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Penetration, accumulation, and swing characteristics of particle cloud in a turbulent axisymmetric opposed-jet flow

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ABSTRACT

The behavior of particle cloud in a high Reynolds number (13500) turbulent opposed-jet flow with a moderate nozzle separation (12 times the nozzle diameter) is investigated by a two-phase large eddy simulation. Euler/Lagrangian approaches are applied to simulate gas and particle phases, respectively. Two-way coupling is considered, and a deterministic hard-sphere collision model is used to deal with the interparticle collision. Three particle Stokes numbers (8, 37, and 180) and three particle volume fractions (2×10^{-5}, 1.5×10^{-4}, and 4.8×10^{-3}) are tested. Particle inertia and interparticle collisions are found to exert a significant effect on particle distribution and velocity characteristics, a strong interaction is observed between particle cloud and gas impingement plane. Particle inertia strengthens the penetration of particles in the opposite stream, thus widening the particle aggregation region and decreasing the peak value of particle concentration. The mixing of rightward- and leftward-moving particles in the particle penetration distance noticeably decreases the particle axial mean velocity and increases the particle axial fluctuation velocity. Furthermore, interparticle collisions suppress the reciprocating penetration of particles in the opposed jets and force the particles to accumulate near the impingement plane. Meanwhile, interparticle collisions increase the particle radial mean and radial fluctuation velocities by energy transfer from the axial direction to the radial direction. The unstable gas impingement plane can drive the swing of particle aggregation region, especially for the small inertia particles and massive interparticle collisions. By contrast, the particle cloud can enhance the stability of gas impingement plane, which significantly reduces the gas velocity fluctuation in the impinging region.

1. Introduction

Particle-laden turbulent opposed-jet (PTOJ) flow is a unique flow configuration formed by two gas-particle streams impinging against each other on the same axis and creating an impingement region with intense turbulence and great particle concentration. High turbulence kinetic energy (TKE) and large relative velocity between gas and particle phases significantly intensify the interphase heat and mass transfer in the impingement region. Therefore, the particle-laden turbulent opposed jets have been frequently encountered in a variety of chemical processes, such as coal combustion [1], coal gasification [2], solid particle drying [3], and others.

The single-phase opposed-jet flow has been widely studied in the previous years. Several studies focused on the turbulence characteristics of opposed jets. Different turbulent generation plates were used in closely spaced ($L/d < 2$, where L is the nozzle separation and d is the nozzle diameter) opposed jets to generate high TKE in the impingement region [4–6]. Stan and Johnson [7] conducted a detailed study on the turbulence statistics of unconfined opposed jets at larger nozzle separation with $5 < L/d < 20$ by using both particle image velocimetry (PIV) and laser Doppler velocimetry (LDV). Icardi et al. [8] investigated the flow characteristics in confined impinging jet reactors (CIJR) by means of PIV technology and obtained both mean and fluctuation velocity fields. Recently, Li et al. [9] experimentally investigated the flow characteristics in gas particle two-phase opposed jets ($L/d = 12$) by means of a simultaneous two-phase PIV technique. The presence of the particles can distinctly modify the gas-phase characteristics, including both macroscopic turbulence statistics and mesoscopic turbulence structures.

Another research hotspot is the instability feature of the impingement plane in opposed-jet flow. A bifurcation phenomenon in laminar opposed jets (LOJ) with a small nozzle separation was observed by Rolon et al. [10]. The impingement plane may become equally displaced from the geometric centerline in either axial direction. This phenomenon is further studied by Pawlowski et al. [11] and Ciani et al. [12], and the critical Reynolds number (Re) at which this phenomenon occurs was also identified. For turbulent opposed jets (TOJ), Coppola et al. [4] applied proper orthogonal decomposition (POD) method to analyze the flow

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List of symbols

c_s	speed of sound
d	nozzle diameter
d_p	particle diameter
e	restitution coefficient
f_{pi}	summed backward force of particles on the fluid
k	resolved turbulent kinetic energy
k_g	turbulent kinetic energy of the gas-phase
k_{sgs}	SGS turbulent kinetic energy
l_e	length scale of the SGS vortices
n	mean particle number density
n_0	mean particle number density at the nozzle outlet
u	gas velocity
u_{prms}	axial velocity fluctuation of particle
$\tilde{u}_p$	relative velocity between particle and SGS vortices
u_g	instantaneous axial velocity of the gas-phase at the middle point
u_g'	axial velocity fluctuation of the gas-phase at the middle point
u_p	instantaneous velocity of the particle-phase
u_r	relative velocity between particle and gas
v	particle velocity
v_{prms}	radial velocity fluctuation of particle
x_{stag}	axial position of the gas impingement plane
C_{sg}	Smagorinsky constant
CIC	cloud in cell
L	nozzle separation distance
LOJ	laminar opposed jets
Ma	Mach number
MPD	maximum penetration distance
Nc	particle collision rate
P	gas pressure
Re	Reynolds number
Re_p	particle Reynolds number
R_p	particle injection rate
S	gas strain tensor
SGS	subgrid stress
St	particle Stokes number
St_m	modified particle Stokes number
TOJ	turbulent opposed jets
TSC	triangular shaped cloud
TKE	turbulent kinetic energy
U_0	maximum velocity of the gas-phase at nozzle outlet
U_b	bulk velocity of the gas-phase at nozzle outlet
U_g	time-averaged axial velocity of the gas-phase
U_p	time-averaged axial velocity of the particle-phase
V_p	time-averaged radial velocity of the particle-phase
μ_f	friction coefficient
ρ	gas density
ρ_c	correlation coefficient of the instantaneous velocities of two phases at the middle point
ρ_p	particle material density
τ_{sgs}	sub-grid stress
τ_g	fluid characteristic timescale
τ_p	particle characteristic timescale
τ_{rp}	particle aerodynamic timescale
τ_e	eddy lifetime
τ_c	eddy crossing time
ν	gas kinetic viscosity
ϕ_v	particle volume fraction at nozzle outlet
ϕ_m	particle mass loading ratio at nozzle outlet

field of closely spaced TOJ and found that the first mode corresponds to the axial oscillation, whereas the second mode corresponds to a precession motion about the nozzle centerline. Li et al. [13,14] used a flow visualization method and hot-wire anemometry to study the factors influencing the offset of the stagnation point, including *L*, *Re*, and exit velocity ratio of the opposed jets. Then, the flow regimes based on *L*/*d* and *Re* for axisymmetric and planar opposed jets are given. In addition, they studied the modification of flow pattern, in which a forced excitation is imposed on the nozzle outlets, and found that the stagnation plane responds differently according to the various inlet conditions [15,16].

Compared with the continuously increasing number of studies on single-phase opposed jets, the studies on the particle motion in two-phase opposed jets are still limited. Several studies on single-particle behavior mainly focused on the reciprocating penetration of the particle in the opposed jets. Hosseinalipour et al. [17] conducted a detailed study on particle penetration distance, particle residence time, and interphase heat transfer in an impinging stream dryer. In our previous work [18], the maximum penetration distance (MPD) of particles in a LOJ flow was studied by means of numerical simulation, and then a fitting formula was proposed. Moreover, several productive works have been carried out on the multi-particle system (such as particle cloud) in the TOJ flow. Elperin et al. [19] conducted a theoretical analysis of the relationship between collision frequency and particle concentration and found that interparticle collision can be neglected when the particle volume fraction is $<10^{-4}$.

Recently, discrete particle method (DPM) has been used in the simulation of particle motion in TOJ. Li et al. [20,21] and Ni et al. [22] studied the particle behavior in opposed multi-burner coal gasifiers. Thereafter, RANS turbulence model was used to obtain the mean flow fields, whereas direct simulation Monte Carlo method was used to deal with the interparticle collisions and coagulations. A similar method was adopted and modified by Du et al. [23] to study the particle behavior in a gas–particle two-phase impinging stream (GPIS). Despite the method based on the RANS model significantly reducing the computational cost, the unstable gas stagnation plane cannot be captured, thus significantly affecting the particle motion in TOJ flow. Therefore, a high-fidelity simulation, such as direct numerical simulation (DNS) or large eddy simulation (LES), should be used to obtain the unsteady flow field of the TOJ. Recently, Sun et al. [24] combined the LES and DPM methods to simulate the gas–particle axisymmetric TOJ flow, but interparticle collisions, as well as the interaction between particle cloud and impingement plane, were not considered.

Besides the above-mentioned investigations, the effects of particle inertia and interparticle collision on the behavior of particle cloud in opposed jets flow are not thoroughly understood. Furthermore, the interaction between particle cloud and unstable impingement plane, which is of theoretical and practical significance for the actual chemical engineering processes, has yet to be addressed.

In view of this, a LES considering two-way coupling, which is used to capture the modulation of unstable impingement plane, and a deterministic hard-sphere particle collision model were adopted in the present work. Given that the dynamic behavior of the stagnation plane in an axisymmetric TOJ flow has been previously studied in detail [25], the present paper focuses only on the particle motion characteristics in TOJ flow for simplicity. First, the effect of sub-grid scale (SGS) vortices on particle motion was examined, and two grid resolutions were performed to check for grid independence. Then, quantitative statistical characteristics of particle motion, including particle concentration, particle mean velocity, and particle fluctuation velocity, were provided to study the effects of particle inertia and interparticle collisions on the behavior of particle cloud. Finally, the interaction between particle cloud and the gas stagnation plane was also addressed in the context of the velocity correlation between gas and particle phases as well as the position and velocity distributions of the unstable impingement plane.