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SIMULATION OF FUEL MIXING IN FLUIDIZED BEDS USING A COMBINED TRACKING TECKNIQUE

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ABSTRACT

This paper presents an Eulerian-Eulerian-Lagrangian (E-E-L) numerical method to track a limited number of fuel particles in a bulk of inert particles in a gas-solid fluidized bed. The gas and the inert phases are treated as the interpenetrating continua and resolved within the Eulerian-Eulerian framework, whereas the fuel particles are regarded as a discrete phase. To validate the numerical method, the results are compared with experimental data in the form of preferential positions, velocity vectors and the dispersion coefficient of the fuel particles. It is observed that the proposed numerical technique is able to capture the behavior of fuel particles in fluidized beds.

INTRODUCTION

Fluidized-bed energy convertors typically involve multiple particulate phases with considerable differences in particle properties: there is a low mass fraction of large and light fuel particles in a bed of finer and heavier inert particles. The difference in size and density between the two types of particles leads to a special circulation pattern for the fuel particles in the bed. Therefore, to be able to understand the process of combustion of fuel particles in a fluidized bed, one first has to obtain detailed information on their motion.

The motion of a large and light particle in a bulk of smaller and heavier particles has been the subject of many studies (Nienow et al (1), Rios et al. (2), Lim and Agarwal (3), Pallarès and Johnsson (4)). All the works mentioned above are experimental and aim at studying various aspects of the behavior of large particles, such as their circulation motion, rising/sinking velocities and dispersion. Despite the importance of the phenomenon in applications such as the fuel mixing in fluidized beds, there has so far not been much attempt to study it numerically.

In an attempt to model numerically the behavior of fuel particles in a fluidized bed, Farzaneh et al. (5) proposed a multigrid Lagrangian technique adapted to deal with a significant difference in size between the fuel and the inert particles. Two grids, a fine and a coarse one, were used to track the inert and fuel particles respectively. In addition, a moving grid was introduced to calculate the pressure gradient force on the fuel particles. Although the proposed Lagrangian technique is straightforward and gives detailed information on the dynamics of fuel particles, it is computationally demanding and thus still not applicable to large fluidized-bed units.

As an alternative modeling and simulation tool, the two-fluid (Eulerian-Eulerian) model has commonly been used to simulate fluidization systems, typically applying the kinetic theory of granular flow (KTGF) for providing the needed closure laws. However, the available Eulerian-Eulerian models are not suitable for simulating the fuel mixing in fluidized beds. Namely, in the models formulated to study systems with multiple particulate phases, the different particle classes are often close in size and appear in similar volume fractions (e.g. Huilin et al. (6)).Thus, an appropriate numerical model that could deal with the large size ratios between the inert and fuel particles is still missing.

In this paper we propose a numerical technique that is a combination of Eulerian-Lagrangian and Eulerian-Eulerian frameworks. In the technique, the inert phase, which is composed of a large number of sand-like small particles, is treated as a continuous phase. On the other hand, a limited number of large fuel particles are tracked using a Lagrangian method. The computational results are obtained in the form of the dispersion coefficient and the preferential positions of the fuel particles and are compared with available experimental data.

NUMERICAL METHODOLOGY

As indicated above, the gas and the inert phases are here treated as interpenetrating continua and resolved within the E-E framework. In such a way, the velocity and pressure fields of those two phases are obtained. Then, the forces acting on the fuel particles (e.g. the drag and buoyancy) are calculated and the fuel particles are tracked within the E-L framework. It is assumed that the fraction of the fuel particles is so low that the latter do not influence the flow of the bulk phase.

The MFIX (Multiphase Flow with Interphase eXchange] code (https://mfix.netl.doe.gov) is used to resolve the gas and the inert phases. More details about the code are available in MFIX documentation (Benyahia et al. (7); Syamlal et al. (8)).

Tracking Technique

The equation of motion of the fuel particles is written as:

$$m_p \frac{d\vec{v}_p}{dt} = 3 d_p \mu_{\mathrm{mix}} f\left(\vec{v}_{\mathrm{mix}} - \vec{v}_p\right) + m_p \vec{\mathrm{g}} - \rho_{\mathrm{mix}} \vec{\mathrm{g}} V_p \tag{1}$$

In Eq (1), terms on the right hand side represent the interaction force between the mixture (gas and inert solids) and the fuel particles, the weight of the fuel particle and the buoyancy force exerted by the mixture, respectively.

Here, $\vec{v}_p$, m_p, d_p and V_p are the velocity, mass, diameter and volume of a fuel particle respectively. The velocity and density of the mixture of the gas and inert solids are calculated as follows:

$$\vec{v}_{\mathrm{mix}} = \varepsilon_s \vec{v}_s + \varepsilon_{\mathrm{g}} \vec{v}_{\mathrm{g}} \tag{2}$$

$$\rho_{\mathrm{mix}} = \varepsilon_s \rho_s + \varepsilon_{\mathrm{g}} \rho_{\mathrm{g}} \tag{3}$$

Here, $\vec{v}$, ε and ρ are the velocity, volume fraction and the density of the inert solid and the gas phases respectively (subscript s represents the inert solid phase and g symbolizes the gas phase).

Viscosity of the mixture is obtained from the correlation proposed by Graham (9):

$$\mu_{\text{mix}} = \mu_{\text{g}}\left(\frac{4}{9}\left[\frac{1}{1+0.5\psi}\right]\left[\frac{1}{\psi} - \frac{1}{1+\psi} - \frac{1}{(1+\psi)^2}\right] + 1 + 2.5\varepsilon_s\right), \tag{4}$$

$$\psi = \frac{1-\left(\varepsilon_s/\varepsilon_{s,\text{max}}\right)^{1/3}}{\left(\varepsilon_s/\varepsilon_{s,\text{max}}\right)^{1/3}} \tag{5}$$

where μ_{g} is the gas viscosity and $\varepsilon_{s,\text{max}}$ the possible maximum particle concentration., The drag factor for the mixture, f , is calculated by the well-established correlation (Eq. 6) proposed by Schiller and Naumann (10) for particle Reynolds numbers of up to 1000. This correlation is still extensively used for calculation of drag force on spheres (Crow et al. (11)).

$$f = (1 + 0.15\text{Re}_{\text{mix}}^{0.697}) \tag{6}$$

Here, the particle Reynolds number is expressed as:

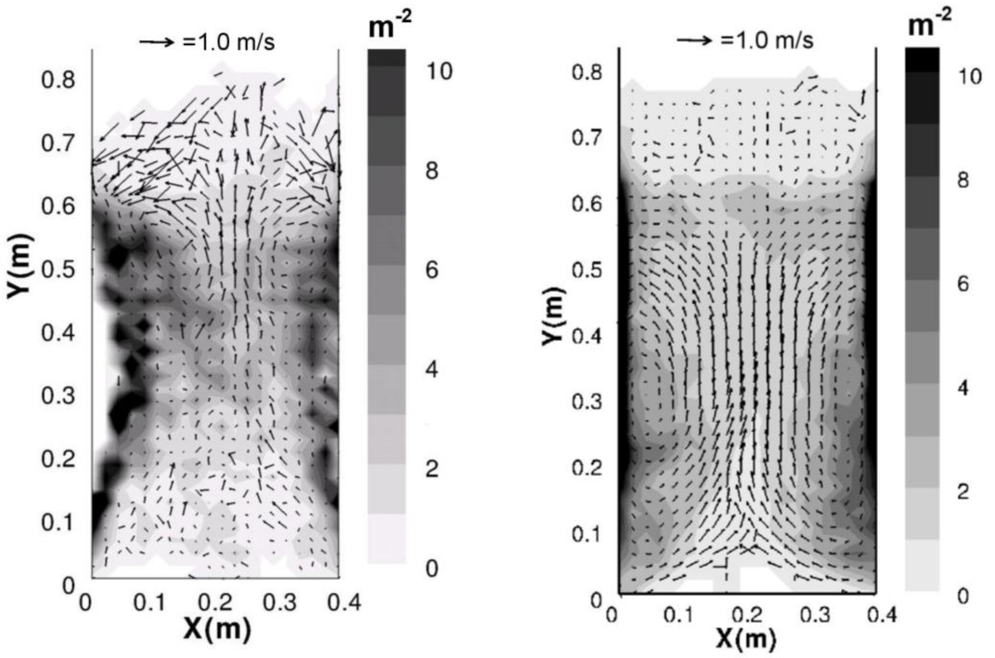
$$\text{Re}_{\text{mix}} = \frac{\rho_{\text{mix}} d_p |\vec{v}_{\text{mix}} - \vec{v}_p|}{\mu_{\text{mix}}} \tag{7}$$

RISULTS AND DISCUSSION

In this work, fluidized beds under different operating conditions are simulated for 100 seconds of real time. The inert particles are the sand-like particles belonging to Group B in the Geldart classification ($\rho_s = 2600\,\text{kg/m}^3$, $d_s = 330\mu\text{m}$ and $U_{\text{mf}} = 0.12\,m/s$). The experiments (Pallarès and Johnsson (4)) were performed using a single cylidrical tracer particle with a density similar to that of the fuel particles ($\rho_p = 985\,\text{kg/m}^3$). However, in numerical simulations we instead use spherical particles with an equivalent diameter and the same density. Furthermore, we use 20 fuel particles in order to get sufficient data for statistical analysis. To accurately formulate the inlet boundary condition, the air supply system is included in the computational domain and the air distributor is modeled as a porous zone with a specified resistance.

The statistical analysis comprises obtaining a probablity density function (PDF) of the presence of fuel partices in a bed. In essence, the PDF represents the preferential positions of the fuel particles in the bed. Additionlly, the horizontal dispersion coefficent of the fuel particles is calculated (see Farzaneh et al. (5) for details on the statistical procedure).

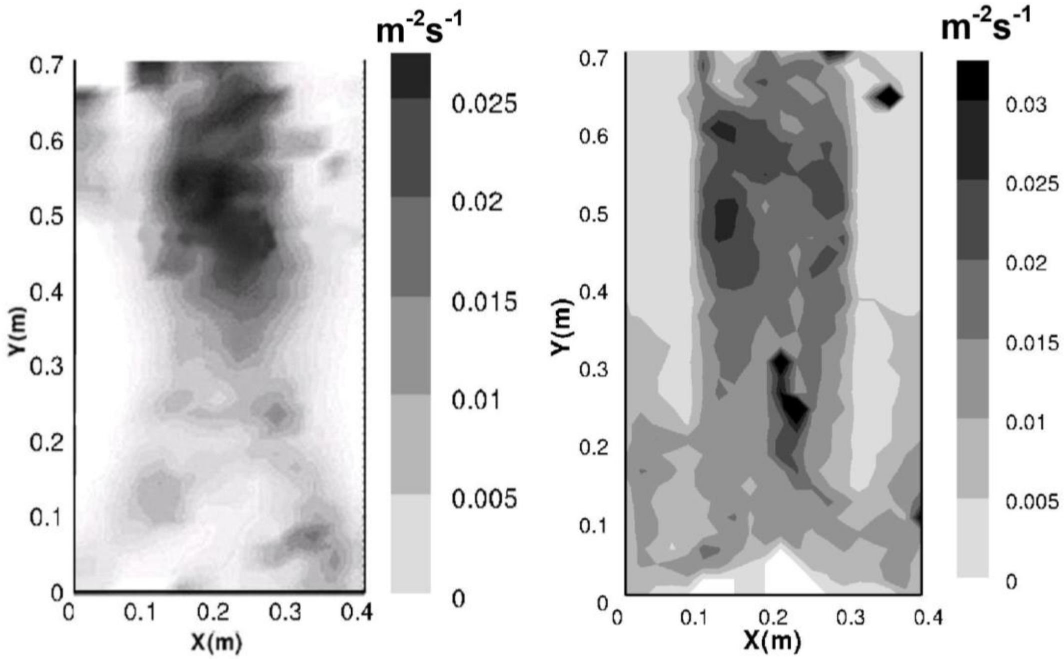
Figure 1 shows the preferential positions and the velocity vectors of the fuel particles in the experiments and the simulations for a case with the initial bed height (H_0) of $0.4\,m$ and the fluidization velocity (U_{f}) of $0.4\,m/s$ $\left(\frac{U_{\text{f}}}{U_{\text{mf}}} = 3.3\right)$. As seen in the figure, the averaged movement of the fuel particles forms two vortices in the bed. In the center of the bed the fuel particles are carried upwards by the upcoming bubbles. Then, on the surface of the bed, they are thrown sidewise towards the walls by the bursting bubbles. In the regions close to the walls, the fuel particles move downwards in accordance with the motion of the bulk phase. The simulations predict well the motion structure, the bubble path in the middle and the two vortices, as observed in the experiments. In addition, the preferred positions of the fuel particles are shown with two dark zones close to the walls. These zones represent the regions in which the fuel particles spent a greatest fraction of time in the bed. The preferred zones observed in the experiments are also well captured by the simulations.



(a) (b)

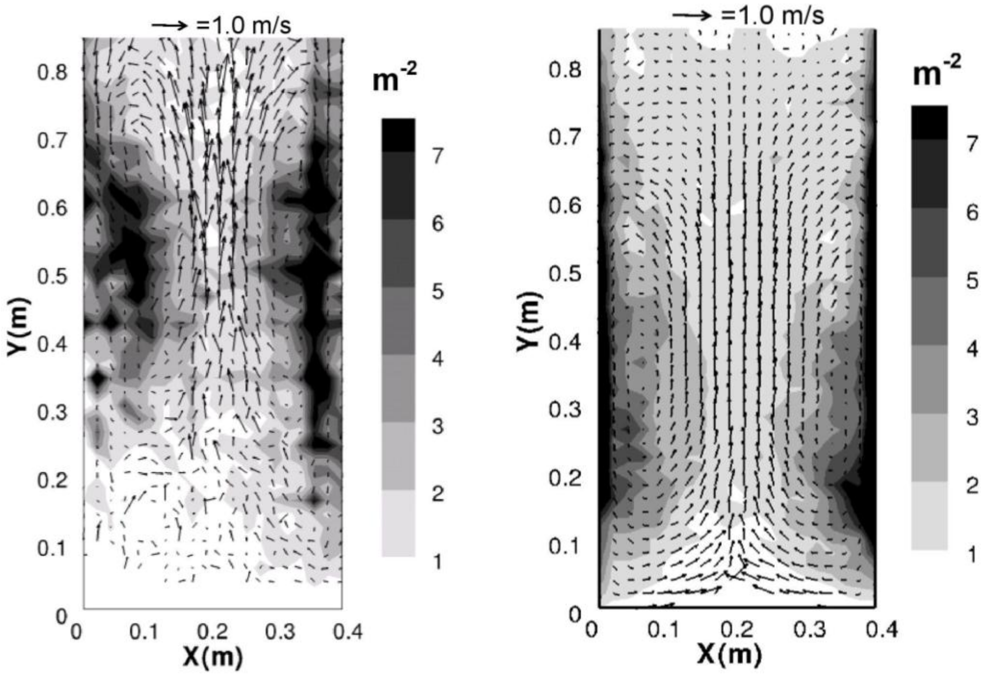
Figure 1. The preferential positions and velocity vectors of the fuel particles ($U_{\mathrm{f}} = 0.4\,m/s\,, H_0 = 0.4$): a) experiments by Pallarès and Johnsson (4); b) present simulations

Figure 2 displays the horizontal dispersion coefficient of the fuel particles. As seen in the experimental results (Figure 2a), there is a high dispersion zone (shown by a dark color) in the middle of the bed, close to the surface. This zone illustrates the horizontal motion of the fuel particles towards the walls. This high dispersion zone is captured by the simulations. However, we can see that this zone is longer in the simulations than it is in the experiments. The difference could be explained by the motion of the fuel particles. As observed in experiments (Figure 1a), there are situations when the fuel particles return to the surface after a short descending. On the other hand, such premature return is less frequent in the simulations and the fuel particles sink to the regions near the distributor. Therefore, the high dispersion zone predicted by the simulations is longer than the one seen in the experiements.



(a) (b)

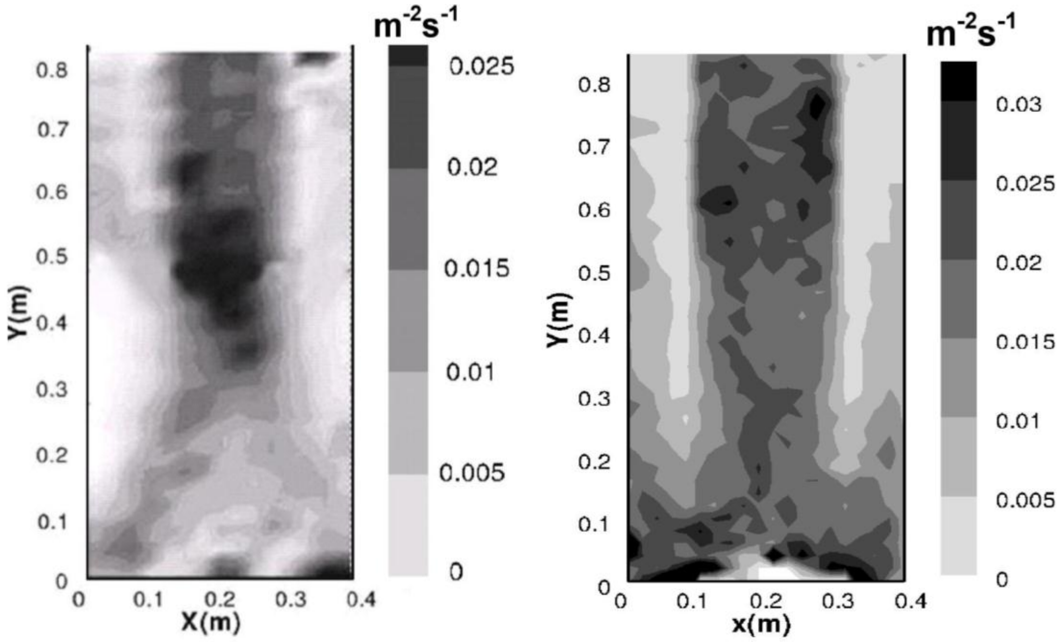
Figure 2. The horizontal dispersion coefficient of the fuel particles ($U_{\mathrm{f}} = 0.4\,m/s\,, H_0 = 0.4$):a) experiments by Pallarès and Johnsson (4); b) present simulations



(a) (b)

Figure 3. The preferential positions and velocity vectors of the fuel particles ($U_{\mathrm{f}} = 0.95\,m/s\,, H_0 = 0.4$); a) experiments by Pallarès and Johnsson (4); b) present simulations

We now study the effect of increasing the fluidization velocity on the distribution pattern of the fuel particles in the bed. Figure 3 shows the velocity vectors and the probability density function of the presence of the fuel particles for the case with the initial bed height of $0.4\,m$ and the fluidization velocity of $0.95\,m/s\left(\frac{U_{\mathrm{f}}}{U_{\mathrm{mf}}}=8.0\right)$. Note that, even though the fluidization velocity is increased, the average movement of the fuel particles is still in the form of two vortices stretched along the walls. In the middle of the bed, the fuel particles are going upwards. A comparison between the experimental and the numerical results demonstrates that the simulations are capable of reproducing the experimental observations with reasonable accuracy. Furthermore, the two preferred zones, illustrated by the two dark regions, are well predicted. However, locations of the two regions predicted by the computations are slightly lower than those seen in the experiments.



(a) (b)

Figure 4. The horizontal dispersion coefficient of the fuel particles ($U_{\mathrm{f}}=0.95\frac{m}{s}, H_0=0.4$):a) experiments by Pallarès and Johnsson (4); b) present simulations

The horizontal dispersion coefficient is also obtained for the case with a higher fluidization velocity and compared with the experiments (Figure 4). As seen in the experimental results (shown in Figure 4a), there is a long and high-dispersion zone in the center of the bed. This zone, which represents the main bubble path, is well captured by the numerical simulations. However, there are still discrepancies between the simulations and the experiments. The differences between the two types of observations could be explained by two facts. First, there are uncertanties in the tracking technique applied in the paper, for example, the drag and buoyancy forces acting on the fuel particles. Namely, the drag and buoyancy correlations used in the current study were originally suggested for fluids. Hence, care should be taken when applying them for solids mixtures. Second, we believe that the E-E models used in the simulations are not suitable for simulating highly dense particulate regimes. The reason for this remark is that we observe somewhat different fluidization patterns when comparing animations of the simulations with available videos of the experiments. The mentioned issues are the subject of the ongoing research.

CONCLUSIONS

In this paper, a numerical technique is proposed to study the problem of fuel mixing in gas-solid fluidized beds. We study the behaviour of a limited number of large and light fuel particles in a bulk of inert particles. The proposed approach combines the two frameworks commonly used in numerical investigations of fluidized beds. The Eulerian-Eulerian (E-E) framework is used to resolve the gas and inert phases as interpenetrating continua, whereas the fuel particles are tracked individually in a computational domain. The proposed model can well capture the overall behaviour of the fuel particles as observed in the experiments. We present the results in the form of the averaged velocity vectors, preferential positions and dispersion coefficeint of the fuel particles. In the cases studied, the average movement of the fuel particles forms two vortices and a single bubble path in the middle of the bed. Finally, we have observed some differences between the numerical and experimental results, which could be explained by uncertanties in the tracking technique and incapability of the available E-E models to deal with friction-dominated gas-solid flows. It is clear that further research is needed on those issues.

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