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Discrete element study of solid circulating and resident behaviors in an internally circulating fluidized bed

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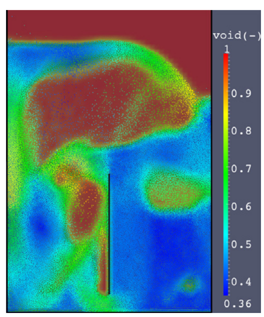
HIGHLIGHTS

- Solid circulation is constructed in the ICFB with the formations of three local rolls.
- Solid cycle time shows a log-normal probability distribution pattern.
- Enlarging the fluidizing velocity in the RC or HEC reduces the solid cycle time.
- Large residence time of solid phase appears in the two corners of the bed.
- Increasing the baffle incline angle or gap height reduces solid residence time in HEC.

GRAPHICAL ABSTRACT

Snapshot of the particle distribution in the ICFB at $t = 8.1$ s.



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ABSTRACT

Three-dimensional modeling of the gas–solid flow in an internally circulating fluidized bed is conducted based on the computational fluid dynamics coupled with discrete element method. The gas flow is resolved at the computational grid level while the solid motion is tracked individually. General circulation pattern and the circulating path of solid phase in the system are investigated. Then, the distribution pattern of solid cycle time is studied. Moreover, the solid resident behaviors from the scales of both the computational grid and particle level are explored. Simultaneously, the influences of operating parameters and bed geometrical configuration on these two aspects are discussed. The results show that solid circulation is constructed in the two chambers with the formations of three local circulation rolls of solid motion. A global path can be identified for solid circulation in the system. Solid cycle time in the bed shows an early-occurred peak with a long tail and distributes in a log-normal probability histogram. Increasing the fluidizing velocity introduced into each chamber or the gap height lowers the solid cycle time. In addition, large solid residence time (SRT) appears in the two corners of the bed. At the particle-scale level, larger SRT is observed in the right chamber as compared with that of the left one, and the increase of fluidizing velocity reduces the SRTs in the two chambers. No-linear evolutionary tendencies of both the cycle time and the SRT in each chamber can be observed with changing the geometrical configuration, which raises a caution on the geometry design of the apparatus.

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Nomenclature

C_s	Smagorinsky constant coefficient
d_p	particle diameter, m
e	solid restitution coefficient
$\boldsymbol{F}_{c,ij}$	contact force between particle i and particle j, N
$\boldsymbol{F}_{d,i}$	drag force exerted on particle i, N
$\boldsymbol{F}_{p,i}$	far field pressure force exerted on particle i, N
$\boldsymbol{g}$	gravitational acceleration, m/s^2
G^*	tangential stiffness coefficient of solid phase
H	initial bed height, m
H_{gap}	gap height, m
I	particle moment of inertia, kg m^2
k	total number of particles in contact with the current one
$k_{n,ij}$	normal stiffness of solid phase, N/m
$k_{t,ij}$	tangential stiffness of solid phase, N/m
m	particle mass, kg
m^*	effective mass of a particle, kg
$\boldsymbol{n}$	normal unit vector between colliding particles
p_f	pressure, Pa
R^*	effective radius of a particle, m
Re_p	particle Reynolds number
$\boldsymbol{S}_p$	momentum sinking item, kg/(m s^2)
$\boldsymbol{S}_{ij}$	deformation tensor of the filtered field or resolved strain rate, 1/s
$S_{n,ij}$, $S_{t,ij}$	normal and tangential damp coefficients
t	time instant, s
$\boldsymbol{T}$	torque on particle, N m
$\boldsymbol{t}$	tangential vector between two colliding particles
t_f	time step of fluid motion, s
t_s	time step of solid motion, s
U_f	gas velocity introduced into RC, m/s
$\boldsymbol{u}_f$	fluid velocity in the computational cell, m/s
U_g	superficial velocity of gas phase, m/s
U_m	gas velocity introduced into HEC, m/s
U_{mf}	minimum fluidization velocity, m/s
$u_{f,i}$, $u_{f,j}$	components of gas velocity, m/s
$\boldsymbol{Us}$	solid velocity, m/s
$\boldsymbol{v}_i$	particle velocity, m/s
$\boldsymbol{v}_{n,ij}$	normal component of relative velocity between colliding pair, m/s
$\boldsymbol{v}_{t,ij}$	tangential component of relative velocity between colliding pair, m/s
V_p	particle volume, m^3
ΔV	volume of the current cell, m^3
x, y, z	coordinate axis
Y_p, Y^*	actual and effective Young modulus

Greek symbols

β_{gs}	inter-phase momentum transfer coefficient, kg/(m^3 s)
$\delta_{n,ij}$	normal displacements between particle i and particle j, m
$\delta_{t,ij}$	tangential displacements between particle i and particle j, m
Δ	sub-grid characteristic length scale, m
Δx, Δy, Δz	mesh size in the x, y and z dimensions, m
ε_f	voidage
ε_p	solid concentration
μ_f	gas dynamic viscosity, kg/(m s)
μ_k	dynamic friction coefficient
μ_s	solid friction coefficient
ρ_f	gas density, kg/m^3
$\boldsymbol{\omega}$	particle angular velocity, 1/s
γ_n	damping coefficient in normal direction, kg/s
γ_t	damping coefficient in tangential direction, kg/s
$\tau_{f,ij}$	viscous stress tensor, Pa
$\tau_{f,ij}^{SGS}$	sub-grid stress tensor, Pa
v	Poisson ratio of solid phase

Operators

$\sim$	filtering operator in LES

Subscripts

c	contact force
d	drag force
f	fluid phase
gs	gas–solid interaction
i	particle i
j	particle j
n	normal component of variable
p	particle phase
t	tangential component of variable

Abbreviations

CFD	computational fluid dynamics
DEM	discrete element method
RC	reaction chamber
HEC	heat exchanging chamber
ICFB	internally circulating fluidized bed
SRT	solid residence time

1. Introduction

The fluidizing apparatus of dense gas–solid flow is frequently adopted in many physical and chemical procedures in the industry due to its easy operation and high gas–solid contacting efficiency [1–4]. Among all the types of fluidizing units, the internally circulating fluidized bed (ICFB) is one of the most promising fluidizing reactors especially when the fast chemical reaction is taken into account. The ICFB is an apparatus with either a centrally located draft tube or a vertically arranged plate to divide its internal domain into two or more chambers for different usages. By introducing different gas flow rates into these different chambers, the internal circulation of solid phase is established in the system. Compared with other fluidizing apparatuses, the ICFB exhibits many favorable advantages in the practical application, such as the reduced height and construction cost, the nice process identification, comparatively small heat loss from the system, high conservation transfer efficiency and a wide range of load control, and so on [5,6]. Thus, it has been utilized in many industrial processes, such as catalytic coal gasification [7,8], the thermal treatment of industrial solid wastes [9,10], desulfurization [11], combustion of liquid bio-fuels [12], biomass pyrolysis and gasification [13,14]. Hence, deeply understanding the hydrodynamics of the ICFB plays an important role in the design and process optimization of the system.

Experimentally investigating the internal gas–solid flow in the ICFB has been conducted by many researchers [14–18]. In addition to the plenty valuable information obtained from the experimental approach, numerical research of the gas–solid hydrodynamics in the dense two-phase flow becomes more and more popular. Compared with the numerical work conducted for the other types of fluidizing apparatuses [19–23], relatively less attention has been