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Multi-fluid Eulerian modeling of limestone particles' elutriation from a binary mixture in a gas–solid fluidized bed

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ABSTRACT

The elutriation of limestone from a binary mixture of particles in a gas–solid fluidized bed was simulated via computational fluid dynamics (CFD) modeling. A multiphase Eulerian model incorporating kinetic theory of granular flow was used. The effect of superficial gas velocity and particle diameter was investigated using the computational fluid dynamics model. The effects of different modeling parameters on the model predictions were evaluated. The results of simulations showed that elutriation of particles increased with increasing the superficial gas velocity and decreasing particle size. The best model predictions were achieved, using Syamlal–O'Brien drag model. The effect of restitution coefficient on the simulation results was negligible. The computed results of the simulations are compared with the experimental findings.

1. Introduction

Elutriation is a process which can be used as a separation method in gas–solid fluidized beds to generate solid aerosols from a mixture of particles. The importance of elutriation arises, noticing several industries require a method of separating particles according to their sizes and densities. However, complexity of the flow behavior during elutriation in fluidized beds results in the challenge of studying and analyzing elutriation's hydrodynamics.

Computational fluid dynamics (CFD) has proved to be a promising tool in studying multiphase flows, with rapid growth of numerical simulations in the recent years [1,2]. Computational fluid dynamics provides new approach to study the complicated hydrodynamics of gas and particulate flows. CFD modeling has shown its reliable accuracy to predict the flow behavior of fluidized beds [3,4].

Two different classifications of CFD models have been applied to fluidized beds; Eulerian–Lagrangian and Eulerian–Eulerian. The Eulerian–Lagrangian models are based on particle trajectories and solve the equation of motion for each particle, considering collision of particles and forces acting on the particles [5]. The particle trajectories are computed individually at specified intervals during the fluid phase calculation [6]. However, the Eulerian–Eulerian models are more appropriate to be applied to fluidized beds [6,7]. In this approach, all solid phases are treated as continuum as the fluid phase and averaged equations of motion are utilized [8–18]. Different averaging methods have been used. Ishii [19] and Drew and Lahey [20] used time averaging while Harlow and Amsden [21], Rietema and Van den Akker [22], and Ahmadi [23] used a volume averaging method. Thus, the averaged equations can be used to simulate multiphase flows containing a significant volume fraction of solid particles, in this approach. Eulerian–Eulerian and Eulerian–Lagrangian approaches were compared by Gera et al. [24]. In order to describe the rheology of particulate phases, many authors have used the kinetic theory of granular flow to obtain the constitutive equations [25–35].

In this study, a multiphase Eulerian computational fluid dynamics model using the kinetic theory of granular flow was developed to study the elutriation of limestone particles in a binary mixture of fluidized bed, with silica sand as the coarse bed particles. The effect of gas velocity and particle size was investigated using the CFD model. The influences of some modeling parameters such as drag models, restitution coefficient, time step size, and convergence criterion were observed with the results of simulations. The results of the simulations are compared with experimental findings [36] to demonstrate the effectiveness of the model.

2. Computational fluid dynamics multi-fluid model

A multi-fluid Eulerian model was used to model the hydrodynamics of the elutriation in the gas–solid fluidized bed. The model involved kinetic theory of granular flow to obtain constitutive equations. Viscous forces and solid pressure of the solid phases can

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Nomenclatures

C_D	drag coefficient [–]
$C_{fr,i}$	friction coefficient [–]
Di	diameter [m]
E_{ss}	restitution coefficient [–]
G	gravity [m/s^2]
$g_{0,ss}$	radial distribution coefficient [–]
$\bar{\bar{I}}$	stress tensor [–]
I_{2D}	second invariant of the deviatoric stress tensor [–]
K_{gs}	gas–solid momentum exchange coefficient [–]
$k_{\Theta s}$	diffusion coefficient of granular energy [kg/s m]
m_i	mass of particles [kg]
n_i	number of particles [–]
p	fluid pressure [Pa]
P_s	solid pressure [Pa]
Re	Reynolds number [–]
T	time [s]
v_i	velocity [m/s]
v_t	terminal velocity [m/s]
Greek letters	
ε_i	volume fraction [–]
Θ_i	granular temperature [m^2/s^2]
λ_i	bulk viscosity [kg/s m]
μ_i	shear viscosity [kg/s m]
ρ_i	density [kg/m^3]
$\bar{\bar{\tau}}_i$	stress tensor [Pa]
$\gamma_{\Theta m}$	collision dissipation of energy [kg/s^3 m]
ϕ_{gs}	transfer rate of kinetic energy[kg/s^3 m]
ϕ	angle of the integral friction [–]
η	effectiveness factor [–]

be described as a function of granular temperature, by taking advantage of the kinetic theory of granular flow [3,37]. No mass transfer was allowed between phases. The model used in this study is described as follows.

2.1. Continuity equations

Gas phase:

$$\frac{\partial}{\partial t}(\varepsilon_g\rho_g) + \nabla\cdot(\varepsilon_g\rho_g\vec{v}_g) = 0 \tag{1}$$

Solid phase:

$$\frac{\partial}{\partial t}(\varepsilon_s\rho_s) + \nabla\cdot(\varepsilon_s\rho_s\vec{v}_s) = 0 \tag{2}$$

where ε, ρ and v are volume fraction, density and velocity respectively.

2.2. Momentum equations

The momentum equation for gas and solid phases
Gas phase:

$$\frac{\partial}{\partial t}(\varepsilon_g\rho_g\vec{v}_g) + \nabla\cdot(\varepsilon_g\rho_g\vec{v}_g\vec{v}_g) = -\nabla p + \nabla\cdot\bar{\bar{\tau}}_g + \varepsilon_g\rho_g\vec{g} + \sum_{s=1}^{N} k_{gs}(\vec{v}_s - \vec{v}_g) \tag{3}$$

where p and $\vec{g}$ are gas pressure and gravity, respectively.

k_{gs} is gas–solid momentum exchange coefficient of gas and solid phase, $\nabla\cdot\bar{\bar{\tau}}_g$ is gas phase tensor.
Solid phase (s = 1, 2, ..., N):

$$\frac{\partial}{\partial t}(\varepsilon_s\rho_s\vec{v}_s) + \nabla\cdot(\varepsilon_s\rho_s\vec{v}_s\vec{v}_s) = \nabla\cdot\bar{\bar{\tau}}_s + \varepsilon_s\rho_s\vec{g} + k_{gs}(\vec{v}_g - \vec{v}_s) + \sum_{n=1, s\neq n}^{N} k_{ns}(\vec{v}_n - \vec{v}_s) \tag{4}$$

where k_{ns}, is solid–solid exchange coefficient and τ_s is solid phase stress tensor.
Gas phase stress tensor:

$$\bar{\bar{\tau}}_g = \varepsilon_g\mu_g[\nabla\cdot\vec{v}_g + \nabla\cdot\vec{v}_g^{\,T}] - \frac{2}{3}\varepsilon_g\mu_g\nabla\cdot\vec{v}_g \tag{5}$$

Solid phase stress tensor of phase s,

$$\bar{\bar{\tau}}_s = -P_s\bar{\bar{I}} + \varepsilon_s\mu_s(\nabla\cdot\vec{v}_g + \nabla\cdot\vec{v}_g^{\,T}) + \varepsilon_s\left(\lambda_s - \frac{2}{3}\mu_s\right)\nabla\cdot\vec{v}_s\bar{\bar{I}} \tag{6}$$

where μ_s and λ_s are solid shear viscosity and bulk viscosity, respectively.
Solid shear viscosity:

$$\mu_s = \mu_{s,\mathrm{col}} + \mu_{s,\mathrm{kin}} + \mu_{s,\mathrm{fr}} \tag{7}$$

Collisional viscosity:

$$\mu_{s,\mathrm{col}} = \frac{4}{5}\varepsilon^2\rho_s d_s g_{0,ss}(1+e_{ss})\left(\frac{\Theta_s}{\pi}\right)^{1/2} \tag{8}$$

where $g_{0,ss}$ is radial distribution, e_{ss} is restitution coefficient, and Θ_s is granular temperature.
Kinetic viscosity [38]:

$$\mu_{s,\mathrm{kin}} = \frac{\varepsilon_s\rho_s d_s\sqrt{\Theta_s\pi}}{6(3-e_{ss})}\left[1 + \frac{2}{5}(1+e_{ss})(3e_{ss}-1)e_s g_{0,ss}\right] \tag{9}$$

Frictional viscosity [39]:

$$\mu_{s,\mathrm{fr}} = \frac{P_s\sin\phi}{2\sqrt{I_{2D}}} \tag{10}$$

where P_s is the solid pressure, ϕ is the angle of the integral friction and I_{2D} is the second invariant of the deviatoric stress tensor
Solid bulk viscosity [40]:

$$\lambda_s = \frac{4}{3}\varepsilon^2\rho_s d_s g_{0,ss}(1+e_{ss})\left(\frac{\Theta_s}{\pi}\right)^{1/2} \tag{11}$$

Solid pressure:
A general model for the solids pressure in the presence of several solid phases by Gidaspow [3]

$$P_s = \varepsilon_s\rho_s\Theta_s + \sum_{n=1}^{N}\frac{\pi}{3}g_{0,ns}d_{sn}^3 n_s n_n(1+e_{sn})f(m_n, m_s, \Theta_n, \Theta_s) \tag{12}$$

where $d_{ns} = d_n + d_s/2$ is the average diameter, n_n and n_s are the number of particles, m_n and m_s are the masses of particles in the phase phases n and s, and f is a function of the masses of the particles and their granular temperatures.

However, this equation can be simplified to give the following form [6]

$$p_s = \varepsilon_s\rho_s\Theta_s + \sum_{p=1}^{N}2\frac{d_{ns}^3}{d_n^3}(1+e_{ns})g_{0,ns}\varepsilon_n\varepsilon_s\rho_s\Theta_s \tag{13}$$