Eur. Phys. J. Appl. Phys. (2016) 74: 24613
DOI: 10.1051/epjap/2016150408

THE EUROPEAN PHYSICAL JOURNAL APPLIED PHYSICS

Regular Article

Thermofluid effect on energy storage in fluidized bed reactor*

Nadjiba Mahfoudi[1,a], Mohammed El Ganaoui[2], and Abdelhafid Moummi[1]

[1] Laboratoire de Génie Civil, Hydraulique, Développement Durable et Environnement, LAR-GHYDE, Université Mohamed Khider, BP 145 RP, 07000 Biskra, Algeria
[2] Université de Lorraine, Laboratoire d'Energétique de Longwy/LERMAB, IUT Henri Poincaré de Longwy, 186 rue de Lorraine, 54400 Cosnes et Romain, France

Received: 3 August 2015 / Received in final form: 20 December 2015 / Accepted: 1 February 2016
Published online: 3 May 2016 –

Abstract. The development of innovative systems of heat storage is imperative to improve the efficiency of the existing systems used in the thermal solar energy applications. Several techniques were developed and realized in this context. The technology of the sand fluidized bed (sandTES) offers a promising alternative to the current state-of-the-art of the heat storage systems, such as fixed bed using a storage materials, as sand, ceramic, and stones, etc. Indeed, the use of the fluidization technique allows an effective heat transfer to the solid particles. With the sand, an important capacity of storage is obtained by an economic and ecological material [N. Mahfoudi, A. Moummi, M. El Ganaoui, Appl. Mech. Mater. **621**, 214 (2014); N. Mahfoudi, A. Khachkouch, A. Moummi B. Benhaoua, M. El Ganaoui, Mech. Ind. **16**, 411 (2015); N. Mahfoudi, A. Moummi, M. El Ganaoui, F. Mnasri, K.M. Aboudou, *3e Colloque internationale Francophone d'énergétique et mécanique, Comores, 2014*, p. 91]. This paper presents a CFD simulation of the hydrodynamics and the thermal transient behavior of a fluidized bed reactor of sand, to determine the characteristics of storage. The simulation shows a symmetry breaking that occurs and gave way to chaotic transient generation of bubble formation after 3 s. Furthermore, the predicted average temperature of the solid phase (sand) increases gradually versus the time with a gain of 1 °C in an interval of 10 s.

1 Introduction

Energy storage is needed in many applications when the availability and demand for energy do not concur. As old as civilization itself, thermal energy storage (TES) has been used under its simple form to save energy. People have stored solar heat in rock, and have harvested ice and stored it, for later use. However, large TES systems have only recently been developed and exploited for several applications for both particular and industrial usage, extending from solar hot water storage to solar plant. Nowadays TES is one of the key technologies for energy management. TES seems an important alternative to correcting the mismatch between supply and demand of energy. TES can contribute significantly to meet society's needs for more efficient, environmental kindly for energy use [1]. The main characteristics of a good TES are little thermal losses and high reasonable release efficiency.

Generally, there are three types of TES: sensible heat storage, latent heat storage and thermochemical storage [2]. The choice of TES type is mainly dependent on various factors such as the storage period (diurnal, seasonal), operating conditions, economic considerations, and so on. For storage media, there are a wide variety of choice (water, rock, water/ice, salt hydrates, sand, etc.).

The fluidization technology has a long list of successes, mainly related to several industries such as renewable energy, chemical industry, mineral, oil and mechanics. New developments of fluidized beds focus on their use in the storage of thermal energy and the reuse [3]. The use of fluidizes solids as alternative to other storage/exchange medium, like molten salts, excludes the possibility of the degradation of the storage container by using of environmentally unfriendly fluids or operates at much higher temperature.

The scientists were attracted to the study of the application of fluidized beds for storing thermal energy; Izequierdi-Barrientos et al. [4] listed down the advantage of this technology of storing solar energy. Botterill [5] investigated experimentally the storing of energy in a fluidized bed to be used for a domestic water heating purpose.

[a] e-mail: nadjiba213@yahoo.fr

* Contribution to the topical issue "Materials for Energy Harvesting, Conversion and Storage (ICOME 2015) – Elected submissions", edited by Jean-Michel Nunzi, Rachid Bennacer and Mohammed El Ganaoui

2 Granular dynamic and heat transfer in fluidized bed

The fluidized bed reactors are increasingly used in chemical industry and in physical gas-solid process (e.g., drying). New developments propose its use in solar energy capture/storage systems or industrial waste heat recovery, to replace thermal fluids or molten salts as transfer and storage media [6].

The gas-solid fluidized bed presents an attractive choice for thermal heat storage applications relative to other type of reactors (liquid-solid), due to the important heat transfer rate between gas and solid phase caused by increasing of contact area between the two phases [7].

A fluidized bed consists of several key components: a riser section where the physical and chemical processes occur, a cyclone, which separates solids from air, a standpipe to collect solids from the cyclone and supplies a solids reservoir, and a solid re-circulation valve, that feeds solids back into the riser. The riser is the most important part in the fluidized bed system.

Multiphase flows exhibit different regimes depending on the geometry of the process equipment, operating condition and the properties of the gas and solid phases. Therefore, Geldart classification (Geldart, 1973) chart often provides a useful starting point to examine fluidization quality. It highlights the relation between the size of solid particles and the different flow regimes [8].

The thermal behavior of the fluidized beds is enhanced by their hydrodynamics. It's so complex and requires more investigations, in particular to size the industrial scale devices [9].

The fluidization regime diagrams with increasing gas inlet velocities have been proposed [10–12]. Except the fixed bed operation, these fluidization regimes enclosed bubbling, turbulent, fast fluidization and pneumatic transport. Each stated fluidization regime had its special flow characteristics [13–15].

With the increasing of the computational potential coupled with diminution in hardware costs have given advance to the use of computational fluid dynamic (CFD) in the modeling of multiphase systems. Therefore, the major problem in the modeling of the hydrodynamics of the fluidized beds is the transient flow of two phases of which the interface is not determined and the interaction between the different variables are defined just for limited conditions.

Based on the deep analogy with kinetic theory of dense gas, the kinetic granular theory is able to describe the granular flow witch characterized by different regimes. It allows to define for a given solid component all the physical properties that owns any gas, viscosity, particulate pressure, stress tensor, etc. The analogy can also define the concept of granular temperature, which forms the core of the kinetic granular theory [12]. All the physical properties cited below are dependent on the granular temperature. Furthermore, the distribution of granular temperature in fluidized bed is an indicator of the particle mixing and inter-particle heat transfer [16].

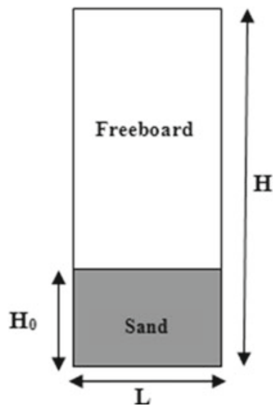

Fig. 1. Geometry of fluidized bed.

Table 1. Material properties of gas and solid phases and simulation parameters.

Flow type	Laminar
Gas-solid model	Euler-Euler with kinetic theory
Time step used	0.001 s
Convergence criteria	10^{-3}
Superficial gas velocity	0.25 m/s
Max. solid packing volume fraction	0.60
Initial air temperature	473 K
Initial sand temperature	300 K
Initial height of sand	40 cm
Sand heat capacity	830 J kg^{-1} K^{-1}
Sand density	2650 kg m^{-3}
Sand particle diameter	162 μm

This work presents a CFD simulation devoted to describe the hydrodynamics and thermal behavior of a fluidized bed reactor in order to characterize the heat storage potential of this technology. The flow structure in the fluidized bed is described in detail using solid volume fraction distribution and pressure drop. In this context, an algebraic form of the granular temperature equation was adopted after an initial study to optimize computational cost and attest accuracy of results. It is pertinent for dense fluidized bed where the convection and the diffusion term can be neglected under the assumption that production and dissipation of granular energy are in equilibrium [10].

Investigation of the flow structure can give an idea about the zones of low and high heat transfer, which is essential for optimal design and scale up of fluidized bed reactor.

3 Model description

The computational domain for simulation is shown in Figure 1. It is represented by a 2D planar with a width of L and a height of H. The initial height of packed bed of the dispersed bed (sand) is H_0.

The Eulerian approach describes the system as a mixture of two phases: continuous phase (gas) and dispersed phase (solid). The flow of the two phases is incompressible and the velocity of the gas in the bottom of the bed

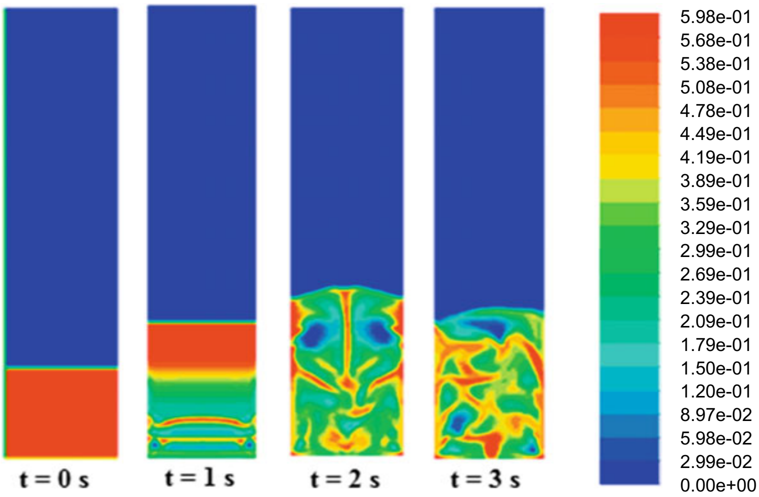

Fig. 2. Contours of the solid volume fraction in the fluidized bed for time period 0–3 s.

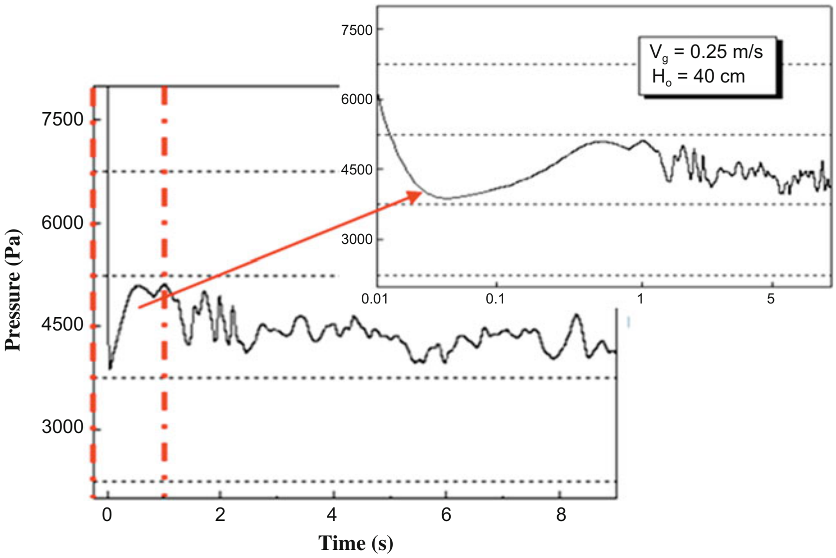

Fig. 3. Variation of the pressure drop in the fluidized bed.

is supposed uniform. The governing equations of mass, momentum and energy of both phases are listed below:

- Mass conservation for phase k ($k = c$ for gas and d for solid):

$$\frac{\partial}{\partial t}(\emptyset_k \rho_k) + \nabla(\emptyset_k \rho_k u_k) = 0, \quad (1)$$

with:

$$\sum_{k=1}^{n} \emptyset_k = 1, \quad (2)$$

where $\emptyset$ and ρ are respectively the volume fraction and the density of the phase k.

- Momentum conservation for continuous phase:

$$\frac{\partial}{\partial t}(\emptyset_c \rho_c u_c) + \nabla(\emptyset_c \rho_c u_c u_c) = -\emptyset_c \nabla p + \nabla \bar{\bar{\tau}}_c + \emptyset_c \rho_c g - \beta_{cd}(u_c - u_d). \quad (3)$$

- Momentum conservation for dispersed phase:

$$\frac{\partial}{\partial t}(\emptyset_d \rho_d u_d) + \nabla(\emptyset_d \rho_d u_d u_d) = -\emptyset_d \nabla p - \nabla p_d + \nabla \bar{\bar{\tau}}_d + \emptyset_d \rho_d g - \beta_{cd}(u_c - u_d), \quad (4)$$

where u_k is the velocity of the phase k, p is the pressure, $\bar{\bar{\tau}}_k$ is the stress tensor of the phase k, and β_{cd} is the inter-phase momentum exchange coefficient.

- Thermal energy conservation continuous phase:

$$\frac{\partial}{\partial t}(\emptyset_c \rho_c H_c) + \nabla(\emptyset_c \rho_c u_c H_c) = -\nabla \emptyset_c k_c \nabla T_d + h_{dc}(T_c - T_d). \quad (5)$$

- Thermal energy conservation dispersed phase:

$$\frac{\partial}{\partial t}(\emptyset_d \rho_d H_d) + \nabla(\emptyset_d \rho_d u_d H_d) = -\nabla \emptyset_d k_d \nabla T_d + h_{dc}(T_c - T_d), \quad (6)$$

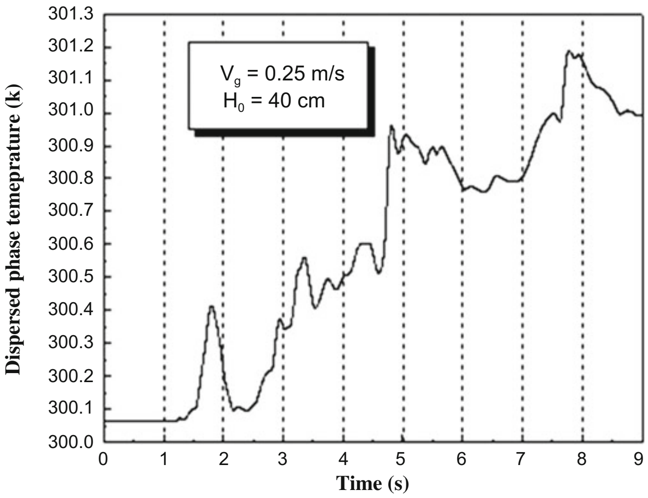

Fig. 4. Variation of the volume fraction of the dispersed phase at height of $H = 15$ cm.

where H_k is enthalpy of the phase k, k_k is the thermal conductivity of the phase k, h_{dc} is the heat transfer coefficient between c and d phase, and T_k is the temperature of the phase k.

- The algebraic granular temperature was adopted [9]:

$$0 = \left(-p_d \bar{\bar{I}} + \bar{\bar{\tau}}_d\right) : \nabla u_d - \gamma_d - 3\beta_{cd}\theta_d, \quad (7)$$

where θ_d is the granular temperature.

4 Results and discussion

Material property and simulation parameters used for simulation are listed in Table 1. Figure 2 shows the contour of solid volume fraction in the fluidized bed between 0 and 3 s. The increase in bed expansion and variation of the fluid-bed voidage can be observed. The solid fraction is already decreasing at the bottom region of the bed. At the time of about 1 s, large bubbles form and start rising through the fluidized bed until reach the surface. Subsequently, the bubbles coalesce producing then bigger bubbles as they move upwards and become stretched as a result of bed wall effects and interaction with other bubbles. After $t = 2$ s, a symmetry breaking is observed giving way to chaotic transient generation of bubble formation.

As indicated in Figure 3, and after about 2 s, the bed overall pressure drop decreased significantly at the beginning of fluidization and then fluctuated around near steady-state value. Pressure drop fluctuations are expected as bubbles continuously split and coalesce in transient manner in the fluidized bed. Figure 4 shows the time variation of the mean dispersed phase temperature at eight of $H = 15$ cm. Note that, the average solid temperature shown is the mean of the particle temperature averaged across the section of the column at a given height. It is seen that in a time of about 9 s the solid temperature increases gradually with gain of 1 °C. The fluctuations observed are due to the passage of the bubbles through the bed allows both the cooling and the heating of the sand particle.

5 Conclusion

In this paper, both hydrodynamics and thermal behavior of gas-solid fluidized bed were studied. The 2D laminar Eulerian-Eulerian model was used for modeling the fluidized bed reactor in order to predict the potential of the technology for heat recovery. The model includes continuity, momentum equations, as well as energy equations for both phases and the equations for granular temperature of the dispersed phase. Moreover, continuous and dispersed phases temperature distributions in the reactor were computed, considering hydrodynamics and heat transfer of fluidized bed using Syamlal-O'Brien drag expression. The results show that a break of symmetry in fluidized bed occurred after 2 s of the start of fluidization. The chaotic formation of the bubbles allowed a good heat transfer between the continuous phase (gas) and dispersed phase (solid). This work is in progress to understand the impact of the break of symmetry and the transition between the different regimes, on heat transfer in fluidized bed.

The authors are grateful to the partners who contributed to this study, the PNR Algero-Français program as well as the IUT of Longwy (Laboratoire d'Energétique/LERMAB) and PHC Hubert Curien Project.

References

1. I. Dinçer, M.A. Rosen, *Thermal Energy Storage Systems and Applications*, 2nd edn. (Willy, UK, 2011)
2. S. Harmeet, R.P. Saini, J.S. Saini, Renew. Sust. Energ. Rev. **14**, 1060 (2010)
3. G. Flamant et al., Chem. Eng. Sci. **102**, 567 (2013)
4. M.A. Izequierdi-Barrientos, C. Sobrino, J.A. Almendos-Ibanez, Chem. Eng. J. **230**, 573 (2013)
5. J.S. Botterill, *Fluidized Bed Heat Transfer*, 1st edn. (Academic Press, London, 1975)
6. M.A. Hamdan, I.A. Abuzahra, Heat and Technology **12**, 127 (1994)
7. European Union, 7th Framework program for research and technical development CSP2 concentrated solar power in particles, EU Grant Reference: 282932, 2011
8. A. Brems, G. Caceres, R. Dewil, J. Baeyens, F. Pitie, Energy **50**, 493 (2013)
9. G.G. Silva, N.P. Jiménez, O.F. Salazar, *Fluid Dynamics of Gas – Solid Fluidized Beds, Advanced Fluid Dynamics* (Intech, Croatia, 2012), DOI: 10.5772/1520
10. M. Lungu, J. Wang, Y. Yang, Powder Technol. **269**, 139 (2015)
11. H.T. Bi, J.R. Grace, Int. J. Multiphase Flow **21**, 1229 (1995)
12. D. Bai, K. Kato, Powder Technol. **101**, 183 (1999)
13. K.S. Lim, J.X. Zhu, J.R. Grace, Int. J. Multiphase Flow **21**, 141 (1995)
14. A.K. Das, J. De Wilde, G.J. Heynderickx, G.B. Marin, J. Vierendeels, E. Dick, Chem. Eng. Sci. **59**, 167 (2004)
15. B. Chalermsinsuwa, P. Piumsomboon, D. Gidaspow, Chem. Eng. Sci. **64**, 1195 (2009)
16. B. Chalermsinsuwa, P. Piumsomboon, Chem. Eng. Sci. **66**, 5602 (2011)