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Liquid-like granular film from granular jet impact

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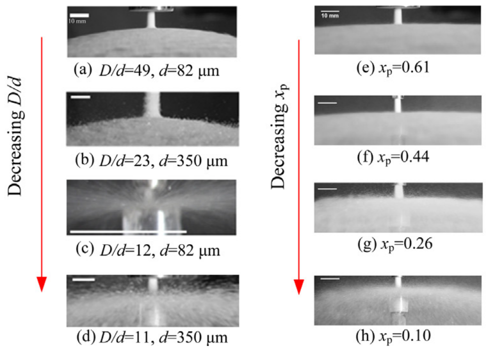
HIGHLIGHTS

- The granular film and the diffuse pattern from granular jet impact are identified.
- A new method of changing solid content ratio is used to modulate the flow patterns.
- The solid content ratio is a key factor to the regimes of granular jet impact.
- The circular motion of particles is important for the formation of the granular film.

GRAPHICAL ABSTRACT



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ABSTRACT

Dynamic behaviors of dense granular jets impacting a flat target are experimentally studied and numerically simulated using the Discrete Element Method. Effects of the granular jet velocity ($u_0 \leqslant 6.5$ m/s), the particle diameter ($82 \leqslant d \leqslant 350$ μm), the jet diameter ($1 \leqslant D \leqslant 12$ mm), and the volumetric solid content ratio of the granular jet ($0.05 \leqslant x_p < 0.62$) on the flow patterns are investigated. Two patterns were identified: the thin, liquid-like granular film and the diffuse pattern. The profile and thickness of granular films have been characterized. The transition critical parameters and maps of the two patterns are obtained in this work. Results show that the regimes of the granular jet impact are primarily determined by the ratio of jet diameter to particle diameter (D/d) and solid content ratio (x_p). A compacted dead zone over the target forms with large D/d and x_p, which subsequently causes rapid interparticle inelastic collisions and circular motion of the granular film.

1. Introduction

Numerous natural phenomena such as landslides, avalanches, and debris flows as well as industrial processes such as fluidization (Ge et al., 2007; Verma et al., 2013) and particle transport (Lu et al., 2012; Cong et al., 2013) are associated with granular flows. In the last two decades, granular flows have become a frontier within the field of fluid mechanics, physics, and rheology. Though granular materials are cohesionless and highly dissipative, dynamic phenomena such as the free surface wave (Conway et al., 2003), shear instability (Goldfarb et al., 2002), and Rayleigh-Plateau instability (Prado et al., 2011) have been observed in dense granular flows. These granular collective behaviors, which closely resemble the dynamic phenomena observed in classical liquids, are called liquid-like behaviors. Granular jet impacts are important for many industrial applications such as the pulverized coal gasifier, ink-jet printing, impinging jet grinding, and blast cleaning, and have attracted considerable attention in recent years (Boudet et al., 2004, 2007; Cheng et al., 2007, 2014; Huang et al., 2010; Johnson

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Nomenclature

Roman letters

a	ratio of the particle velocity at the edge of the target to exit granular jet velocity
d	particle diameter [μm]
d_t	target diameter [mm]
D	granular jet diameter [mm]
F_c	centripetal force [N]
g	gravity [m/s^2]
h	thickness of the granular film [mm]
L	impact separation [mm]
m_p	bulk mass flow rate [kg/s]
P	air pressure [Pa]
R	curvature radius [m]
u_0	exit granular jet velocity [m/s]
u_t	particle velocity at the edge of the target [m/s]
x, y, z	three dimensional coordinates
x_p	volumetric solid content ratio of the granular jet
x_{pt}	volumetric solid content ratio of the granular film at the edge of the target

Greek letters

ρ_p	glass bead density, kg/m^3

Abbreviation

DEM	discrete element modeling

and Gray, 2011; Guttenberg, 2012; Sano and Hayakawa, 2012, 2013; Ellowitz et al., 2013).

When a liquid jet impinges on a circular target at normal incidence, a water bell (Clanet, 2000, 2001) or thin liquid sheet (Clanet and Villermaux, 2002; Villermaux and Clanet, 2002) will appear. Generally, when some particles collide with a smooth wall they will rebound and be back-scattered. However, a liquid-like granular cone or sheet has also been observed when a dense cohesionless granular jet impacts a circular target (Cheng et al., 2007, 2014; Ellowitz et al., 2013).

The flow dynamics of liquid jets impinging on a circular target has been studied (Clanet, 2000, 2001; Clanet and Villermaux, 2002; Villermaux and Clanet, 2002; Bremond et al., 2007; Bhagat and Wilson, 2016). In addition, the liquid-like behaviors of dense granular jets such as the clustering instability (Möbius, 2006; Royer et al., 2009), capillary waves (Amarouchene et al., 2008; Luu et al., 2013), oscillating instabilities (Liu et al., 2012; Fang et al., 2016), and bubble formations (Lu et al., 2013, 2014) have been intensively investigated. Despite previous research, experimental studies on liquid-like granular sheets from granular jet impact are rare.

Cheng et al. (2007) experimentally investigated the liquid-like granular cone or sheet, and found the opening angle quantitatively agrees with that of the water bell. Their results also indicate that the granular sheet gradually changes to a diffuse spray pattern as the number of particles in the jet decreases. They also found that the particle material and surface roughness, the pushing gas property, and the experimental ambient pressure have little effect on the flow patterns of granular jet impact. Later, they demonstrated the anisotropic characteristic of granular sheets by performing granular jet impacts with noncircular cross sections (Cheng et al., 2014). Their results imply that the solid content ratio of the granular jet plays an important role in the granular sheet (Cheng et al., 2007, 2014). Huang et al. (2010) used the discrete element modeling (DEM) to simulate the granular jet impact and found that the opening angle of the conical granular sheet is influenced by the particle diameter, jet diameter, and coefficient of restitution. Guttenberg (2012) applied a hard-sphere model to simulate the granular sheet, and found that the opening angle is determined by dissipation of energy during the impact process. Ellowitz et al. (2013) used an experimental method similar to Cheng et al. (2007) along with simulation to study granular jet impact. Their results show that a large dead zone forms over the target and that the surface structure and roughness of the target play an insignificant role in the opening angle. Above investigations have suggested that the liquid-like behavior of granular jet impact primarily results from the rapid particle collisions during impact of the target. Until now, the detailed effects of the solid content ratio of the granular jet and the impact region on formation of the granular sheet have not been determined.

Several researchers have investigated the dynamic behavior of dense granular jets impinging on a large plane. Boudet et al. (2004, 2007) experimentally studied the dynamics of a granular jet impinging on a large horizontal plane. This work showed that a thin granular sheet forms and then quickly evolves to a thicker sheet with ripples due to granular deposit and jump as a result of the surface friction. They called this phenomenon the granular jump, which is similar to the hydraulic jump of liquid jet impact (Bush and Aristoff, 2003). Johnson and Gray (2011) investigated the granular jump of a granular jet impinging on a large inclined plane. Various flow patterns were characterized in detail, such as steady hydraulic jumps and periodic avalanches. It should be noted that due to the different size of impact surface and granular jet velocities, the mechanism of the granular jump is intrinsically different with the granular sheet. The granular jump mainly results from a reduction and deposition in surface flow due to surface friction, while the granular sheet may be primarily developed due to rapid particle collisions during the impact of the granular jet on the target.

It can be seen from above researches that though the dynamics of the granular cone and sheet have been investigated, study on the influencing factors and underlying mechanisms of the liquid-like

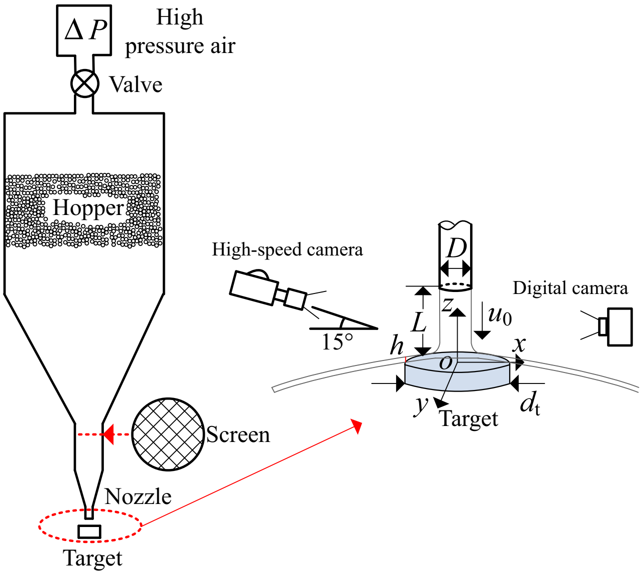

Fig. 1. Sketch of the experimental setup and coordinate system.