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A theoretical and experimental study of the time-dependent radiative properties of a solar bubbling fluidized bed receiver

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Abstract

In order to evaluate the potential of solar bubbling fluidized bed receivers compared to other methods for the solar heating of gases at high temperature, a thorough knowledge of the heat transfer of the receiver is necessary. Since the external energy source of the system is radiative and because of high working temperatures, it is particularly important to model the radiative heat transfer to later predict the temperature field in the solar receiver. The aim of this study is to model the radiative flux distribution in a fluidized bed by taking into account the time-dependent absorption and scattering of light in the particulate medium. For this purpose, we propose a model using the Monte Carlo Method as well as a time-dependent field of optical properties that was predicted using a Computational Fluid Dynamics tool implemented with an Eulerian model. A statistical treatment using the k-distribution method was later applied to the time-dependency of the radiative properties of the solar fluidized bed receiver. This method has proven to be useful to reduce computational time while keeping a good accuracy. An experimental set-up was designed to validate the numerical predictions of the particle volume fraction and the penetration of radiation into the fluidized bed. The good agreement of the current model with the experimental data confirms its suitability.

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1. Introduction

Fluidized beds are conventionally used as media of thermal exchanges for high temperature processes because of their excellent performance in terms of heat transfer. To improve the performance of thermodynamic cycles for solar electricity production and to obtain temperatures above 1000 K at the entrance of a turbine, technological gaps involving direct gas heating in solar receivers would need to be bridged. One of the best solutions would be to use solid particles in a fluidized bed that are directly exposed to the concentrated solar flux. The main advantages of the fluidized bed receiver are its thermal efficiency, an improved resistance to thermal stress compared to metallic and ceramic receivers and its adaptability to beam down concentrators that allow producing electricity directly on the ground. For these reasons, fluidized bed solar receivers and reactors were designed and studied by numerous scientists: Flamant and Olalde (1983), Haddad and Elsayed (1988), Muller et al. (2003), Trommer et al. (2005) and Chen et al. (2004). However, even nowadays, some technical issues are still not well understood such as the high radiative losses of the system and the appearance

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Nomenclature

ρ	density (kg m^{-3})
α	volume fraction (–)
ΔP	pressure drop (Pa)
ΔH	height (m)
$\vec{g}$	gravity (m s^{-2})
$\vec{v}$	instantaneous velocity vector (m s^{-1})
$\bar{\bar{\tau}}$	phase stress–strain tensor (Pa)
K_{gs}	gas/solid momentum exchange (kg m^{-3} s)
μ	viscosity (Pa s)
$\underline{\lambda}$	bulk viscosity (kg s^{-1} m)
$\bar{\bar{I}}$	unity matrix
C_D	drag coefficient (–)
Re	Reynolds number (–)
p_s	solid pressure (Pa)
θ_s	granular temperature
e_{ss}	restitution coefficient (–)
$g_{0,ss}$	radial distribution coefficient (–)
$\mu_{s,\mathrm{col}}$	collisional viscosity (Pa s)
$\mu_{s,\mathrm{kin}}$	kinetic viscosity (Pa s)
$\mu_{s,\mathrm{fri}}$	frictional viscosity (Pa s)
d	diameter (m)
$\gamma_{\theta s}$	collisional dissipation energy (kg s^{-3} m)
ϕ_{gs}	transfer rate of kinetic energy (kg s^{-3} m)
g	gravity (m s^{-2}), HG phase function coefficient or cumulative distribution function
Q	optical efficiency
E	absorbed fraction of incoming light
S_0	surface of the radiation source (m^2)
u_0	radiative emission direction
P	random point on S_0
γ	optical path originated from P in the direction u_0
$l^-_{\gamma,n}$	nth entry point coordinates of optical path γ in gas volume elements
$l^+_{\gamma,n}$	nth exit point coordinates of optical path γ in gas volume elements
σ	curvilinear abscissa in the nth intersection interval between γ and gas volume elements
$p(\gamma;\ P,\ u_0)$,	distribution function representing the existence probability of a given optical path γ
$\Gamma_{(P,u_0)}$	space of optical paths γ originated from P in the direction u_0
$T_{\gamma,n}$	transmissivity of the optical path γ from P to $l^-_{\gamma,n}$
Δt	time bandwidth (s)
Φ	a given function
f	distribution function

Subscripts

s	solid or scattering
g	gas
a	absorption

of hot spots on the walls of the receiver under high solar flux.

To evaluate the potential of the fluidized bed solar receiver and address its weaknesses, it is necessary to model heat transfer and calculate the temperature field in the solar receiver. Since the external energy source is radiative and because of high working temperatures, it is particularly important to model radiative heat transfer to later predict the temperature field in the solar receiver and the thermal fluxes on the walls of the receiver.

Several models have been used to predict radiative properties of fluidized particles and estimate radiative heat transfer in fluidized beds. Two major types of methods to determine radiative properties were used. The first one is based on mathematical or empirical steady-state radiative properties of the fluidized bed. In this category, we can name Gordillo and Belghit (2010) or Mendes et al. (2008) using the Rosseland approximation, Von Zedtwitza et al. (2006) or Hua et al. (2004) using the Monte Carlo Method (MCM), Selçuk et al. (2002) using the Discrete Ordinates Method (DOM) and Arancibia-Bulnes and Cuevas (2004) using the P1 method. The second one is based on time-dependent radiative properties that are calculated with the help of Computational Fluid Dynamics (CFD) tools. In this category, we refer to the work of Reuge et al. (2009) using the Rosseland approximation, Lathouwers and Bellan (2001) using the six flux method or Klein et al. (2007) using the MCM method.

However, only few studies paid attention to both the time-dependence of the radiative properties of the fluidized bed and the multiple scattering of light in the particulate medium. For this reason, this paper focuses on determining the time-dependent radiative properties of bubbling fluidized beds to allow the calculation of the radiative source term. The Radiative Transfer Equation (RTE) is solved through its integral formulation using the MCM, which takes into account the absorption and the multiple scattering of light in the particulate medium. An experimental setup was designed to validate the numerical predictions of the particle volume fraction and the penetration of radiation into the fluidized bed at room temperature.

2. Modeling methodology

2.1. Modeling of particle volume fraction

2.1.1. Modeling strategy

To our knowledge, no commercial CFD tool is capable of predicting flow fields, temperature distributions as well as convective and radiative fluxes simultaneously and

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