Powder Technology 336 (2018) 199–209

Contents lists available at ScienceDirect

Powder Technology

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

DEM study of liquid-like granular film from granular jet impact

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ARTICLE INFO

Article history:
Received 26 January 2018
Received in revised form 17 May 2018
Accepted 23 May 2018
Available online 26 May 2018

Keywords:
Dense granular jet
Jet impact
Liquid-like granular film
Discrete element method
Collision dynamic

ABSTRACT

Dynamic behaviors of a dense granular jet impacting on a circular target are numerically studied by Discrete Element Method (DEM), and the simulation results are compared with experimental data in our previous paper. Firstly, effects of solid fractions of granular jet (x_p) and ratios of jet diameter to particle diameter (D/d) on the flow pattern of granular jet impact are investigated. Results show that increasing x_p and D/d both increase the interparticle collision frequencies, which decrease the interparticle collision forces and relative velocities, and give rise to the liquid-like granular film, consequently. Secondly, liquid-like wave structures on the granular film are simulated by a granular jet impact with pulsation. Results indicate that the granular wave is primarily determined by the pulsation amplitude and Strouhal number (St) of granular jets. The granular jet impact with pulsation displays distinct wave structures as the optimal St is in the range of 0.2–0.8

1. Introduction

Granular material impact is important for geological phenomena such as the craters [1,2] as well as industrial applications such as the ink-jet printing [3], blast cleaning [4], impinging jet milling [5], and abrasive finishing [6]. Although granular materials are cohesionless, it is interesting to observe that a dense granular jet impacting perpendicularly on a circular target will give rise to a radially propagating thin granular film [7,8], which resembles a thin liquid film from liquid jet impact [9–13]. This liquid-like granular film is attracting increasing attention of many researchers over the years [7,8,14–22].

Until now, many efforts have been made to address the underlying mechanisms of the granular film and their influencing factors by means of experiments and numerical simulations. Cheng et al. [7,14] experimentally investigated the dynamic behavior of granular jet impact, and found that the opening angle of the granular film quantitatively agrees with that of the liquid film. Their results indicate that as the ratio of granular jet diameter to particle diameter (D/d) decreases, the granular film will change to a diffuse pattern. Furthermore, results in our recent experimental study of granular jet impact show that, besides D/d, the formation of the granular film is also determined by the solid fraction of granular jet [8]. Ellowitz et al. [15] demonstrated the internal flow characteristic of the granular film by capturing the granular motion in a cross-section. A dead zone with very small particle velocity over the target is identified, which is absent for the liquid film. Recently, interesting liquid-like wave structures were first captured on the granular film as the granular jet was unstable [16]. It should be pointed out that due to the limitation of experimental technology, some important collision-level information during the impact process and the relation between the wave structure and disturbed granular jet are difficult to characterize.

In recent years, discrete element method (DEM) has become an important method for the research of granular jet impact, as it resolves collisions and can obtain some key features of particle dynamic. Huang et al. [17] used two-dimensional DEM to simulate the flow of granular jet impact, and found that the opening angle of the granular film is affected by the granular jet diameter, particle diameter, and coefficient of restitution. Guttenberg [18] performed two-dimensional simulation of granular jet impact by a hard-sphere model, and demonstrated that a dead zone over the target was observed depending on the frictional interaction between the particles and target. Simulation results of Ellowitz et al. [15] verify the dead zone on the frictional target, and show that the surface structure and roughness of the target have insignificant effects on the opening angle. Sano and Hayakawa [19,20] performed three-dimensional DEM to further study the pressure and shear viscosity of the granular flow after impingement, and suggested that the impact process is strongly nonequilibrium. Later, Müller et al. [21] numerically investigated the three-dimensional granular jet impact by a hard-sphere model, and effects of the particle diameter, coefficients of restitution and friction, target size, and solid fraction of the granular jet on the opening angle were analyzed in detail and the granular dynamics were compared with the ideal fluid flow. Recently, Su et al. [22] conducted DEM simulations of granular jet impact using elliptical particles, and found that the dead zone enlarges and the fluctuation of particle

Abbreviation: CFD, Computational Fluid Dynamics; DEM, Discrete Element Method.

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https://doi.org/10.1016/j.powtec.2018.05.044
0032-5910/

velocity in the zone decreases. It can be seen from above simulation results that various factors influencing the opening angle and flow characteristic of the granular film have been studied, while the collision-level information of granular jet impact and especially the wave structure on the granular film have not been clearly revealed yet.

Motivated by the contribution of above investigations, dense granular jets impacting on a circular target are numerically studied by DEM in this article. Firstly, the model parameters and simulation results are validated by the experimental data in our previous studies [8,16]. Then, the collision-level information such as the collision frequency and force distributions at different ratios of jet diameter to particle diameter and solid fractions is obtained to understand the underlying mechanism of the granular film. Especially, liquid-like wave structures on the granular film are also simulated by DEM, and detailed effects of the exit pulsations of granular jets on the granular wave are investigated.

2. Methodology

In current study, dense granular jet impacts were simulated via three-dimensional DEM (EDEM, version 2.7). The dynamics of each particle were obtained by solving Newton's motion laws in the Lagrangian framework [23]. The soft-sphere contact model of Hertz-Mindlin (no slip), which is based on the theory of Hertz [24] and Mindlin [25,26], was applied to deal with the collisions. The damping and stiffness components in the contact model were adopted as described by Tsuji et al. [27], and the damping and stiffness coefficients were related to the coefficient of restitution, shear modulus, and Poisson's ratio for given particle properties. Detailed descriptions on this modeling scheme and numerical equations can be found in precursor's works [28–31]. A proper time step is key for the accurate and efficient calculation. As the energy of interparticle collision procedure is transferred by the Rayleigh waves [28,29,32], the calculation time step should be smaller than the Rayleigh time step, i.e. the time taken for a shear wave to propagate through a solid particle and is estimated by [28,32].

$$T_R = \pi R \left(\frac{\rho_p}{G}\right)^{\frac{1}{2}} / (0.1631\nu + 0.8766) \quad (1)$$

where R is the particle radius, ρ_p is the particle density, G is the shear modulus of the particle, and ν is the Poisson's ratio of the particle. On the other hand, a too smaller time step is very time-consuming. Here, a proper time step (t_s) of $0.2T_R$ was used [29], which was small enough to resolve the interparticle collision procedure and make calculation stable. The spatial resolution (l_c) for the detection of collisions was $2R$ within the available memory allocation of the computer. In particular, the option of Track Collisions was enabled to record the number and forces of collisions between particles.

The geometric parameters of the granular jet in the DEM simulation were set according to experiments. For the experiments, the particle was spherical glass bead, and the granular jet impinged on a circular and flat plexiglass target below the jet exit. The detailed experimental setup and method can be found in our recent work [8,16]. Fig. 1 shows the sketch of simulation configurations. The original point o of the coordinate system is located at the center of the target surface, and r and z represent the radial and vertical directions, respectively. The normalized impact separation from the jet exit to the target surface (L/D) was 2.5. The normalized diameter of the target (d_t/D) was 2.5. In this work, the material parameters of the particle were taken according to the properties of glass bead used in the experiments. The typical value of restitution coefficient of the glass bead is 0.8 [7,17]. The static friction coefficient of the glass bead measured by FT4 Powder Rheometer is 0.435. As considering the glass bead is spherical and smooth, it is proper to set the rolling friction coefficient as 0.01. Details of the material and model parameters adopted are listed in Table 1, and a summary of simulation conditions is listed in Table 2. The exit solid volume fraction (x_p) of the granular jet is defined as

$$x_p = \frac{2Q_0 d^3}{3u_0 D^2} \quad (2)$$

where Q_0 is the exit flow rate of the particle number in the granular jet, d is the particle diameter, D is the diameter of the granular jet, and u_0 is the exit velocity of the granular jet. The flow of granular jet impact has rotational symmetry about z-axis, and the time-averaged interparticle collision-level information such as frequency and force was analyzed in a region across the radial central section, as marked in Fig. 1, which was composed by cubic grid cells with equal normalized lengths (l_a/d) of 2 and total number of 1 × 28 × 28.

It should be noted that the DEM simulations were gas-free. The granular jet impact is collision-dominated flow and the particle is about 2066 times the momentum of air at identical velocity in atmospheric pressure, so the gas can be neglected [17–22]. In addition, interparticle cohesive forces such as van der Waals and electrostatic forces, which are nearly zero [7], were not considered. Small amount of particle velocity fluctuation in the jet exit, which has been demonstrated to play an insignificant role in the flow pattern and particle dynamic of granular jet impact, was also not considered [21].

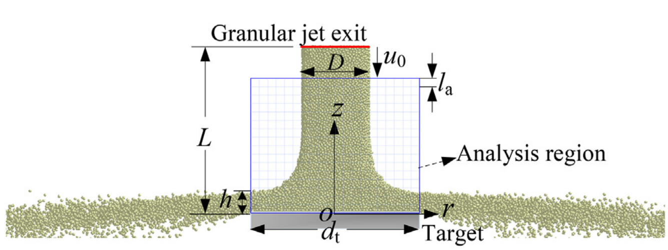

Fig. 1. Sketch of simulation configurations.

Table 1
Summary of material and model parameters for simulation.

Properties	Values
Densities of the particle, target (kg/m^3)	2490, 1200
Poisson's ratios of the particle, target	0.25, 0.35
Shear modulus of the particle, target (Pa)	2.2×10^{10},
Gravitational acceleration (m/s^2)	1.1×10^9
Restitution coefficients of particle-particle, particle-target collision	9.8
Static friction coefficients of particle-particle, particle-target	0.8, 0.8
Rolling friction coefficients of particle-particle, particle-target	0.435, 0.5
Normalized time step (t_s/T_R)	0.01, 0.01
Normalized spatial resolution for the detection of collisions (l_c/R)	0.2
Data save interval (s)	2
	5×10^{-5}

Table 2
Summary of conditions and parameters for simulation.

Items	Values
Particle diameter (μm)	350, 82
Granular jet diameter (mm)	1.0–12.0
Normalized impact separation (L/D)	2.5
Normalized diameter of the target (d_t/D)	2.5
Exit granular jet velocity (m/s)	0.8–16.0
Exit solid volume fraction of granular jets	0.05–0.58