Chemical Engineering and Processing 76 (2014) 6–15

Contents lists available at ScienceDirect

Chemical Engineering and Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep

Simulation and investigation of periodic deflecting oscillation of gas–solid planar opposed jets

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ARTICLE INFO

Article history:
Received 15 June 2013
Received in revised form 31 October 2013
Accepted 15 November 2013
Available online 1 December 2013

Keywords:
Gas–solid planar opposed jets
Two-fluid model
Oscillation
Entropy production rate
Residence-time distribution

ABSTRACT

In this study, the Eulerian–Eulerian approach based on kinetic theory of granular flow (KTGF) was used to simulate the gas–solid planar opposed jets. The periodically deflecting oscillation was observed, i.e., the two opposed jets deflect off each other and swing up and down periodically. The system entropy production rate was calculated to explain this periodic oscillation for the first time. It was found that the periodic deflecting oscillation was dominated by a self-adjusting mechanism of planar opposed jets with the combined action of the pressure release and the entrainment of continuous jets. The effects of nozzle separation, initial jet Reynolds number and particle parameters on the oscillation period were analyzed. The period decreases as the jet Reynolds number or mass loading increases, but increases as the nozzle separation or the particle diameter increases. Furthermore, it is found that the residence time of particles was increased by increasing the mass loading.

1. Introduction

The gas–solid flows exist widely in the industrial processes for which the main concern is how to intensify the inter-phase interaction. The impinging streams (IS) are a specific flow configuration that creates an impingement zone with the high particle concentration and the intensive fluctuation. The relative velocity between particles and the opposed gas jets could be increased obviously, and the residence time of particles in inter-phase interaction zone would be prolonged due to particles reciprocating penetration. In such a way, the inter-phase heat and mass transfer can be strengthened obviously [1,2], which is essential and critical to many chemical engineering processes [3], like the opposed multi-burner gasifier [4] and the reaction injection molding [5].

Recently, many experiments and numerical simulations have been carried out to study the flow regime of simplified IS, i.e., single-phase opposed jets [6–10]. Due to the different geometric structures of nozzles, the flow configuration of the planar opposed jets is obviously different from that of axisymmetric opposed jets [11]. Denshchikov et al. [12,13] found that two opposed jets deflected off each other and swung up and down periodically in a water-filled tank. Li et al. [11,14] investigated the flow regime of single-phase opposed jets by numerous experiments. For planar opposed jets, the deflecting oscillation was always observed when the nozzle separation was larger than 6 [14]. The experimental measurements showed the period of oscillation was closely related to the jets Reynolds number and the nozzle separation [11]. Moreover, the deflecting oscillation was investigated by adopting the acoustic excitation in the experiments [14]. It was found that the oscillation would disappear, if the acoustic excitation amplitude or phase displacement of excitation was changed in some certain ways. So it was inferred that the asymmetric structure of planar opposed jets caused the oscillation. The experimental results suggest that the deflecting oscillation is common for the planar opposed jets. But the experimental investigation is confined to the single-phase opposed jets.

Besides experimental measurements, the numerical simulation is another effective way to investigate the opposed jets. The planar opposed jets are usually considered as a two-dimensional (2D) case, because the width-length ratio of planar nozzles is much less than 1 [15]. It is confirmed that the geometric structure and the exit Reynolds number of jets determine multiple flow regimes including oscillation in a periodic or random way [15–17]. Pawlowski et al. [15] showed the map which displayed how the Reynolds number and the nozzle separation affect the flow regime including the deflecting oscillation. Devahastin and Mujumdar [17] found that the flow began to oscillate more easily when the ratio of the nozzle separation to the width of the inlet jet was larger than 3 for the laminar opposed jets, and showed the change of flow parameters like velocity during the oscillation. The simulation conducted by Hasan and Khan [18] investigated the opposed jets with non-isothermal different fluids numerically. Interestingly, the mixing and heat transfer could be enhanced by oscillation [17–20], which is a promising feature to be utilized in gas–solid flow. In addition,

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http://dx.doi.org/10.1016/j.cep.2013.11.009

Nomenclature

Roman	letters
C_d	a coefficient for drag relation
d_p	particle diameter, μm
e	restitution coefficient of inter-particle collision
e_w	restitution coefficient of collision between particle and wall
g	gravitational acceleration, m s^{-2}
g_0	radial distribution function
H	nozzle height, m
K_{gs}	turbulent interaction between gas and solids phase, J/kg
k	gas phase turbulent energy, m^2 s^{-2}
L	nozzle separation, m
l	length of accelerating section, m
m	solid phase mass loading
P	static pressure, kg m^{-1} s^{-2}
P_s	solids phase pressure, kg m^{-1} s^{-2}
Re_H	Reynolds number based on nozzle height and initial gas velocity
S	total entropy production rate
$\dot{s}$	instantaneous-irreversibility rate
T	oscillation period, s
T_r	reference temperature, (295 K)
U_0	initial gas velocity, m s^{-1}
U_g	time-average of gas X-axial velocity, m s^{-1}
U_s	time-average of gas X-axial velocity, m s^{-1}
V_g	gas phase mean radial velocity, m s^{-1}
V_s	solids phase mean radial velocity, m s^{-1}

Greek letters

α	volume fraction
β	drag coefficient
ε	dissipation rate of gas turbulence
μ	shear viscosity
κ_s	effective conductivity coefficient
ρ	density
τ	characteristic time
τ_g	gas stress tensor
τ_s	solids phase stress tensor
τ_g^t	time scale of gas turbulent eddy
τ_{gs}^F	particle relaxation time
τ_{gs}^t	fluid Lagrangian interal time scale
τ_g^C	time scale of particles collision
λ_s	solids phase bulk viscosity
Θ_s	granular temperature

Subscripts

g	gas phase
s	solids phase

Abbreviations

IS	impinging streams
GPIS	gas–solid impinging streams
KTGF	kinetic theory of granular flow
2-D	two-dimensional
3-D	three-dimensional

the detailed information of flow field can be acquired easily by the numerical simulation, which is helpful to analyze the deflecting oscillation based on the second law of thermal dynamics. For a given dynamic system, its stability is related to its entropy production rate which is always greater than zero [21,22]. Chen and Zheng [23] calculated the total entropy production rate for confined laminar planar opposed jets. The results showed that some peak values of the total entropy generation number emerged, and finally, the values decreased to minimum as the opposed jets developed fully. It means the system entropy production rate could be related to the formation and development of the opposed jets. However, the entropy production rate of large-scale turbulent opposed jets has still not been studied so far.

The numerical simulation is also widely used to study the gas–solid impinging streams (GPIS), because it is much more difficult for experimental measurement to obtain detailed information of the particles in the impingement zone due to the complicated behavoir including impinging and reciprocating pentration [3,24]. There are two classic models for gas–solid flows: Eulerian–Lagrangian (EL) model and Eulerian–Eulerian (EE) model. A simple gas–solid opposed jets was simulated by Kitron et al. [25] and the particle concentration along the axis of jets was in qualitative agreement with experimental measurements by Elperin [2]. Du et al. used Direct Simulation Monte Carlo (DSMC) method to simulate a three-dimensional (3D) reactor [24], which showed particles motion behavior. The opposed multi-burner gasifier was also simulated by the EL method [4,26]. However, the EL model is greatly constrained by the computational cost which sharply increases with the number of simulation particles. For the EE model, both gas and solid phases are considered as continuum and fully interpenetrating. Transport equation and constitution relations are deduced to describe pseudo-fluid properties of solid phase, which are based on the kinetic theory of granular flow (KTGF) [27]. Many dilute and dense gas–solid two-phase flows have been simulated by this method, which saves CPU time effectively in the simulations [28,29]. Nevertheless, there is no simulation to study the deflecting oscillation in gas–solid planar opposed jets, and the effect of the particles on the oscillation still remains unknown.

The main objective of the present work is to investigate the oscillation of large-scale gas–solid planar opposed jets by the numerical simulation. The well-established two-fluid model is adopted using open-source software MFIX [30,31]. MFIX offers well-documented source codes and make it possible to program a desired new model, and has been developed by National Energy Technology Laboratory (NETL). In this paper, we aim to study the oscillation mechanism based on the system entropy production rate and analyze the influence of nozzle separation, exit Reynolds number, and particle parameters on the flow regime. In addition, the residence-time distribution of particles is also discussed.

2. Model description

2.1. Multiphase fluid dynamics modeling framework

Multiphase computational fluid dynamics (CFD) based on the kinetic theory of granular flow is suitable for describing hydrodynamics of gas–solid flows. In the EE method, both gas and solid phase are described with similar governing equations. The gas–solid turbulence model used in the present work was developed by a group led by Simonin et al. [32–34] and has been used by different researchers to study the gas–solid flow [35,36]. The model is summarized in Appendix A. Within this model, the gas turbulence is solved by the modified k–ε model which includes the inter-phase turbulence exchange and the extra dissipation of gas turbulence caused by solids phase (see (Eq. (A.3), Eq. (A.4) and Eq. (A.11))). For solids phase, the particle relaxation time and collision time are combined to formulate the constitution relations (see (Eq. (A.14) and Eq. (A.18))). This approach connects the dilute zone where the main inter-phase mechanism is drag with the dense zone where particle collisions are the dominant mechanism in a harmonic way.