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Influence of tube configuration on the gas–solid hydrodynamics of an internally circulating fluidized bed: A discrete element study

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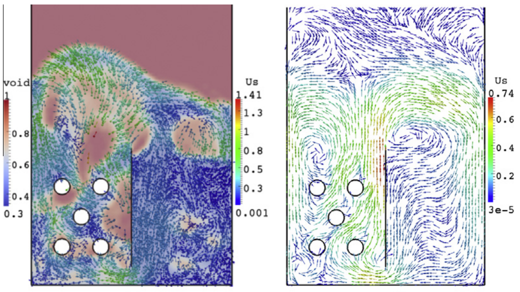
HIGHLIGHTS

- Gas–solid flow dynamics in a baffle-type ICFB with immersed tubes are studied.
- Variation of solid circulation time with the change of tube number is identified.
- Influence of tube number on the solid residence time in the chambers is quantified.
- Influence of tube number on the solid mixing behavior is clarified.
- Erosion pattern around the circumference of each tube is addressed.

GRAPHICAL ABSTRACT

(a) Snapshot of solid motion at time instant of $t = 8$ s of the ICFB with 5 tubes locating in the RC and (b) vector plot of the time-averaged solid velocity of the ICFB with 5 tubes locating in the RC.



(a) (b)

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ABSTRACT

Three-dimensional modeling of the gas–solid flow in an internally circulating fluidized bed is conducted by means of the computational fluid dynamics combined with the discrete element method to explore the effect of the tube bundle on the gas–solid hydrodynamics of the system. Gas motion is resolved at the computational grid level, while solid motion is obtained in the Lagrangian view. The influences of tube bundle on the interaction of two chambers, the circulating and resident behaviors of solid phase are evaluated. Moreover, solid mixing behavior and tube erosion are discussed. The results show that the immersed tubes obviously enlarge the gas/solid velocity in the vicinity of the partition plate and lower the interaction intensity of the two chambers. Solid cycle time of the system with or without tubes processes a log-normal distribution. Furthermore, different resident behaviors of the solid phase can be obtained in the two chambers, and inserting the tube bundle in the reactor chamber enlarges the solid residence times of the two chambers. More tubes inserted into the bed enlarge both the cycle time and residence time of the solid phase. On the other hand, the presence of tube bundle enhances the solid mixing intensity. Finally, different erosion distributions appear around the circumferential positions of each tube, and the latent erosion pattern can be identified from the distribution of the time-averaged solid flux.

1. Introduction

The internally circulating fluidized bed (ICFB) is a type of fluidizing reactor with a vertically inserted draft tube or a centrally located partition plate that divides the bed into two or more chambers. These separated chambers of the ICFB result in the internal solid circulation established between them, and also provide a flexible condition of the gas–solid motion with different gas flow rates introduced into the chambers. Compared with other types of fluidizing apparatuses, the ICFB has several promising advantages, such as the reduced height and construction costs, low heat/mass

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Nomenclature

d_p	particle diameter, m
d_t	diameter of tube, m
e	solid restitution coefficient
E	erosion quantity, m^3
F_c	particle – particle interaction force, N
F_p	interphase momentum exchange, N m^{-3} s^{-1}
g	gravitational acceleration, m s^{-2}
H	initial bed height, m
I_p	particle rational inertia, kg m^2
k_n	normal stiffness of solid, N m^{-1}
k_t	tangential stiffness of solid, N m^{-1}
m_p	particle mass, kg
N_p	particle number in a fluid cell
$\boldsymbol{n}_{ij}$	normal vector between two colliding particles
p	pressure, Pa
P_H	Vickers hardness, Pa
Re	Reynolds number of particle
S_n	normal damp coefficient
S_t	tangential damp coefficient
t	time, s
t_f	time step for fluid phase, s
t_s	time step for solid phase, s
$\boldsymbol{t}_{ij}$	tangential vector between two colliding particles
T_f	sub-grid stress tensor, N m^{-2}
T_p	torque on the solid particle, N m
U_f	superficial gas velocity to RC, m s^{-1}
U_m	superficial gas velocity to HEC, m s^{-1}
U_i, U_j, U_k	three components of fluid velocity vector, m s^{-1}
U_{mf}	minimum fluidization velocity, m s^{-1}
V_p	particle volume, m^3
V_{cell}	volume of the computational grid, m^3
$\overrightarrow{v_p}$	solid velocity, m s^{-1}
v_r	relative velocity of the colliding particles, m s^{-1}
x_i, x_j, x_k	three components of orthogonal coordinate
Y_p	young modulus, Pa

Greek letters

β_{gs}	interphase momentum exchange coefficient
γ	impacting angle between the impacting particle and surface, °
δ	displacement between two colliding particles, m
ε_f	volume fraction of fluid
ε_p	volume fraction of solid
λ_f	fluid molecular viscosity stress tensor, Pa s
ρ_f	density of fluid phase, kg m^{-3}
ρ_s	density of solid phase, kg m^{-3}
τ_f	fluid viscosity stress tensor, N m^{-2}
μ	fluid laminar viscosity, Pa s
μ_k	dynamic friction coefficient
μ_s	friction coefficient
μ_t	fluid turbulent viscosity, Pa s
v_p	SOLID translational velocity, m s^{-1}
ω_p	solid angularvelocity, rad s^{-1}
γ	impact angle between the colliding particle and surface, °
γ_n	normal damp coefficient
γ_t	tangential damp coefficient
v_s	solid Poisson's ratio

Operators

$\sim$	filtering operator in LES

Subscripts

f	fluid (gas phase)
p	particle (solid phase)
s	solid
t	tangential
gs	gas–solid interaction
n	normal
i, j, k	index of three coordinates

Acronyms

CFD	computational fluid dynamics
DEM	discrete element method
HEC	heat exchange chamber
GBF	gas bypassing flux
ICFB	internally circulating fluidized bed
LES	large eddy simulation
RC	reaction chamber
SCF	solid circulation flux
SF	solid flux
SRT	solid residence time
TFM	two-fluid model

transfer coefficient, and nice pollutant control performance [1,2]. Thus, the ICFB has been frequently adopted in many industrial processes especially when the chemical reaction is taken into account, such as the thermal treatment of industrial solid wastes [3], coal combustion [4], the gasification of coal or biomass [5,6], combustion desulfurization [7–9], and so on. To develop an efficient reactor, the internal gas–solid hydrodynamics of the ICFB should be deeply investigated.

With the extensive experiments conducted in the past years, many valuable information on the hydrodynamics of the ICFB have been proposed, such as the circulation rate of solid phase [10–12], the gas-bypass [13,14], the transport disengaging height and solid entrainment rate [15], and the scale-up of the system [16].

Besides the experimental studies, numerical investigation of the gas–solid flow in the fluidizing apparatus has been rapidly conducted with the developments of the computational algorithm and the computer technology. The existing approaches to model the particle flow can be mainly categorized into two branches, namely the two-fluid method (TFM) and the computational fluid dynamics combined with the discrete element method (CFD–DEM) [17–21]. The main difference between them focuses on the method adopted to track the solid motion. The former treats the solid phase as a continuous medium at a macroscopic level, while the latter tracks the motion of each particle individually. Based on the numerical simulation, the hydrodynamics of the dense two-phase flow have been widely studied [22–25]. However, numerical evaluation of solid transportation in the ICFB has been comparatively less reported. Marschall and Mleczko [26] explored the complex hydrodynamics of an ICFB with the TFM approach to improve the reactor design and to optimize reactor conditions. They noted that the height of the annulus plays an important role in the control of the circulation of solids. Bin et al. [27] simulated the gas–solid flow of a two-dimensional ICFB with the Eulerian–Lagrangian approach. The results demonstrated that the particle circulation improves the mixing of particles in the transverse direction, which will deeply affect the particle dispersion, heat/mass transfer, and the chemical reaction in the bed. Zhang et al. [28] performed a numerical simulation on the hydrodynamics of