Modeling and simulation of Cold Flow Fluidized Bed Reactors

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Motivation:

Simulations of cold flow fluidized gas-solid systems have been conducted for both riser and bubbling bed reactors, alone and combined in a circulating fluidized bed reactor. An Eulerian continuum two-fluid model with the Constant Particle Viscosity closure for the stresses term has been employed for the granular phase whereas an algebraic turbulence model was used for the gas phase.

An in-house code has been developed, based upon the Finite Volume Method applied to the governing equations with a staggered grid arrangement.

The velocities for both gas and solid phases are obtained solving the 1D Reynolds averaged Navier-Stokes equations using a coupled solver, while a pressure correction equation allows to solve for pressure based on gas continuity. The void fraction profile is computed from the solid continuity.

Cold flow simulations of fuidized systems form the basis for the modeling of chemical processes such as Sorption-Enhanced Steam Methane Reforming.

Model Equations[2,3]:

For gas

Continuity

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\right)+\frac{\partial}{\partial z}\left(\alpha_g\rho_g v_g\right)=0$$

Momentum

$$\begin{aligned}\frac{\partial}{\partial t}\left(\alpha_g\rho_g v_g\right) \quad + \quad & \frac{\partial}{\partial z}\left(\alpha_g\rho_g v_g v_g\right)= \\ & -\alpha_g\frac{\partial p_g}{\partial z}+\frac{\partial}{\partial z}\left(\alpha_g\mu_g^t\frac{\partial v_g}{\partial z}\right)-\alpha_g\rho_g g+\beta\left(v_p-v_g\right)-\frac{2f_g\alpha_g\rho_g|v_g|v_g}{D_h}\end{aligned}$$

$$f_g = \begin{cases} \frac{16}{Re_g} & Re_g < 2100 \\ \frac{0.0791}{Re_g^{1/4}} & 2100 < Re_g < 10^5 \\ \frac{1}{\left(4.0\ log\left(Re_g\sqrt{f}\right)-0.4\right)^2} & 2300 < Re_g < 4\times 10^6 \end{cases}$$

For solids

Continuity

$$\frac{\partial}{\partial t}\left(\alpha_p\rho_p\right)+\frac{\partial}{\partial z}\left(\alpha_p\rho_p v_p\right)=\Gamma$$

Momentum

$$\begin{aligned}\frac{\partial}{\partial t}\left(\alpha_p\rho_p v_p\right) \quad + \quad & \frac{\partial}{\partial z}\left(\alpha_p\rho_p v_p v_p\right)= \\ & -G\frac{\partial \alpha_p}{\partial z}-\alpha_p\frac{\partial p_g}{\partial z}+\frac{\partial}{\partial z}\left(\alpha_p\mu_p^t\frac{\partial v_p}{\partial z}\right)-\alpha_p\rho_p g+\beta\left(v_g-v_p\right)-\frac{2f_s\alpha_p\rho_p|v_p|v_p}{D_h}\end{aligned}$$

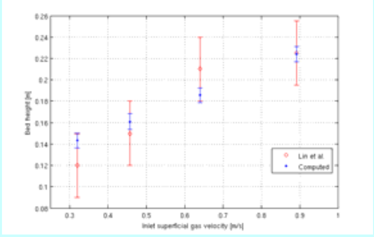
$$\begin{aligned} G &= 10^{-10.46\ \alpha_g+6.577}\ \frac{N}{m^2} \\ f_s &= \frac{0.0025}{|v_p|}\end{aligned}$$

Interfacial forces: Drag

$$\begin{aligned}\beta &= \begin{cases} 150\frac{\alpha_p^2\mu_g\rho_p}{(\alpha_g d_p\phi_p)^2(\rho_p-\rho_g)}+1.75\frac{\rho_g\rho_p|v_g-v_p|\alpha_p}{\alpha_g d_p\phi_p(\rho_p-\rho_g)} & \alpha_g < 0.8 \\ \frac{3}{4}Cd\frac{\rho_g\rho_p|v_g-v_p|\alpha_p}{d_p\phi_p(\rho_p-\rho_g)}\alpha_g^{-2.65} & \alpha_g \geq 0.8 \end{cases} \\ Cd &= \begin{cases} \frac{24}{Re}\left(1+0.15\ Re^{0.687}\right) & Re \leq 1000 \\ 0.44 & Re > 1000 \end{cases} \\ Re &= \frac{|v_g-v_p|d_p\rho_g\alpha_g}{\mu_g}\end{aligned}$$

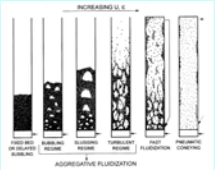
Validation

The model results were compared against experimental results found in the literature, involving the expansion of the bed of solids in a bubbling bed reactor at different inlet gas velocities.[1]



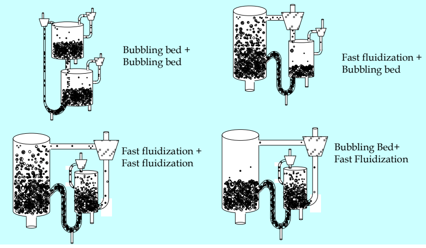
Discussion:

Flow regimes are important for the reactor perfomance[2]:



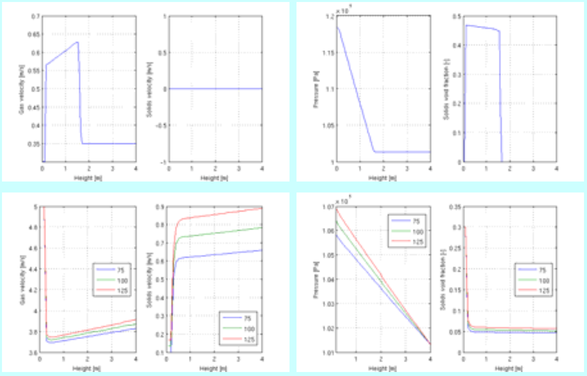
- Residence times
  - SE-SMR
  - Regeneration of sorbent
- Heat integration between reactor units
- Pressure drop balance
- Pellet size

According to their flow regimes, the fluidized units can be configured in different ways, for example:

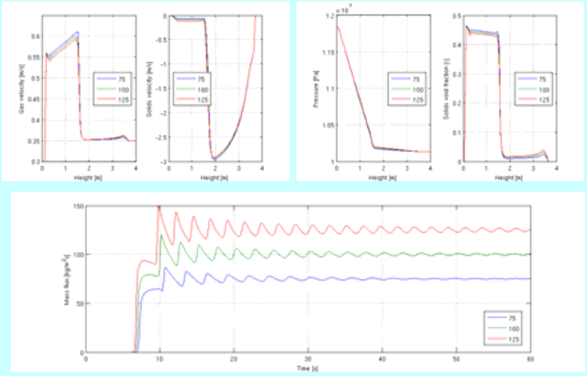


Results:

Typical industrial-size riser and bubbling bed units were simulated alone and combined in a circulating fluidized bed reactor. The riser was run with a constant inventory of solids, corresponding to solid fluxes of 75, 100 and 125 kg/m^{2}s, which are typical values found in the literature[4], allowing 10 seconds to reach full inlet gas velocity. The bubbling bed was simulated with an initial bed height of 1.2 m at minimum fluidization conditions.



For the circulating fluidized bed reactor, the solids mass flux coming out of the riser is introduced into the bubbling bed unit through the top and the same amount is taken from the bottom and reintroduced into the riser. Equilibrium profiles for the riser are similar, while for the bubbling bed they are different.



Conclusion:

A cold flow model for gas-solid systems was developed for two coupled fluidized units.

Results for the expansion of a bed of solids on a fluidized bed reactor were in good agreement with experimental data from the literature.

Riser and bubbling bed systems were simulated alone and combined in a circulating fluidized bed reactor, obtaining profiles such as solid void fraction and mass fluxes. These form the basis for further work on chemical processes like Sorption-Enhanced Steam Methane Reforming, where transport of solids between fluidized units is crucial for successfully taking into account the changes in particle properties due to adsorption/desorption processes.

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