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Transient thermal performance response characteristics of porous-medium receiver heated by multi-dish concentrator

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ABSTRACT

The transient thermal performance response characteristics of porous-medium receiver have a major impact on the operability of a solar thermal power plant (STPP). To investigate the transient thermal performance response characteristics of porous-medium receiver, method coupled to the Monte Carlo ray tracing (MCRT) and finite volume method (FVM) was developed to establish a 2D transient state heat-transfer model using a local thermal non-equilibrium (LTNE) calculation. The effects of the fluid thermophysical characteristics, the fluid-phase type, and the solid-phase thermal conductivity on the unsteady-state heat-transfer performance were investigated to determine the transient thermal performance response characteristics of porous-medium receiver. The numerical results indicated that the variation in the air thermophysical properties due to the high working temperature can induce a very small transient thermal performance response in porous-medium receiver (a maximum deviation of 1.9% was observed in this study). A porous-medium receiver with a high thermal conductivity can benefit from the dispersion of concentrated energy. The dimensionless solid-phase temperature eon the center point of receiver in case of $\lambda = 40$ W/(m·K) was 1.05 at $t = 240$ s, decreasing to 0.92 in case of $\lambda = 120$ W/(m·K).

1. Introduction

According to the IEA, 50% of power plants will be built in the future and will be powered by clean, sustainable energy [1]. Solar energy comes at the top of the list of candidate energy sources due to its abundance distribution in nature [2]. As the efficiency of a solar thermal power plant (STPP) is proportional to the operating temperature, a modern STPP demands high-grade energy to achieve high temperature levels and, therefore, achieve efficient power generation with a compact plant size and the shortest possible payback period [3,4].

In an STPP, the solar energy is concentrated on a focal point or line by mirrors or lenses, thus giving rise to medium- or high-temperature heat [5,6]. A receiver/reactor is placed in correspondence of the solar radiation [7]. The receiver is a key component in the solar energy conversion process: it absorbs the concentrated solar radiation and transfers it to a heat-transfer fluid (i.e. air, water, or molten salt) at a high temperature [8]. Due to the large heat and mass transfer surface but low pressure drop [9], porous medium is widely used for concentrated solar thermal applications: it had been successfully used on a 3 MW concentrated solar plant during the SOLAIR project [10]; ETH researchers adopted a porous medium for the reactor in solar thermochemical applications [11].

To further investigate the heat-transfer performance of a porous-medium solar receiver/reactor, several numerical studies have been conducted. Cheng et al. adopted the local thermal equilibrium (LTE) model to research the steady-state coupled heat-transfer performance of a porous-media receiver [12]. By using Gaussian heat flux distribution, Vilafán–Vidales analyzed the steady-state thermal performance of a 1 kW thermochemical porous-medium reactor [13]. A steady-state 1D model with LTNE calculation was developed by Kribus et al. to identify the optimum porous-medium receiver operational parameters [14]. A method combining MCRT and FVM was developed by Wang et al. [15] to investigate the steady-state thermal performance of a porous-medium receiver/reactor.

As known, the transient thermal performance response characteristics of porous-medium receiver are crucial to the operation of an STPP, which can greatly affect the reliability of the receiver and system efficiency, as well as operability of the STPP. A literature survey shows that many steady-state heat-transfer performance analyses of porous-media solar receivers/reactors had been performed [15–17] and that the transient modeling of a porous-medium solar air receiver had been established with a Gaussian heat flux distribution as a boundary condition [18].

In order to present the temperature distribution variation with time more accurately, a method combining the MCRT and FVM methods has been developed to study the transient thermal performance response characteristics of a porous-medium receiver. The effects of the fluid

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Nomenclature

c_p	specific heat, J/(kg·K)
c_R	Concentration ratio
G	Total integrated intensity, W/m^2
h_i	Partial enthalpy of species i, J
h_v	Transfer coefficient, W/(m^3·K)
k_α	Absorption coefficient
k_e	Extinction coefficient
k_s	Scattering coefficient
A_1	Linear-anisotropic scattering factor
I_b	Intensity of black body
G_c	Collimated integrated intensity, W/m^2
G_s	Diffuse integrated intensity, W/m^2
q_s	Radiative heat flux, W/m^2
L	Length of receiver, m
r	Radius, m
S	Source term of energy equation
T	Temperature, K
u	Velocity in x direction, m/s
v	Velocity in y direction, m/s
x,y	Coordinates in flow region, m
Greek symbols	
ρ	Density, kg/m^3
ϕ	Porosity
α	Absorptance
μ	Dynamic viscosity, kg/(m·s)
λ	Conductivity, W/(m·K)
ε	Emittance
σ	Stefan–Boltzmann constant
τ	Optical thickness
ω	Albedo
Subscripts	
Conv	Convective heat transfer
eff	Effective
f	Fluid phase
max	Maximum temperature
rad	Radiative heat transfer
ref.	Reference temperature, 300 K
s	Solid phase
w	All

thermophysical characteristics, fluid-phase type, and solid-phase thermal conductivity on the unsteady-state heat-transfer performance has been investigated.

2. Mathematical model

Due to the reason that transient thermal performance response analyses of a porous-medium receiver has not been conducted previously by the authors, the transient heat-transfer models of a porous-medium receiver are listed as follows.

2.1. Continuity conservation equation

$$\frac{\partial(\phi\rho)}{\partial\tau}+\nabla\cdot\left(\rho\vec{u}\right)=0 \tag{1}$$

2.2. Momentum conservation equation

$$\frac{\partial\left(\rho\vec{u}\right)}{\partial\tau}+\nabla\left(\rho\vec{u}\,\vec{u}\right)=\nabla\cdot\left(\mu\nabla\vec{u}\right)-\nabla(p)+\vec{F} \tag{2}$$

where $\vec{F}$ designates the pressure correction term for a porous strut and is calculated by user-defined functions (UDFs) in the Fluent software, based on the following correlation [18]:

$$\vec{F}=-\frac{1039-1002\phi}{{d_s}^2}\mu u-\frac{0.5138\phi^{-5.739}}{{d_s}^2}\rho_f u^2 \tag{3}$$

It should be noted that the above equation is only applicable when the porosity is within the range of $0.66<\ \phi<0.93$ and the Reynolds number is within a range of $10<\text{Re}<400$.

2.3. Energy equation

With the aim of providing more information on the fluid-phase and solid-phase temperature distribution, an LNTE model was adopted [19,20].

For the fluid phase:

$$\phi\frac{\partial\left(\rho_f c_{p,f}T_f\right)}{\partial\tau}+\nabla\left(\rho_f c_{p,f}\ \vec{u}\ T_f\right)=\nabla\cdot\left(\lambda_{eff,f}\nabla T_{\boldsymbol{f}}-\sum_{i=1}^{n}h_i\vec{J}_i\right)+S_{conv,f} \tag{4}$$

For the solid phase:

$$(1-\phi)\frac{\partial\left(\rho_s c_{p,s}T_s\right)}{\partial\tau}=\nabla\cdot\left(\lambda_{eff,s}\nabla T_s\right)+S_s \tag{5}$$

where the source term $S_{\text{conv,f}}$ designates the convective heat transfer between the fluid phase and solid phase ($S_{\text{conv,f}}$):

$$S_{\text{conv,f}}=h_v(T_s-T_f) \tag{6}$$

In the above equation, h_v is the volumetric convective heat-transfer coefficient, calculated using [18]

$$h_v=\frac{\lambda_f\left(32.504\phi^{0.38}-109.94\phi^{1.38}+166.65\phi^{2.38}-86.98\phi^{3.38}\right)\text{Re}^{0.438}}{{d_s}^2} \tag{7}$$

The source term $S_{\boldsymbol{s}}$ in Eq. 5 is the volumetric heat source term resulting from the radiative heat transfer (S_{rad}), convective heat transfer ($S_{\text{conv,s}}$), and radiative heat dissipation through the fluid entrance surface (S_w):

$$S_s=S_{\text{conv,s}}+S_{\text{rad}}+S_w \tag{8}$$

where

$$S_{\text{conv,s}}=-S_{\text{conv,f}}=-h_v(T_s-T_f) \tag{9}$$

$$S_w=-\varepsilon_w\sigma\left(T_s^4-T_0^4\right) \tag{10}$$

To obtain the radiative source term S_{rad} in Eq. (8), the radiative transfer equation (RTE) must be solved [21]:

$$\frac{dI(s)}{ds}=-k_e I(s)+k_a I_b(s)+\frac{k_s}{4\pi}\int_{4\pi}I\left(s,\overrightarrow{\Omega'}\right)\Phi\left(\overrightarrow{\Omega'},\vec{\Omega}\right)d\Omega' \tag{11}$$