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Improving the thermal performance of fluidized beds for concentrated solar power and thermal energy storage

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ABSTRACT

Fluidization technology displays a long record of success stories, mostly related to applications to thermal and thermochemical processes, which is fostering extension to novel and relatively unexplored fields. Application of fluidized beds to collection and thermal storage of solar radiation in Concentrated Solar Power (CSP) is one of the most promising, a field which poses challenging issues and great opportunities to fluidization scientists and technologists. The potential of this growing field calls for reconsideration of some of the typical design and operation guidelines and criteria, with the goal of exploiting the inherently good thermal performances of gas-fluidized beds at their best. “Creative” and non-conventional design and operation of fluidized beds, like those based on uneven or unsteady (pulsed) fluidization, may be beneficial to the enhancement of thermal diffusivity and surface-to-bed heat transfer, improving the potential for application in the very demanding context of CSP with thermal energy storage.

1. Introduction

Development and deployment of Concentrated Solar Power (CSP) generation is gaining renewed interest. The US Department of Energy has launched the SunShot program [1] so as to challenge CSP to reducing LCOE to less than 6 cent/kWh. The European Commission has laid the path to CSP development and deployment in the Framework Programmes and in the forthcoming SET plan [2]. A recent survey by IEA analyzed priorities and opportunities associated with CSP [3], highlighting the key role of integrated thermal energy storage (TES) and fuel-power hybridization for the successful exploitation of concentrated solar power.

The potential of gas–solid suspensions acting as particle receivers in CSP has been widely recognized. Concentrating solar radiation onto dense gas-fluidized beds has been explored as early as in the 80s [4–6]. The use of fluidized solids as alternative to other storage/exchange media, like molten salts, entails the possibility to overcome issues associated with the use of corrosive or environmentally unfriendly fluids and to operate the receiver at much higher temperature (with associated improved overall efficiency of the energy conversion cycle). Fluidized bed solar receivers have been investigated in a variety of configurations/layouts at the proof-of-concept or lab-scale levels: dense stationary gas fluidized beds, dilute- or dense-phase circulating fluidized beds [4–12]. Full exploitation of these concepts at the demonstration scale is still missing, but early operation of pilot installations based on the 150 kW stationary-compartmented dense fluidized bed [11] and on the 150 kW dense-phase circulating fluidized bed [12] is encouraging.

The present study addresses the potential of a dense gas-fluidized bed as a core component of a CSP receiver, aimed at accomplishing the three basic complementary tasks:

> Collection: Effective collection of incident solar radiation is targeted at limiting re-emission of the incident radiation and at minimizing local overheating at the surface of the receiver exposed to densely concentrated incident radiation.
> Transfer: The fluidized state of the solids warrants enhanced transfer of the incident power to immersed tube bundles, for optimal integration of the receiver in high-efficiency steam and/or organic Rankine cycles (ORC).
> Storage: The fluidized solids are exploited as an effective thermal energy storage medium, with the aim of equalizing the inherent time-variability of the incident radiation for stationary CHP generation.

The concept is based on the well established properties of dense fluidized beds of featuring large bed-to-surface heat transfer coefficients, in the order of hundreds of W/m^2K, which can be tuned and tailored by acting on the fluidization parameters. Moreover fluidized beds feature large effective thermal diffusivities, in the order of 0.001–0.1 m^2/s, associated with convective transfer due to bubble-induced

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and gulf stream motion of fluidized solids. Thermal diffusivities exceed by far those typical of most monolithic, granular or fluid media that have been considered so far for collection of solar radiation with thermal storage. Both features may be optimized by proper selection of fluidized solids type and size and fluidization regime.

Albeit very promising, application of fluidized beds to concentrated solar power requires careful selection of process operation and design to effectively exploit their positive features and limit their drawbacks.

2. Design of fluidized bed for improved thermal performance

Fluidized bed technology has plenty of success stories to display, mostly related to application to a variety of thermal and thermochemical processes. In some cases the entire path from fundamental study to commercial exploitation has been successfully completed, as is the case for combustion/gasification of solid fuels, thermal processing of ores, fluid catalytic cracking.

Successful application of fluidized beds in thermal processing is fostering their application to novel and relatively unexplored fields, like collection and storage of solar radiation in CSP and thermal energy storage.

There are some prerequisites that fluidized beds must fulfill for effective application to CSP, like:

1. very large thermal diffusivity, so as to minimize temperature gradients in the presence of very intense, strongly localized (and time-dependent) energy inputs;
2. large surface-to-bed heat transfer coefficients, so as to accomplish high volumetric density exchange of radiative fluxes between the bed and internals (tube bundles, radiation cavities).
3. minimization of parasitic energy losses associated with the establishment of the fluidized state, by reducing the amount of fluidizing gas required to establish the required bed properties.

On the other hand, there are some degrees of freedom that application to CSP can enjoy from, compared with thermochemical processes, like:

1. No constraints are posed to the fluidizing gas feedings by the stoichiometry of chemical reactions.
2. No external constraint is posed to the selection of bed solids by the physical and chemical nature of materials to be processed.

This may give the designer of a fluidized bed CSP process some freedom as to the selection of process conditions and bed solids which should essentially fulfill technical criteria related to thermal performance, plant robustness and dependability, in addition to economic constraints. Constraints related to maximization of surface-to-bed heat transfer and to minimization of parasitic energy losses are typically met by selecting relatively fine bed solids, in the A or A–B groups of the Geldart classification of powders, and by operating at gas superficial velocities just beyond incipient fluidization. A remarkable exception to the latter criterion may be represented by conditions under which the bed is operated as a volumetric radiative receiver in the dilute mode.

Design and operation may be made even more effective by considering non-conventional operation of fluidized beds. Along this path, we will hereby consider possible advantages associated with uneven fluidization of bed solids and/or unsteady (pulsed) fluidization by an assessment of their influence on the effective thermal properties of the bed. More specifically, the effectiveness of these operational modes for augmented bed thermal diffusivity will be estimated by means of simple theoretical approaches.

2.1. Improving the thermal performance of fluidized beds by uneven fluidization

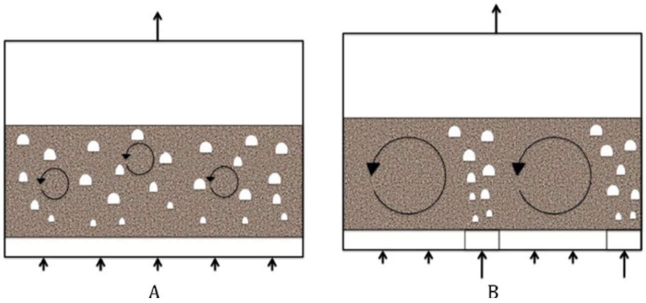

Fig. 1. Qualitative outline of the solid flow patterns in dense gas fluidized beds: A) even fluidization; B) uneven fluidization.

Figs. 1 and 2 provide the mechanistic background for the assessment of the potential of uneven fluidization, possibly enhanced by the use of bed internals, for improved thermal performance. Fig. 1 is a qualitative outline which compares the gross solids flow patterns that are likely to establish in the case of even (Fig. 1A) and uneven (Fig. 1B) fluidization. Fig. 2 further reinforces the qualitative features displayed in Fig. 1, and reports snapshots from 2D CFD computations of the flow structures of fluidized beds of Geldart group B particles ($d_p = 2.5 \times 10^{-4}$ m; $\rho = 2560$ kg/m^3) operated with even (Fig. 2A) and uneven (Fig. 2B) fluidization. In uneven fluidization, it is assumed that a fraction f of the bed cross-section is fluidized at a gas superficial velocity exceeding U_{mf}, whereas (1 − f) is the fractional cross-section of the bed that is kept at incipient fluidization.

The qualitative features of the flow structures in Figs. 1 and 2 suggest that, as extensively documented in the fluidization literature, uneven fluidization promotes large scale particle circulation, or “gulf stream” [13,14].

Thermal diffusivity in a dense gas fluidized bed is controlled by lateral dispersion of solids, which typically largely exceeds contributions due to conduction, radiation and gas convection. Dispersion of solids in dense fluidized beds has been extensively studied in the literature [15–23], which provides a rich body of experimental data, CFD-based studies, mechanistic or empirical equations. We will hereby base our reasoning on the simple approach due to Borodulya et al. [15] who discussed the relative importance of different mechanisms of solid dispersion in the bed. The grid zone is generally characterized by increased porosity which varies with height, and particle–jet interaction may be the dominant particle mixing mechanism in this zone. In the bulk of the bed the dominant mechanism is represented by the well established drift- and wake-components of particle motion associated with the passage of a bubble. Finally, a zone of bursting of gas bubbles (splash zone) established above the bed, where the dominant mechanism is the ejection/fall out of bed solids. The relative importance of these zones is not proportional to their sizes, owing to the different character of particle mixing in them. In all the three zones horizontal particle transfer is dependent on the passage of gas bubbles through the bed.

Following Borodulya et al. [15], by analogy with the coefficient of turbulent diffusion, the dispersion coefficient D of bed solids is defined as:

$$D \cong V_s \cdot \lambda \tag{1}$$

where V_s is representative of the velocity of the bubble-induced solids motion, and λ is a length scale of bubble-induced particle circulation.

Under the assumption that solids convection largely prevails over conduction, radiation and gas convection as the mechanism relevant to heat transfer inside the bed, the effective bed thermal diffusivity can be simply equated to solids dispersion coefficient:

$$\alpha = D. \tag{2}$$