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Hydrodynamic study of a multiphase spouted column

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HIGHLIGHTS

- CFD simulation of three phase spouted bed.
- Euler multiphase transport model predict hydrodynamic characteristics.
- The $k–\varepsilon$ and $k–\omega$ turbulence models equally goods for the two phase (air–water).
- The SST turbulence models better than for $k–\varepsilon$ three phase (air–water–sand) simulations.
- Drag closure: Ishii–Zuber for (air–water), Schiller–Naumann for (water–sand).

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ABSTRACT

The capability of Euler multiphase averaged transport model to predict hydrodynamic characteristics (pressure drop, gas holdup and solid concentration) of a multiphase spouted column is analyzed using computational fluid dynamic (CFD). The Navier–Stokes equation is solved with ANSYS CFX built-in closures: two equations turbulence ($k–\varepsilon$, $k–\omega$, SST), and semi-empirical correlations for interphase forces (drag, turbulent dispersion and lift forces, virtual force). To ensure the reliability of the CFD simulations, the models are validated against experimental data for the two phase air–water and the three phase air–water–sand system in a spouted column with a draft tube and a conical base at 25 °C and 1 atm and varying superficial air velocity (0.572 m/s, 0.00.0944 m/s, 0.1605 m/s, 0.2172 cm/s) [22]. Steady state conditions capture the flow conditions for the two-phase (air–water) system while transient conditions is need the for three-phase simulations (air–water–sand). The mixing regions and the moment exchange is correctly characterized by a free-wall turbulence using $k–\varepsilon$ and $k–\omega$ two equations turbulence closure models for the two phase dispersed air–water system [30,32], while the SST turbulence model instead of $k–\varepsilon$ model is needed to improve predictions of solid concentrations close to internal walls for the dispersed air–water–sand system. The drag is the most significant coupling force, for the two and three phase system. Ishii–Zuber drag model is compared against and Grace adjusted drag model for air–water system, it predict the hold-up within 0.14% while Grace model within 0.44% requiring greater computational cost to tune the model empirical parameter [31,32], and the Schiller–Naumann drag coefficient is used for sand-water. For the two phases system best concordance between the simulated and experimental data are achieved for inlet gas velocity (u_0) of 0.2172 m/s (2% error in the predicted air hold-up). For the three phases system, in the concentric tube, and for an air superficial velocity of 0.2172 m/s, the deviation in the estimated sand concentration is near 23% a while the error in the predicted air hold-up is within 2%. The observed deviation can be attributed to the chosen effective bubble size of the dispersed phase in the two phase system and the choice of drag force models and turbulence closure the three phase system.

1. Introduction

Multiphase systems are often found in different industrial processes such as: chemical, biochemical, petrochemical, environmental, pharmaceutical and metallurgical. Multiphase bubble columns and slurry reactors are the contactors of choice for processes providing better heat and mass transfer with heat and mass transfer limitations at lower operating cost, for these reasons the design and scale up has been the focus of several researchers in the last 20 years [1,2]. They are simple vessels into which gas is injected, usually at the bottom, and random mixing is produced by the ascending bubbles (air). This fluid dispersion is attained when the injected gas is fed from the bottom of the reactor, so that in

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Nomenclature

A	Ishii–Zuber parameter
D	diameter [m]
D_{axL}	liquid axial dispersion
d_b	bubble diameter [m]
re	drag force coefficient
$C_{D,cap}$	drag force coefficient Newton regime
$C_{D,Ellipse}$	drag force coefficient Allen regime
$C_{D,Sphera}$	drag force coefficient Stokes regime
C_D^{Dense}	drag force coefficient dense volume fraction
C_D^{dis}	drag force coefficient dilute volume fraction
$C_{D\infty}$	drag force coefficient dilute volume fraction
$C_{D,sand\text{–}water}$	drag force coefficient sand–water iteration
C_L	lift force coefficient
C_S	solid concentration [kg m^{-3}]
C_{TD}	turbulence dispersion force coefficient
C_{VM}	virtual mass force coefficient
C_μ; C_l; C_2; σ_k and σ_ε	k–ε model constants
Eo	Eötvös number
fi	interphase force i
g	gravity acceleration [m/s^2]
G_T	turbulence kinetic energy production
k	turbulent kinetic energy [m^2/s^2]
M	Morton number
P	pressure [Pa]
p	Grace exponent parameter
Re	Reynolds number
Re_B	bubble Reynolds number
Re_m	mixture Reynolds number
T	temperature [°C]
t	time [s]
u	superficial velocity [m/s]
u_c	continuous phase superficial velocity [m/s]
u_d	discontinuous phase superficial velocity [m/s]
u_0	entry gas superficial velocity [m/s]
U_T	terminal velocity [m/s]
V	volume [m^3]

Greek

ε	turbulent dissipation energy [m^2/s^3]
ε_G	air volume fraction (air holdup)
ε_c	continuous phase volume fraction
ε_d	discontinuous phase volume fraction
δ	delta de Kroneker
μ	dynamic viscosity [Pa s]
μ_c	continuous phase dynamic viscosity [Pa s]
μ_L	liquid phase dynamic viscosity [Pa s]
μ_m	mixture dynamic viscosity [Pa s]
μ_{Turb}	turbulent viscosity [Pa s]
$\mu_{L,Turb}$	liquid phase turbulent viscosity [Pa s]
v	kinematic viscosity [m^2/s]
ρ_i	phase "I" density [kg/m^3]
σ	superficial tension [m^2/s]
ω	turbulent kinematic energy frequency
τ	stress tensor

its ascent it drags the solid particles and liquid, thereby inducing a movement of the denser phase along the reactor with a fountain type effect. In such systems, the movement is produced by the density difference between the particles and fluids within the reactor. The phase behavior within a bubbling reactor and the way to produce homogenization and mixture thereof can be understood as a complex iteration of the four distinct areas (Inlet, Riser, Disengaging zone, Downcomer). These type reactors improve gas–liquid contact and liquid mixing and create the needed hydrodynamics regimens to enhance the kinetics in the riser and in the downcomer. The design and scale up strategies of these pneumatically operated reactors is limited by the inside complex flow structures. The system hydrodynamic is determined by holds ups spatial distributions and liquid flow fields. Empirical correlations and axial dispersion models are often used with and with limited precision for the design and scale up strategies [3]. The working differential equations used in the axial dispersion models do not account for the interphase forces or for the turbulence that provide the needed contact area for the competing momentum, mass and heat transfer phenomena within such systems.

Computational Fluid Dynamic (CFD) is the numerical solutions of the Eulerian volume-averaged transport models, starting from fundamental principles, seek to capture the physics of the problem modeled by mass and momentum balance, and closure models. The momentum and continuity of each phase with its characteristic flow properties are based on the solution of the Reynolds-Averaged Navier–Stokes (RANS) equation. The interphase forces and turbulence models are the needed closures for the moment balance to correctly describe the observed physical phenomena. The two-fluid Euler–Euler (E–E) has shown to be numerically efficient, particularly in domains with high concentration of the dispersed phase. It provides better understanding of design parameters such as gas hold–up, flow regime, dispersion characteristics and bubble size distributions. In spite of the high computational cost associated with three dimensional simulations (3D), it becomes the required standard to study the fluid dynamic behavior for bubble columns [4–11]. Despite the great effort of researchers, modeling and simulation of fluidized beds using CFD is far from being predictive due to the complexity of the problems and the difficulty of model implementation ([5,12–18] among others).

The purpose of work is study the capability of the Euler multiflow modeling framework using CFX built in interphase and turbulence closure models on accurately predicting the pressure drop, gas holdup and solid distribution within the bubble column. The two phase air–water and three phase air–water–sand system are here studied using CFD simulation in 3D, cylindrical geometry. A cold study or simulation without chemical reaction provide the needed insight about the multiphase flow hydrodynamic, specifically it provides better understanding on gas retention, phase distribution and axial dispersion [19]. The interfacial forces between the dispersed gas phase and the continuous liquid phase are obtained from semi-empirical correlations (e.g. drag, lift and added mass forces, i.e., virtual mass). The two equations turbulence closure models: k–ε model [20] and the k–ω model [21] are used for the two phase air–water system while k–ε and SST models are used with the three phase air–water–sand system. To ensure the reliability of the CFD simulations, the models are validated against experimental data [22]. This is done by systematically changing parameters and comparing the results against the Pironti et al. [22] experimental data.

2. Theory

The turbulence within the two phase spouted bed is characterized by strong coupling and fluctuations and is irregular in space and time and thus irreproducible in details. The features for this