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Effects of reducing the reactor diameter on the dense gas–solid fluidization of very heavy particles: 3D numerical simulations

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ABSTRACT

In this study, 3D numerical simulations using an Eulerian n-fluid approach of a gas–solid fluidized bed composed of very dense particles of tungsten (19,300 kg m^{-3}) were carried out to examine the behavior of this suspension, especially the effects of the reduction of the fluidization column diameter on the fluidization quality. Tungsten was selected as a surrogate material of U(Mo) (Uranium molybdene) which is of interest for new nuclear fuels with limited enrichment. Comparisons between experiments and computations for the axial pressure profile of a 5 cm diameter column demonstrate the capability of the mathematical models of the NEPTUNE_CFD code to simulate the fluidization of this powder located outside the classification of Geldart. The numerical results show that the mobility into the bed of these very dense particles is very low. The reduction of the fluidization column diameter from 5 cm to 2 cm does not have significant effect on the local solid circulation but strongly decreases the axial and radial mixing of the particles due to wall-particles friction effects. These results confirm and allow to better understand the wall effects experimentally evidenced.

1. Introduction

Gas–solid fluidized beds (FB) are widely used in industrial applications such as drying, coal combustion (Basu, 1999) and gasification (Hofbauer et al., 2002), oil refining and nuclear application (Kunii and Levenspiel, 1991). This is due to the fact that FB reactors have excellent heat and mass transfer capabilities, high throughput rates, and can operate continuously, thus reducing operating costs (Ydstie and Du, 2011; Liu and Xiao, 2014).

In the nuclear field, new fuels, with limited enrichment in ^{235}U, are under development for research reactors. U(Mo) (Uranium molybdene) fuel powders dispersed in an aluminum matrix are among the most promising materials. But the coating of U(Mo) by a barrier material is necessary to limit interfacial interactions between the fuel and its matrix under irradiation (Mazaudier et al., 2008). Silicon seems to be a good candidate (Zweifel et al., 2013). Among other technics, the Fluidized Bed Chemical Vapor Deposition process (FB-CVD) is under study to deposit uniform silicon layers on U(Mo) particles (Vanni et al., 2015a). FB-CVD is an efficient technology to uniformly coat powders by a great variety of materials (Vahlas et al., 2006). There is an interest in being able to treat weights of U(Mo) as low as possible by the FB-CVD process. It is to

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Nomenclature

Roman symbols

Ar	Archimede number (–)
d_p	particle diameter (m)
e_c	particle–particle normal restitution coefficient (–)
g	gravitational constant ($m\,s^{-2}$)
m_p	particle mass ($kg\,m^{-3}$)
P	mean gas pressure ($N\,m^{-2}$)
q_p^2	random kinetic energy ($m^2\,s^{-2}$)
$U_{k,i}$	mean velocity of phase k ($m\,s^{-1}$)
U_{mf}	minimum fluidization velocity ($m\,s^{-1}$)
$u'_{k,i}$	fluctuating velocity of phase k ($m\,s^{-1}$)
V_f	superficial gas velocity ($m\,s^{-1}$)

Greek symbols

α_k	volume fraction of phase k (–)
μ_g	gas viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ_k	density of phase k ($kg\,m^{-3}$)
Θ_p	granular temperature ($kg\,m^{-2}\,s^{-2}$)

Subscripts

g	gas
p	particle

be noted that for preliminary experiments a tungsten powder (19,300 $kg\,m^{-3}$, 75 μm of median diameter) whose properties are very close to those of U(Mo) (17,500 $kg\,m^{-3}$, 50 μm median diameter) has been used as a surrogate powder. Both powders are of very high density. The maximum dimensionless density is 10,000 in the Geldart's classification, but the dimensionless density of the tungsten particles clearly exceeds the upper limit (Fig. 1). First experiments have demonstrated that the FB-CVD technology can uniformly coat 1,500 g of tungsten powder with silicon in a reactor of 3.8 cm in diameter. Other experiments have shown that this weight cannot be decreased in the reactor of 3.8 cm because the target deposition temperature (650 °C) cannot be reached since heat exchange between the reactor walls and the bed of particles becomes too low (Vanni et al., 2015a).

An experimental study has been conducted in glass and steel columns to specifically analyze the impact of decreasing

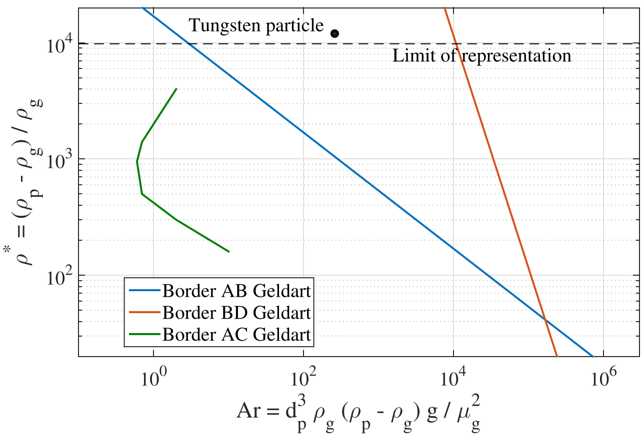

Fig. 1 – Representation of the tungsten particles with a diameter of 75 μm in Geldart's classification modified by Yang (2007).

the reactor diameter from 5 to 2 cm on the fluidization hydrodynamics of the tungsten powder (Vanni et al., 2015b). It was found that uniform silicon deposition could only be achieved if the fluidized bed hydrodynamics was of good quality, i.e. if it involves high thermal and mass transfer rates between the gas and the solid phases. This experimental study has shown that wall effects decreasing the quality of bed hydrodynamics appear in the reactor of 2 cm for 100 g and 180 g of powder. This was evidenced by an increase of the hysteretic behavior of the pressure drop curves, an increase of the minimum fluidization velocity and a decrease of the bed voidage. This was especially evident in a glass column where the electrostatic effects cannot be neglected (Vanni et al., 2015b).

The aim of the present study is to complement the experimental work by using 3D numerical simulations to analyze more precisely the influence of a decrease of the reactor diameter on some key local parameters of the fluidized bed hydrodynamics. The results are expected to be helpful in the FB-CVD process design and in the choice of its optimal gas flow parameters.

Very few studies are available in the literature about the numerical simulation of fluidized beds involving such dense particles. For UO_2 particles of 2 mm in diameter, Liu et al. (2015a) studied the impact of particle density up to 10,800 $kg\,m^{-3}$ on the fluidization behavior of particles in spouting bed using 2D CFD-DEM coupling. The particle cycle time, spout behavior, dominant spout frequency and gas–solid contact efficiency was discussed and a flow pattern map under different densities and different gas velocities was obtained. Pannala et al. (2007) also studied conical spouted bed with heavy particles (up to 6,050 $kg\,m^{-3}$ zirconia particles for nuclear fuel coaters) by 2-D Eulerian–Eulerian numerical simulations.

Miniaturization of chemical reactors, which is one of the most popular research areas in chemical engineering, has led to the concept of micro-fluidized bed reactors (Wang et al., 2011). Wang et al. (2011) have shown by CFD simulations that for Geldart A particles, the onset of turbulent fluidization is advanced significantly in micro fluidized beds. Zivkovic and Biggs (2015) pointed out the importance of wall surface forces relative to volumetric forces, such as gravity, on micro-scale fluidized beds (the cross-sectional dimensions of the microchannels were 400 × 175 μm^2). Liu et al. (2015b) performed several 2D Eulerian–Eulerian numerical simulations for a gas–solid micro-fluidized bed (channel width 3 mm) for Geldart A particles (53 μm and 1,400 $kg\,m^{-3}$) and compared the predicted minimum bubbling velocity and bed voidage to experimental measurements. They used very fine meshes (of approximately one particle diameter). Using the Gidaspow drag model, their simulations have shown that the predicted minimum bubbling velocities were significantly lower than their experimental data (Liu et al., 2015b). Wang and Fan (2011) have established a flow regime map from experimental results obtained in column diameters starting from 0.7 mm to 5 mm in size for FCC particles. Their results revealed an increase in the minimum fluidization and bubbling velocities compared to those in large-scale fluidized beds. To the best of our knowledge, no numerical work has been reported concerning reduced diameter fluidized beds of heavy particles, which are studied in the present article.

The experimental fluidization set-up will be first presented before detailing the numerical model and presenting and discussing the results of the simulation.