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Modelling of heat transfer in a fluidized bed reactor irradiated indirectly by concentrated solar energy.

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Abstract

A two phases model of air heating in bubbling fluidized bed of sand particles with concentrated solar radiation as source of energy is developed. This model is based on the *Kato* and *Wen's model* (1969) for the hydrodynamic aspect which was modified to take account the thermic aspect. Nine algebraic equations were established in permanent regime for different heat and mass balances as well as heat losses against surrounding media. The Newton Raphson's method was used to solve this system of equations. Results have shown that the model developed is able to predict the temperature profiles of gas and particles in the bubble and emulsion phases, the wall temperature along the reactor, the heat flux transferred to the bed and heat losses by forced convection and radiation to surrounding air. The effects of the fluidizing air velocity, total mass of particles and the wind velocity on the thermal behaviours were examined. Model predictions seem reasonable looking for its comparison agreement with bibliographical data.

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Keywords: Fluidized bed; simulation; solar energy; air heating;

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1. Introduction

The fluidized beds have considerable advantages for material processing: excellent gas-solid contacting, no hot spots even with highly exothermal reactions, good gas-to-particle and bed-to-wall heat transfer due to the intense mixture of the solid material by the presence of gas bubbles. Hence, it is obvious that moving particles play an important role in the wall-to-bed heat transfer process that is higher than those in single-phase gas flow as well as those in fixed beds. [1, 2] The fluidized beds are of increasing importance for gas-solid and gas-catalytic reactions, and recently they are used in solar energy capture.

The present work intends to develop a two phase model in a bubbling fluidized bed heated with solar radiation as the source of energy. The model predicts the temperature profiles of gas and solid particles in bubble and emulsion phases.

Nomenclature

A	bed cross sectional area (*m²*)
C_{ps}	specific heat of solid ($kJ.kg^{-1}.K^{-1}$)
D_r	bed diameter (*m*)
D_b	bubble diameter (*m*)
d_p	mean particle diameter (*m*)
h_{gp}	convection heat coefficient between solids and gas ($kJ.s^{-1}.m^{-2}.K^{-1}$)
h_{pw}	heat transfer coefficient by conduction and radiation between the gas-particle suspension and reactor-walls ($kJ.s^{-1}.m^{-2}.K^{-1}$).
K_{eb}	mass transfer coefficient between emulsion gas and bubbles (s^{-1})
k_p	mass transfer coefficient of solids between emulsion and bubble phases (s^{-1})
f_b	volume fraction of bubbles ($m^3 bubbles/m^3 reactor$)
f_w	volume fraction of wake (m^3 *solids*/m^3 *reactor*)
U	gas input superficial velocity ($m.s^{-1}$)
U_{mf}	minimum fluidization velocity ($m.s^{-1}$)
Subscripts	
B	Bubble phase
E	Emulsion phase
P	Solid particules
Greek symbols	
ε_{mf}	bed voidage at minimum fluidization conditions
ρ_s	density of the particles (kg/m^3)

2. Solar radiation in Algeria

Algeria is situated in the center of North Africa between the *38-35* of latitude north and *8-128* longitude east, it has an area of *2, 381,741* km^2. The Sahara represents *80%* of the area of the country. The climate is transitional between maritime (north) and semi-arid to arid (middle and south). According to a study of the German Aerospace Agency based on satellite imaging, Algeria has with *1,787,000* km^2 the largest long term land potential for the Concentrating Solar Thermal Power Plant technologies (CSTPP). In addition, solar radiation fall between *4.66* kWh/m^2 and *7.26* kWh/m^2, this corresponds to *1700* $kWh/m^2/yr$ in the north and *2650* $kWh/m^2/yr$ in the south, it is considered as being one of the best insolated areas in the world. The average solar duration over the quasi-totality of the national territory exceeds *2000 h* annually and may reach *3900 h* in the Sahara.

Ouargla located in the south of Algeria receives approximately fourteen hours of daily solar radiation in summer and approximately ten hours in winter. The intensity ranges between *410* and *830* W/m^2. Such useful natural energy can generally be used in two different applications: (i) Direct utilization to increase the working fluid temperature for further usage (such as in a Rankine steam cycle); and (ii) Electricity generation through photovoltaic cells.

All these indicators make Algeria an ideal country for the implementation of the Concentrating Solar technologies. [3]

3. Model development

The aim of the present study is to combine heat provided by solar radiation and fluidized bed technology in order to heat up an air current to sufficiently high temperature to ensure certain unit operations involving heat transfer such as drying of solid particles. As a first step, we have started by simulation of hydrodynamic and thermal behaviour of a cylindrical fluidized bed with *100 mm* i.d. and *450 mm* in height filled with sand particles which characteristics are reported in Table 1. The fluidizing air at *20 °C* is injected in the column at a velocity twice the minimum fluidizing velocity at *20°C*. the dish solar concentrator consists of a satellite dish, its diameter is of *1.05m*.

Table 1. Characteristics of particles used in simulation.

Solid particules
Total mass : *2.8631 kg*
Particle diameter : *350 µm*
Particle density: *2650 kg/m³*
Particle heat capacity: *1050 J/kg.K*
Minimum fluidising velocity : *0,08 m/s*

The developed model is based on the bubble assemblage mode introduced by Kato and Wen [4] what has been improved take account for the thermal exchanges due to the convection between gas and particles, and due to the conduction and radiation between particles and the reactor walls.

3.1. Model assumptions

The two phase theory of fluidization is implemented. Therefore, the emulsion and the bubble phases are separated so that the mass and heat transfer occurs between the bubble and the emulsion phases [5,6, and 7] and that the heat transfer occurs both between the bubbles and reactor walls and between emulsion and reactor walls.

The bubble diameter grows as they rise in the reactor by coalescence and by increase of gas volumetric flux while heated. For bubbles in the same level in the reactor, the diameter is uniform This is known as effective bubble size [7]. The following assumptions are made regarding the reactor operation:

- Ideal behaviour of gas is considered ;
- The dense region is subdivided into a number of elementary compartments ;
- Convective heat transfer between air and particle is considered ;
- Convective heat transfer between air and wall is considered ;
- Radiative and convective heat transfer between particle and the walls are taken into account;
- Sand particles are spherical and of uniform size ;

3.2. Model presentation

The mass and heat balances are written for the gas and solids in the emulsion and bubble phases respectively for each compartment as follows (Table 2):

Table 2. Model equations.

Mass balances

Mass balance for gas in the bubble phase (continuity equation)

$$\left[\frac{1}{M_a}.\rho_{ab}\left(U_g-U_{mf}\right).S\right]_{N-1}-\left[\frac{1}{M_a}.\rho_{ab}\left(U_g-U_{mf}\right).S\right]_N+\left[K_{be}.V_b.\frac{1}{M_a}.(\rho_{ae}-\rho_{ab})\right]+\left[q_{eb}\right]_N=0 \quad (1)$$

Mass balance for gas in the emulsion phase (continuity equation)

$$\left[\frac{1}{M_a}.\rho_{ae}.U_g.S\right]_{N-1}-\left[\frac{1}{M_a}.\rho_{ae}.U_g.S\right]_N-\left[K_{be}.V_b.\frac{1}{M_a}.(\rho_e-\rho_{ab})\right]-\left[q_{eb}\right]_N=0 \quad (2)$$

Heat balances

Heat balance for gas in the bubble phase

$$\left[\frac{1}{M_a}.\rho_{ab}\left(U_g-U_{mf}\right).H_{ab}.S\right]_{N-1}-\left[\frac{1}{M_a}.\rho_{ab}\left(U_g-U_{mf}\right).H_{ab}.S\right]_N+\left[K_{be}.V_b.\frac{1}{M_a}.\left(\rho_{ae}.H_{ae}-\rho_{ab}.H_{ab}\right)\right]_N \tag{3}$$
$$+\left[\frac{6}{d_p}.f_w.\left(1-\varepsilon_{mf}\right)h_{gp}.V_b.\left(TP_b-T_b\right)\right]+\left[\mathrm{q}_{eb}.H_{ae}\right]_N+f_b.\left[\left(1-f_w\right)+\varepsilon_{mf}.f_w\right].\left[\pi.D_r.d_b.h_{wg}.\left(T_{w\mathrm{int}}-T_b\right)\right]=0$$

Heat balance for gas in the emulsion phase

$$\left[\frac{1}{M_a}.\rho_{ae}.U_{mf}.H_{ae}.S\right]_{N-1}-\left[\frac{1}{M_a}.\rho_{ae}.U_{mf}..H_{ae}.S\right]_N+\left[K_{be}.V_b.\frac{1}{M_a}.\left(\rho_{ab}.H_{ab}-\rho_{ae}.H_{ae}\right)\right]_N \tag{4}$$
$$+\left[\frac{6}{d_p}.\left(1-\varepsilon_{mf}\right).V_e.h_{gp}.\left(TP_e-T_e\right)\right]_N-\left[\mathrm{q}_{eb}.H_{ae}\right]_N+\varepsilon_{mf}.\left(1-f_b\right).\left[\pi.D_r.d_b.h_{gw}.\left(T_{w\mathrm{int}}-T_e\right)\right]_N=0$$

Heat balance for solid in the bubble phase

$$\left[F_{PA}.C_p.\left(TP_b-T_{ref}\right)\right]_{N-1}-\left[F_{PA}.C_p.\left(TP_b-T_{ref}\right)\right]_N-\left[K_p.V_b.\rho_p.C_p.\left(TP_e-TP_b\right)\right]$$
$$-\left[h_{pb}.V_b.\left(TP_b-T_b\right)\right]_N+\left[f_w.f_b.\pi.D_r.d_b.\rho_p.\left(1-\varepsilon_{mf}\right).h_{pw}.\left(T_{w\mathrm{int}}-TP_b\right)\right]_N+\left[F_{BE}.C_p.\left(TP_e-T_{ref}\right)\right]_N=0 \tag{5}$$

Heat balance for solid in the emulsion phase

$$\left[F_{PD}.C_p.\left(TP_e-T_{ref}\right)\right]_{N+1}-\left[F_{PD}.C_p.\left(TP_e-T_{ref}\right)\right]_N-\left[h_{gp}.\frac{6}{d_P}.\left(1-\varepsilon_{mf}\right).V_e.\left(TP_e-T_e\right)\right]_N \tag{6}$$
$$-\left[K_p.V_b.\rho_p.C_p.\left(TP_e-TP_b\right)\right]-\left[F_{BE}.C_p.\left(TP_e-T_{ref}\right)\right]_N+\left(1-\varepsilon_{mf}\right)\left[\pi.D_r.d_b.\left(1-f_b\right).h_{wp}.\left(T_{w\mathrm{int}}-TP_e\right)\right]_N=0$$

Where F_{PA} is the solid flux, which is given by :

$$\left[F_{PA}\right]_N=\left[f_w.\left(1-\varepsilon_{mf}\right).\rho_P.S.\left(U_g-U_{mf}\right)\right]_N \tag{7}$$

Heat balance at the wall

$$\Phi_N=\left(1-f_b\right).\varepsilon_{mf}.\left[\pi.D_r.d_b.h_{gw}.\left(T_{w\mathrm{int}}-T_e\right)\right]_N+f_b.\left(\varepsilon_{mf}.f_w+\left(1-f_w\right)\right).\left[\pi.D_r.d_b.h_{gw}.\left(T_{w\mathrm{int}}-T_b\right)\right]_N$$
$$+\left(1-\varepsilon_{mf}\right)\left(1-f_b\right).\left[\pi.D_r.d_b.h_{pw}.\left(T_{w\mathrm{int}}-TP_e\right)\right]_N+\left(1-\varepsilon_{mf}\right).f_b.f_w.\left[\pi.D_r.d_b.h_{pw}.\left(T_{w\mathrm{int}}-TP_b\right)\right]_N \tag{8}$$

Conduction trough the wall

$$\left[\frac{K_w}{L_w}.\pi.d_b.\left[D_r+2.\frac{L_w}{2}\right].\left(T_{w\mathrm{int}}-T_{wext}\right)\right]_N=\Phi_N \tag{9}$$

Exchange wall- exterior

$$E-\rho_w.E-\left[h_{wa}.\pi.\left(D_r+2.L\right).d_b^N.\left(T_{wext}-T_a\right)\right]_N=\Phi_N \tag{10}$$

The convective heat transfer coefficient between gas and solid particles (h_{gp}) is calculated using the Ranz and Marshall's correlation[8], the convective heat transfer coefficient between gas and reactor walls (h_{gw})is calculated using the correlation of Dittus-Boelter [9] and the convective and radiative heat transfer coefficient between gas and reactor walls (h_{pw})is calculated using Wender et Cooper's correlation [10].

Thus, the model consists of nine algebraic non linear equations with nine variables (T_b,T_e, T_{Pb}, T_{Pe}, T_{wint}, T_{wext}, U_g, Q_{eb} and ϕ). Resolution of this set of equations is done using Newton and Raphson's method.

4. Results and discussion

4.1. Presentation of typical simulation results

It will be noticed that the mean values of direct irradiation taken is that measured by Gama [11] (*750 W/m²*). This value is obtained in the "centre of applied researches in renewable energy" of Ghardaia, which has the same weather as Ouargla. These two towns are *200 Km* far from each other.

Figures 1 and 2 show the temperature profiles of gas in bubble and emulsion phases throughout the bed. As can be seen, gas temperature increases quickly as it moves upwards in the reactor. It reaches high levels only a few centimetres above the distributor (*2 cm*). Then, the gas temperature stays sensibly constant throughout the bed. The increase for both phases (bubble and emulsion) gas temperature from *20°C* to *137°C* is due to the high convective heat transfer coefficient between the gas and the solid particles (*281,25 W/m².K*). On the other hand, theses figures let somebody see that the gas of the two phases reaches the same temperature level, which indicates that a good mixing of gas between the two phases occurs.

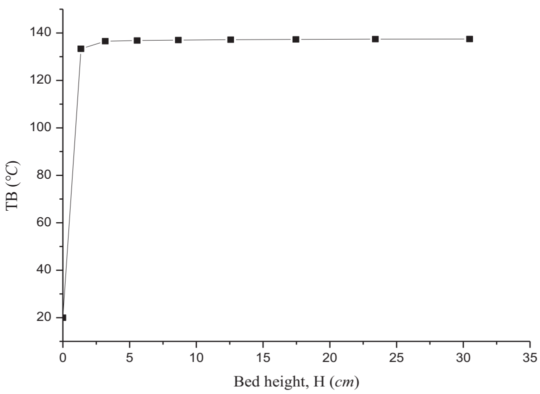

Fig.1. Gas temperature profile in bubble phase.

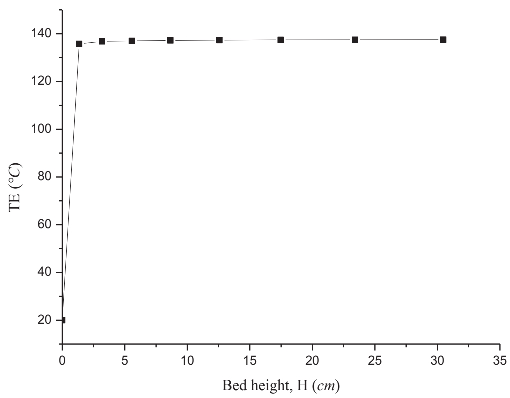

Fig.2. Gas temperature profile in emulsion phase.

Figure 3 plots the particles temperature in the bubble and emulsion phases as a function of the bed high. It appears that the particles temperature converge to the same value in the two phases. This result indicates that there is a good axial mixing of particles due to high bubbling activity in these simulation conditions. The bed is therefore homogenous in temperature, which provide to the fluidisation technique its most important advantage. This was already seen by several authors (Bouhadda 2011[12], Lakhdari 2007[13], Dounit, Hémati 2008[14])

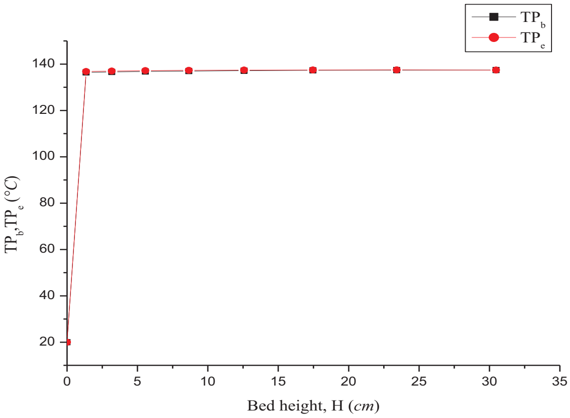

Fig. 3. Solid particles temperature profile.

4.2. Effect of operating parameters

The influence of input gas velocity, total solids mass in the reactor and wind speed on the thermal behaviour of the reactor was examined. The effect of the total solids mass in the reactor has been investigated by changing it between *1.18* and *2.86 kg*. The superficial gas velocity was kept constant; equivalent to twice the minimum fluidization velocity of particles. The results are shown in figure 4. An increase in total solids mass in the reactor from *1.18* to *2.86* (about *1.5 kg* of solid) produces a small effect on the process behaviour because of the little rise in outlet gas temperature (only *11°C*). Such results can be attributed to the surface exchange between the fluid bed and the reactor walls which is slightly increased.

The axial temperature profiles of gas estimated at various axial positions are shown in Figure 5 at various gas velocities. Four values of gas velocity are investigated, namely *1, 2, 3* and *3.5* times U_{mf} at *20 °C*. These profiles show that when the inlet gas velocity is increased, the outlet gas temperature is decreased. This is due to the fact that at low gas velocity, the mean residence time of air in the reactor increases. As shown in the figure 5, when the gas velocities equal to minimum fluidising velocity, the gas temperature can reach *231°C*.

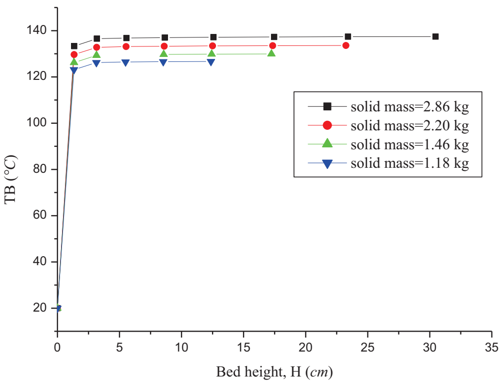

Fig.4. Gas temperature profile throughout the fluidized bed: effect of mass solid

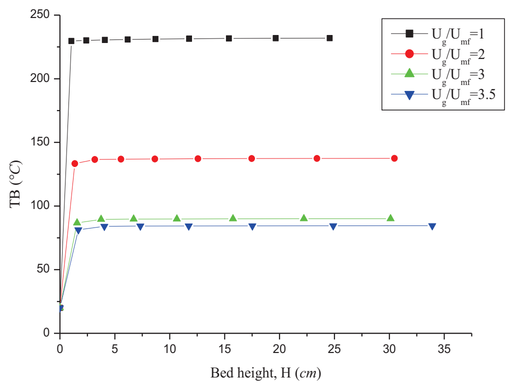

Fig.5. Gas temperature profile throughout the fluidized bed: effect of gas velocity

Because Ouargla is a windy zone especially in spring in which the direct solar irradiation level is high [11], it is interesting to examine the influence of wind speed in the process behaviour. Figure 6 shows the effect of wind speed on the bubble's temperature along the bed. It is pointed out that *2.9 m/s* and *4.2 m/s* are mean velocities of wind in winter and in summer respectively, while *3.6 m/s* is the mean speed of wind by a year in Oaurgla.
The solids mass in the bed and the input gas velocity were kept constant, at *2.86 kg* and two times the minimum fluidizing velocity of particles. As shown in figure 6, the wind speed has a significant effect on the heating process. The gas temperature reaches *137°C* when we suppose that there is no wind, while its values do not exceed *75°C* when the wind speed is of *4.2 m/s*. The heating process seems to be very sensitive to this aspect.

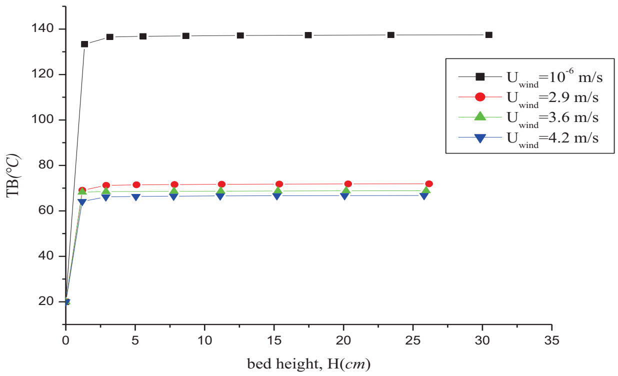

Fig.6. Gas temperature profile throughout the fluidized bed: effect of wind speed

5. Conclusion

This work is focused on the heating of gas in fluidized bed of sand particles irradiated indirectly by concentrated solar energy. A theoretical study of this process in the dense region of the fluidized bed reactor has been presented. The model predicts the temperature profiles of gas and solids in emulsion and bubble phases. The predictions of the model indicate that heating of air takes place very quickly in the bottom region of the fluidized bed (few centimetres above the distributor) and that its temperature was raised from *20°C* to *137°C*. This temperature is high enough to ensure certain unit operations that involve heat transfer. Simulations realised at different operation conditions has show that the bed acts as an isotherm media due to the important particles mixing caused by bubbles movements.
The study of the effects of some operational parameters has pointed out that the heating process is strongly affected by the gas fluidizing velocity and the wind speed. In the conditions of low fluidizing velocities as well as low wind speed, the outlet air temperature is high. In opposite, the total solids mass in the reactor exerts a very weak effect on this process.
Because of the lack in the literature of studies concerning heating of fluidised bed indirectly using concentrated solar radiation, a comparison of calculated fluidised bed properties with experimental data is not attempted. In fact, the there are big differences between the process configuration modelled here and those reported in the bibliography. However, the comparison of the obtained results with the experimental ones obtained by Bounaceur [14] show that the present model predictions are interesting.

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