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# Two-phase heat transfer model of a beam-down gas-solid fluidized bed solar particle receiver

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ABSTRACT

Beam-down concentrating solar power for thermochemical and energy absorption applications stands as an attractive approach that can enhance the renewable energies deployment. This work explores the integration of beam-down optics with fluidized bed technology proposing a model to calculate both gas and bed temperatures. The beam-down system concentrates the energy from the solar field into a fluidized bed receiver. A novel phenomenological model is proposed to adapt the well-known two-phase theory to the heat transfer process of a bed operating in the bubbling regime while it is directly irradiated from the top. In this way, this simple model can be used as a design tool for beam-down fluidized bed receivers. The top bed surface is considered as an opaque diffuse layer formed by gray particles. A single layer model is applied to estimate the effective emissivity between the heterogeneous bed surface and the ambient conditions in the freeboard. The vertical temperature profile is obtained considering particle phase heat conduction, particle to gas heat convection, solid convection, bubble convection and radiation heat transfer mechanisms. The model is validated using silicon carbide and zirconia fluidized bed experiments reported in the literature. The model shows that the solid convection is the dominant heat transfer mechanism for a beam-down fluidized bed receiver. Further results explore the influence of the operating conditions on the fluidized bed receiver for a bed of silicon carbide particles, showing that energy concentration fluxes of $35 \cdot 10^4$ W/m$^2$ can reach bed temperatures of 1000 °C when operating at a gas velocities of $3{\cdot}U_{mf}$.

## 1. Introduction

Renewable energy deployment should be the sustainable response of the industry and the scientific community to meet the growing energy requirements of our society. Among renewable technologies, wind and solar systems have shown its feasibility to replace conventional non-renewable technologies in many commercial applications. The integration of concentrating solar power (CSP) systems with thermal storage is one of the most promising technologies due to its high dispatchability (Siegel et al., 2013; Tregambi et al., 2017). This technology enhances also the possibility of managing heat generation on a local level for thermochemical processes such as calcium looping (Siegel et al., 2013; Tregambi et al., 2017; Ortiz et al., 2017; Alovisio et al., 2017).

In this line, the concentration of sunlight on particle-based receivers appears as an interesting technology for such applications due to the use of solid particles as the heat transfer medium, which can reach high temperatures (~1000 °C). Recent concepts of central particle receivers have been reviewed in Ho (2016), showing four main types of direct particle heating receivers: free-falling, obstructed flow, rotating kiln/centrifugal and fluidized particle receivers. In these systems, the particle receiver is located on the top of a central tower, where all heliostats concentrate the sunlight.

However, it is possible to substitute the tower by a secondary reflector system, redirecting the concentrated solar energy to a ground receiver. In this way, the energy of all heliostats is focused to a beam-down reflector, where the radiation is redirected to the top of a particle receiver reaching high energy concentrations (Segal and Epstein, 2000). This heliostats configuration eases the operation and maintenance of the ground reactor and reduces the costs of the tower and the heat transport system (Yadav and Banerjee, 2016). The beam-down disadvantages are the costs associated to the construction of the secondary reflector and the large magnification at the ground receiver (Vant-Hull, 2013). Therefore, a cost-benefit analysis should be considered for each process. Examples of the beam-down reflector coupled with a fluidized bed receiver have shown its usefulness (Calvet et al., 2016; Kodama

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**Nomenclature**

*Abbreviations*

| | |
|---|---|
| CSP | concentrating solar power |
| CFD | computational fluid dynamics |
| DEM | discrete element method |

*Symbols*

| | |
|---|---|
| $a_B$ | bubbles fraction (-) |
| $a_{BW}$ | bubbles and wakes fraction (-) |
| $a_p$ | specific surface of particles ($m^{-1}$) |
| $A_{bed}$ | bed surface ($m^2$) |
| $A_{p,sL}$ | effective heat transfer area of all particles at the top layer surface ($m^2$) |
| $c_p$ | specific heat (J/kg/K) |
| $d_p$ | sieve particle diameter (μm) |
| $d_B$ | bubble diameter (m) |
| $D$ | bed diameter (m) |
| $f_w$ | wake volume fraction (-) |
| $f_v$ | particle volume fraction (-) |
| $F_{b-a}$ | vision factor (-) |
| $F_{ij}$ | coaxial parallel disk vision factor (-) |
| $g$ | gravity ($m/s^2$) |
| $H$ | settle bed height (m) |
| $ID$ | internal diameter (m) |
| $h_{gp}$ | particle to gas heat transfer coefficient ($W/m^2$ K) |
| $h_{bc}$ | bubble gas to dense bed heat transfer coefficient ($W/m^2$ K) |
| $k_e$ | effective thermal conductivity (W/m K) |
| $k_e^0$ | effective thermal conductivity of a fixed bed with a stagnant gas (W/m K) |
| $k_g$ | thermal conductivity of gas (W/m K) |
| $k_r$ | radiative conductivity (W/m K) |
| $k_s$ | particle conductivity (W/m K) |
| $\dot{m}$ | mass flow (kg/s) |
| $n$ | refractive index (-) |
| $q_r$ | radiative heat flux ($W/m^2$) |
| $Q_a$ | absorption scatter property (-) |
| $Q'''_{sc}$ | heat transferred by the solid circulation ($W/m^3$) |
| $Q'''_{gs}$ | heat gained by emulsion gas ($W/m^3$) |
| $Q'''_{bbs}$ | heat gained by bubbles ($W/m^3$) |
| $Re_p$ | particle Reynolds number (-) |
| $t$ | time (s) |
| $T$ | temperature (K) |
| $T_{sky}$ | effective temperature for radiative heat losses (K) |
| $U$ | gas velocity (m/s) |
| $U_0$ | superficial gas velocity (m/s) |
| $U_{mf}$ | minimum fluidization velocity (m/s) |
| $U_r$ | relative superficial gas velocity (-) |
| $w$ | circulation rate based on bulk phase (m/s) |
| $z$ | bed height (m) |

*Greek symbols*

| | |
|---|---|
| $\alpha_{bed}$ | effective isothermal bed absorptivity (-) |
| $\beta_R$ | mean extinction coefficient ($m^{-1}$) |
| $\Delta P_{dist}$ | distributor pressure drop (Pa) |
| $\Delta P_{bed}$ | bed pressure drop (Pa) |
| $\varepsilon_{eff}$ | effective bed surface emissivity (-) |
| $\varepsilon_p$ | particle emissivity (-) |
| $\varepsilon_0$ | void fraction (-) |
| $\varepsilon_e$ | emulsion void fraction (-) |
| $\eta_g$ | receiver gas thermal efficiency (-) |
| $\rho$ | density ($kg/m^3$) |
| $\sigma$ | Stephan-Boltzman constant ($W/m^2$ $K^4$) |
| $\tau$ | open loop time constant (s) |
| $\phi_{in,a_p}$ | total energy flux absorbed at the bed surface per surface of particles ($W/m^2_{A_{p,sL}}$) |
| $\phi_{in}$ | energy flux received at the bed surface per bed surface ($W/m^2$) |

*Subscripts*

| | |
|---|---|
| *amb* | ambient |
| *b* | bubble |
| *e* | emulsion |
| *g* | gas |
| *s* | solid |

et al., 2010). Another beam-down approach has been recently presented in Gómez-Hernández et al. (2017) where, instead of focusing on a single point, the beam-down reflector concentrates linearly on the particle receiver while the solids are moving horizontally. Therefore, the beam-down with a ground receiver approach enhances the application of fluidized bed technology to thermochemical processes (Segal and Epstein, 1997; Segal and Epstein, 2003; Kodama et al., 2010; Gokon et al., 2012), or energy capture processes (Calvet et al., 2016; Kodama et al., 2013; Kodama et al., 2017).

Gas-solid fluidized beds are used in many industrial applications due to their heterogeneous medium, which is characterized by high heat transfer rates and high energy densities. Many efforts have been made to analyze the complex hydrodynamic behavior of the dense gas-solid flow in these reactors. Numerical models, such as Eulerian-Eulerian or Eulerian-Lagrangian, together with computational fluid dynamics (CFD) and discrete element method (DEM) models have been developed to obtain accurate flow characteristics (Van Wachem et al., 2001; Bellan et al., 2018). Analogously, the heat transfer process between the gas and the particles has been carefully analyzed such as in conventional fluidized bed dryers, gasifiers or combustors (Davidson et al., 1985; Chen et al., 2005; Molerus, 1997; Chen and Chen, 1981; Tien, 1988). However, in contrast to traditional fluidized bed heat transfer processes, beam-down fluidized bed receivers collect the energy at the top layer of particles and therefore, the question about how this thermal energy is transferred through the bed is still open. To solve that, the particle phase heat conduction, particle to gas heat convection, solid convection, bubble convection and radiation heat transfer mechanisms should be considered. Furthermore, the complex nature of the gas-solid flow makes the modeling of these heat transfer processes not straightforward. To the best author knowledge, only Flamant (1982), which determined the penetration of the radiation in a fluidized bed, and Tregambi et al. (2016), which studied the solids circulation parameter in a fluidized bed at different gas velocities, have analyzed the heat transfer processes for beam-down optics coupled to fluidized beds. Here, a classical approach is proposed to describe the heat transfer of a fluidized bed that directly receives the radiation to the bed surface.

In this work, a theoretical transient model is proposed to describe the heat transfer process of a directly irradiated gas-solid bubbling fluidized bed. The proposed model provides clear information to guide design and operation of beam-down irradiated particle receivers, as it takes into account the hydrodynamic behavior of the bed when solving the heat transfer problem. The model is based on the well-known two-phase theory of fluidization as it is simpler and with lower computational costs than other numerical models. The validation of the model is carried out using data previously reported by Flamant (1982) for silicon