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Coupled radiation and flow modeling in ceramic foam volumetric solar air receivers

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Abstract

Ceramic foams are promising materials for the absorber of volumetric solar air receivers in concentrated solar thermal power (CSP) receivers. The macroscopic temperature distribution in the volumetric solar air receiver is crucial to guarantee that volumetric solar air receivers work steadily, safely and above all, efficiently. This study analyzes the temperature distribution of the fluid and solid phases in volumetric solar air receivers. The pressure drop in the ceramic foams and the interfacial heat transfer between the flowing fluid and solid are included in the model. The radiative heat transfers due to concentrated solar radiation absorption by the ceramic foam and the radiation transport in the media were modeled with the P_1 approximation. The energy fields of the fluid and solid phases were obtained using the local thermal non-equilibrium model (LTNE). Comparison of the macroscopic model with experimental results shows that the macroscopic model can be used to predict the performance of solar air receivers. Sensitivity studies were conducted to analyze the effects of velocity, porosity, mean cell size and the thermal conductivity of the solid phase on the temperature fields. The results illustrate that the thermal non-equilibrium phenomena are locally important, and the mean cell size has a dominant effect on the temperature field.

Keywords: Volumetric solar air receiver; Ceramic foam; P_1 model; Local thermal non-equilibrium model; CFD

1. Introduction

The large specific surface area of porous media and the tortuous flow path inside the porous media make it a useful material for many industrial applications, especially in applications where the heat transfer is important. Cellular ceramics are promising materials for the absorbers of volumetric solar receivers in concentrated solar thermal power. The knowledge of the temperature difference between the flowing fluid and the solid matrix, and its influencing factors are crucial to the entire system where the porous media is used as the heat exchanger. In CSP technology, this knowledge is linked with the solar air receivers′ safety, efficiency, operability and the robustness of the whole solar tower power plant.

Studies of the temperature field inside porous media have widely used the local thermal non-equilibrium model (Alazmi and Vafai, 2002; Kim and Jang, 2002; Khashan et al., 2006; Nouri-Borujerdi et al., 2007; Hayes et al., 2008). However, the radiation heat transfer has not been taken into account in these studies. The radiation heat transfer plays a dominant role in the heat transfer when the porous is in a high temperature environment (Zhao et al., 2004a,b). The working temperature of volumetric solar receiver is very high, generally range from ambient temperature to 1000 °C or higher. Thus the radiation heat transfer is important. Volumetric solar receivers have been studied for more than 20 years. Flamant et al. (Flamant et al., 1988) and

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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 (Wm^{-3} K^{-1})
I	radiation intensity (Wm^{-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 (Wm^{-3})
Q	heat flux (Wm^{-2})
Re	Reynolds number ($\rho ud/\mu$)
T	temperature (K)
$\bar{u}_D$	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 (Wm^{-1} K^{-1})
σ_s	scattering coefficient (m^{-1})
ϕ	porosity
ρ	density (kg m^{-3})
μ	dynamic viscosity (kg m^{-1} s^{-1})
v	kinematic viscosity (m^2 s^{-1})
ε	dissipation rate (m^2 s^{-3})
ε_e	apparent emissivity
σ_k, σ_ε	$k - \varepsilon$ model constants

Subscripts

c	conduction
eff	effective
f	fluid
in	inlet
out	outlet
r	radiation
s	solid
v	volume
$_{lv}$	local and volumetric

Superscripts

i	volume average

Variot et al. (Variaot et al., 1994) investigated the combined heat transfer in a two-slab selective volumetric solar air receiver made of a multilayer packed bed. Pitz-Paal et al. (Pitz-Paal et al., 1991) numerically investigated the air and wall temperature distribution in a selective solar receiver which consisted of a ceramic foil receiver covered by a matrix of square channels of quartz glass. These volumetric solar receivers used the same selective absorptive concept in which the maximum temperature locates inside of the volumetric solar receiver. However, because of the complexity of the structures, the selective-absorbing volumetric solar receiver has not been studied much more. Researchers then switched to a volumetric solar receiver structure without a semitransparent layer. Fend et al. (Fend et al., 2004) proposed an ideal temperature distribution in the solid phase where the maximum temperature is located inside the absorber. However, experimental data in the literature (Fend et al., 2004) illustrated that the maximum temperature is still located at the front surface of the absorber. So this ideal temperature distribution is very difficult to attain.

The geometric properties (mean cell size, porosity and the shape of the strut cross-section), optical properties (absorptivity, extinction coefficient and scattering phase function), thermo-physical properties (thermal conductivity and thermal capacity) of ceramic foam materials and the fluid properties jointly affect the performance of a volumetric solar receiver. To design a volumetric solar air receiver with a favorable temperature distribution, we need to know the effects of these parameters on the volumetric solar receiver performances. This study simulates the temperature distribution of the fluid and solid phases in a volumetric solar air receiver by solving the coupled volume-averaged governing equations. The studied ceramic foam, see Fig. 1, was assumed isotropic, homogenous and with temperature independent properties. The governing equations were volume-averaged. The pressure drop of ceramic foams, the interfacial heat transfer between the flowing fluid and the solid, and the radiation heat transfer due the concentrated solar irradiance and inside the ceramic foams were included. The pressure drop was calculated using a non-Darcian model. The energy equations of the fluid and solid phases used a local thermal non-equilibrium model with the concentrated solar irradiance been treated as a distributed heat source to the solid phase. The thermal radiation heat transfer between strut surfaces was computed with the P_1 model. The macroscopic model was then used to study the impact of various factors (porosity, mean cell size, etc.) on the temperature field. The macroscopic temperature