consequently, this technology of generating electricity with solar energy is very promising.

To elaborate further the principle of the volumetric air receiver is that the receiver's absorber absorbs and converts the concentrated solar radiation into heat, while cold air simultaneously flows through the absorber and is heated by the absorber. The air in turns leaves the receiver as hot air.

The flow and heat transfer in porous media have been studied for a great deal of time through both experiment (Fu et al., 1998; Younis and Viskanta, 1993; Zhang, 2004; Fuller et al., 2005) and simulation (Boomsma et al., 2003; Wu, 2010; Wu et al., 2010; Wu et al., 2011a; Wu

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Nomenclature

C_1, C_2	k-ε model constants
c_p	thermal capacity (J kg^{-1} K^{-1})
d	mean cell size (m)
DNI	direct normal irradiance (kW m^{-2})
F	source term representing the pressure drop in the porous media
G_i	generation rate of the intrinsic average of k_t
h_{lv}	local volumetric heat transfer coefficient (W m^{-3} K^{-1})
I	radiation intensity (W m^{-2} sr^{-1})
K_1	permeability coefficient (m^2)
K_2	inertial coefficient (m^{-1})
k	absorption coefficient (m^{-1})
k_t	turbulence kinetic energy (m^2 s^{-2})
Nu_{lv}	Nusselt number based on h_{lv}
P	pressure (Pa)
P_i	production rate of $\langle k_t \rangle^i$ due to gradients of $\bar{u}_D$
q	heat source (W m^{-3})
Q	concentrated solar radiation flux (W m^{-2})
Re	Reynolds number ($\rho ud/\mu$)
T	temperature (K)
t	time
$\bar{u}_D$	superficial velocity (m s^{-1})
u'	velocity fluctuation (m s^{-1})
x	x-direction coordinate (m)
z	z-direction coordinate (m)
r	cylindrical coordinate (m)

Greek symbols

α	absorptivity
σ	Stefan-Boltzmann constant
β	extinction coefficient (m^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
σ_s	scattering coefficient (m^{-1})
ϕ	porosity
ρ	density (kg m^{-3})
μ	transient viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
ε	dissipation rate (m^2 s^{-3})
ε_e	apparent emissivity
σ_k, σ_ε	k–ε model constants

Subscripts

a	ambient
c	conduction
eff	effective
f	fluid
in	inlet
out	outlet
r	radiation
s	solid
v	volume
lv	local and volumetric
$steady$	the steady state of the solar air receiver

Superscripts

i	volume average

et al., 2011b). However, there is very little literate investigating the transient flow and heat transfer inside porous media. Volumetric solar air receivers have also been studied for more than 20 years. Different materials, for example, foam (Albanakis et al., 2008), wire mesh (Romero et al., 2002), honeycomb (Koll et al., 2009) and packed bed (Flamant et al., 1988) were trialed as absorbers. Different structures, for example, the two-slab selective air receiver (Flamant et al., 1988; Variaot et al., 1994), selective air receiver (Pitz-Paal et al., 1991), "Porcupine" receiver (Karni et al., 1998), pressurized air receiver (Kribus et al., 2001) and open air receiver (Hoffschmidt et al., 1999) were additionally studied through experiment (Kribus et al., 2001; Hoffschmidt et al., 1999; Chavez and Chaza. 1990; Fricker, 1987) and simulation (Wu et al., 2011b; Becker et al., 2006). Furthermore recently, theoretical and experimental works have been conducted on the flow instability problem of volumetric solar air receiver (Becker et al., 2006; Pitz-Paal et al., 1997; Kribus et al., 1996). In addition, transient simulations (Ahlbrink et al., 2009; Xu et al., 2010) and the control strategy (Gall et al., 2009) of entire tower power plants including the heliostat field were also investigated. However, the simulations in Ahlbrink et al. (2009), Xu et al. (2010) are one-dimensional analysis of a whole volumetric solar air receiver. To the authors' knowledge, there are no open literatures which studied the detailed transient behaviors of volumetric solar air receiver. Accordingly the focus of the model in this paper lies on the detailed flow and heat transfer processes inside the absorber.

The detailed transient behaviors of volumetric solar air receiver are crucial to the entire CSP system, which is linked with the volumetric solar air receiver's safety, efficiency, operability and robustness of the whole solar tower power plant. This study investigated the transient behaviors of volumetric solar air receiver by solving the coupled transient volume-averaged governing equations. The studied ceramic foam, see Fig. 1, was assumed to be isotropic, homogenous and had temperature independent properties.

The pressure drop of the absorber, the interfacial heat transfer between the air and the absorber, and the radiation heat transfer were jointly considered. The pressure drop was calculated using a non-Darcian model (Wu et al., 2010). The energy equations of the air and solid phases used a local thermal non-equilibrium model (Wu et al., 2011a; Alazmi and Vafai, 2002; Kim and Jang, 2002;