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# Simulations of flow behavior of oscillatory opposed dilute gas–solid jets

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ABSTRACT

Flow behavior of gas and particles by means of oscillatory opposed dilute gas–solid mixture jets is presented in this work. Two opposed jets with high velocities of gas-particles mixture are made to oscillate with the same frequency but with a phase shift of π/2. The two opposed jet dilute gas–solid streams are idealization of an array of oscillating opposed jets. Numerical simulations are performed in 3D chamber. The pressure and viscosity of particles and the drag force between gas phase and solid phase are predicted using a commercial FLUENT code. The realizable k–ε model is used to predict turbulence viscosity of gas phase. Flow behavior of gas and particles is investigated with respect to the oscillation frequency of opposed jets. The computational results show that there is an impingement region in the oscillatory flow jets. The solid volume fraction and turbulence kinetic energy of gas phase are high and a stagnation point occurs in the impingement zone. It is shown that the periodic velocities of gas and particles of the opposed jet lead to the horizontal reciprocating movement of impingement zone. The stagnation point with two times frequency of opposed jets oscillates along horizontal reciprocating movement. Further, the analysis shows the large velocities of gas and particles and solid volume fraction in the impingement zone decreases with the increase of frequency of opposed jets. The study shows that low frequency is effective to improve momentum transfer between two opposed jets.



## 1. Introduction

Coal gasification offers one of the most versatile and cleaning ways to convert coal into hydrogen and other valuable energy products. The entrained flow coal gasification has widely found commercial applications for the production of coal-based chemicals such as methanol, ammonia and hydrogen [1]. Generally speaking, the entrained flow coal gasifier is divided into three regions, a combustion region (combustor) in the first or the lower stage, a reduction region in the second or the upper stage, and a diffuser section connecting the combustion section and the reduction section. At both the combustion and the reduction regions, the injectors are placed to form opposite impinging streams or tangential jets. In the opposite impinging system, the gas-particle two-phase impinging coaxial-jets are to send gas-particle streams to impinge against each other at high velocity on the same axis. It is an effective method to enhance mixing between gas phase and particles due to intense turbulence and continuous impingement mixing [2]. Therefore, the gas–solid impinging streams possess promising applications in various industrial processes, such as mixing [1], granulation [3] and combustion of fuels [4–7]. Furthermore, there has been a great deal of interest in fundamental study on the flow characteristic and heat and mass transfer of the gas–solid impinging streams, such as residence time distribution of particles [8], volumetric heat and mass transfer coefficients [9]. However, due to the complicated flow behaviors and interactions, limited numerical studies have been conducted to provide the precise analysis of detailed flow characteristic and particle dynamics involved in the gas–solid impinging streams.

The numerical simulation is widely used to study the gas–solid impinging streams, because it is much more difficult for experimental measurement to obtain detailed information of the particles in the impingement zone due to the complicated behavior including impinging and penetration [1]. Gas–solid flows have been numerically investigated by various multiphase models. The Eulerian–Eulerian two-fluid model (TFM) treats both gas and solid phase as interpenetrating continua and the constitutive relations for solid phase are usually closed using kinetic theory of granular flow (KTGF) [10]. Hongpeng Xu et al. [11] found that the periodically deflecting oscillation was observed, i.e., the two opposed jets deflect off each other and swing up and down periodically by means of two-fluid model with KTGF in the gas–solid planar opposed jets. Simulations showed 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. Furthermore, it was found that the residence time of particles was increased by increasing the mass loading. Xizhong Chen et al. [12] investigated the flow patterns of two impinging gas-particle jets in a channel using three multiphase models of TFM method and dense discrete particle model (DDPM) method. Both TFM and DDPM successfully reproduced the main features of impinging flow at some cases.

In the impinging streams with opposed jets, two opposite gas-particle mixture streams enter the chamber. These two streams contact with each other in the central region of the chamber, leading to the formation of an impingement zone where the local solid volume fraction is high. The position of the impingement zone is fixed due to the great

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impact force caused by violent impinging. The drawbacks of stagnant impingement zone have been highlighted due to the reduction of mixing. The oscillatory opposed jets improve mixing at the stagnant impingement zone due to the change of the position of impingement zone. The periodic oscillations of the impingement zone result in varying local mass and heat transfer coefficients. Comparing with the steady impinging streams with opposed jets, it is expected that the oscillatory opposed jets will change flow behavior due to the continuous oscillation of the impingement zone. The objective of this study is to simulate the hydrodynamics of gas and particles with oscillatory opposed dilute gas–solid jets in a chamber. The effect of amplitudes and frequencies of opposed jets on the impingement zone is analyzed.

## 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. Both gas phase and solid phase are described with similar governing equations. The two-fluid model consists of balance equations for mass and momentum of gas phase and particle phase. The continuity balances of gas phase and particle phase without chemical reactions are [10,13]

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\right)+\frac{\partial}{\partial x_i}\left(\alpha_g\rho_g u_{gi}\right)=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_s\rho_s)+\frac{\partial}{\partial x_i}(\alpha_s\rho_s u_{si})=0 \tag{2}$$

where $\rho_s$ and $\rho_g$ denote the densities of particles and gas phase. $u_s$ and $u_g$ are the velocity of particles and gas phase. $\alpha_s$ and $\alpha_g$ are the volume fractions of particles and gas phases (which add up to unity).

The momentum balances of gas phase and particle phase without chemical reactions are [10,13]

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g u_{gi}\right)+\frac{\partial}{\partial x_j}\left(\alpha_g\rho_g u_{gi}u_{gj}\right)=-\alpha_g\frac{\partial p_g}{\partial x_i}+\alpha_g\rho_g g_i+\beta_{gs}(u_{si}-u_{gi})+\frac{\partial\tau_{gij}}{\partial x_j} \tag{3}$$

$$\frac{\partial}{\partial t}(\alpha_s\rho_s u_{si})+\frac{\partial}{\partial x_j}(\alpha_s\rho_s u_{si}u_{sj})=-\alpha_s\frac{\partial p_g}{\partial x_i}+\frac{\partial p_s}{\partial x_i}+\frac{\partial}{\partial x_j}\tau_{sij}+\alpha_s\rho_s g_i+\beta_{gs}(u_{gi}-u_{si}) \tag{4}$$

where g is the gravitational acceleration, and $\beta_{gs}$ is the drag coefficient. $\tau_s$ and $\tau_g$ are the stress tensors of particles and gas phase. The stress tensor of gas phase is calculated by a Newtonian-type approximation with an effective viscosity which sums of the laminar viscosity and turbulent viscosity of gas.

$$\tau_{gij}=\mu_e\left[\left(\frac{\partial u_{gi}}{\partial x_j}+\frac{\partial u_{gj}}{\partial x_i}\right)-\frac{2}{3}\frac{\partial u_{gk}}{\partial x_{ik}}\delta_{ij}\right] \tag{5}$$

The turbulent (or eddy) viscosity was calculated by means of the realizable k–ε model [14] in the impinging flow. The turbulence kinetic energy, $k_g$, and its rate of dissipation, $\varepsilon_g$, are obtained from the following transport equations:

$$\frac{\partial(\rho_g\alpha_g k_g)}{\partial t}+\frac{\partial(\rho_g\alpha_g k_g u_{gj})}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\frac{\alpha_g\mu_t}{\sigma_1}\frac{\partial k_g}{\partial x_j}\right]+\alpha_g G_k-\alpha_g\rho_g\varepsilon_g+\alpha_g\rho_g\Pi_{k_g} \tag{6}$$

$$\frac{\partial(\rho_g\alpha_g\varepsilon_g)}{\partial t}+\frac{\partial(\rho_g\alpha_g\varepsilon_g u_{gj})}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\alpha_g\frac{\mu_t}{\sigma_2}\frac{\partial\varepsilon_g}{\partial x_j}\right]+\alpha_g\frac{\varepsilon_g}{k_g}(C_1G_k\text{-}C_2\rho_g\varepsilon_g)+\alpha_g\rho_g\Pi_{\varepsilon_g} \tag{7}$$

where $G_k$ represents the generation of turbulence kinetic energy due to the mean velocity gradients,$\prod_{kg}$ and $\prod_{\varepsilon g}$ represent the influence of the solids phase on the gas phase, $C_1$ and $C_2$ are constants, and $\sigma_1$ and $\sigma_2$ are the turbulent Prandtl numbers for $k_g$ and $\varepsilon_g$, respectively.

$\prod_{kg}$ and $\prod_{\varepsilon g}$ are addressed as follows [13]

$$\Pi_{k_g}=\frac{\beta_{gs}}{\rho_g\alpha_g}\left[k_{gs}-2k_g+(\mathbf{u_s}-\mathbf{u_g})\mathbf{u_{dr}}\right] \tag{8}$$

$$\Pi_{\varepsilon_g}=C_3\frac{\varepsilon_g}{k_g}\Pi_{k_g} \tag{9}$$

where $k_{gs}$ is the turbulent kinetic energy of the solid and gas phase, $\mathbf{u}_{dr}$ is the drift velocity, and $C_3$ is constant.

For particle phase, the stress tensor is expressed as a function of viscosity as follows [10,13]

$$\tau_{sij}=\frac{1}{3}\mu_b\frac{\partial u_{sk}}{\partial x_{ik}}\delta_{ij}+\mu_s\left[\left(\frac{\partial u_{si}}{\partial x_j}+\frac{\partial u_{sj}}{\partial x_i}\right)-\frac{2}{3}\frac{\partial u_{sk}}{\partial x_{ik}}\delta_{ij}\right] \tag{10}$$

where the shear viscosity and bulk viscosity of particles phase are

$$\mu_s=\frac{4}{5}\alpha_s^2\rho_s d g_o(1+e)\sqrt{\frac{\theta}{\pi}}+\frac{10\rho_s d\sqrt{\pi\theta}}{96(1+e)\alpha_s g_o}\left[1+\frac{4}{5}g_o\alpha_s(1+e)\right]^2 \tag{11}$$

$$\mu_b=\frac{4}{3}\alpha_s^2\rho_s d g_o(1+e)\sqrt{\frac{\theta}{\pi}}. \tag{12}$$

The solid pressure is a function of solid volume fraction, and expressed by

$$p_s=\alpha_s\rho_s\theta[1+2g_o\alpha_s(1+e)] \tag{13}$$

where $\theta=<\mathbf{c}^2>/3$ is the granular temperature, where $\mathbf{c}$ is the particle fluctuating velocity. The granular temperature is computed by solving a fluctuating kinetic energy equation for the particles in addition to the mass and momentum conservation equations for the solid phase [10]. The equation of conservation of solids fluctuating energy is expressed by

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\alpha_s\rho_s\theta)+\frac{\partial}{\partial x_j}(\alpha_s\rho_s\theta)u_{sj}\right]=\Pi_{ij}\frac{\partial u_{sj}}{\partial x_i}+\frac{\partial}{\partial x_i}\left(k_s\frac{\partial\theta}{\partial x_i}\right)-\gamma_s+\phi_s+D_{gs} \tag{14}$$

where $\Pi$ is the effective solid stress tensor. The thermal conductivity of particles is

$$k_s=\frac{75\rho_s d^s\sqrt{\pi\theta}}{384(1+e)g_o\alpha_s}\left[1+\frac{6}{5}(1+e)g_o\alpha_s\right]^2+2\rho_s d^s g_o(1+e)\alpha_s^2\sqrt{\frac{\theta}{\pi}}. \tag{15}$$

From kinetic theory of granular flow, particles are assumed to be slightly inelastic and smooth spheres, the dissipation fluctuating energy only comes from binary inelastic collisions, what means fluctuation energy is dissipated during a collision of particles [10].

$$\gamma_s=3(1-e^2)\alpha_s^2\rho_s g_o\theta\left(\frac{4}{\sigma}\sqrt{\frac{\theta}{\pi}}-\nabla\cdot u_s\right). \tag{16}$$

The net fluctuation energy exchange between the gas and solids with

$$\phi_s=-3\beta_{gs}\theta \tag{17}$$