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Experimental study of flow regimes and dust emission in a free falling particle stream

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ABSTRACT

The flow regimes in a free falling particle stream and the dust emission rate are experimentally explored in this paper. The results show that the particle stream could be divided successively into the stable regime, the transitive regime and the dispersive regime. The length of each regime is quantitatively identified. In our testing range, the dust emission rate (η_r) increases monotonically with Z and the gratitude gradually increases when the particle stream impacts onto the rigid surface in the transitive regime. The dust generation rate shows linear to the dimensionless drop height. However, the rate decreases slightly monotonically with the drop height (Z) when the particle stream impacts onto the surface in the dispersive regime. The dust generation rate presents an exponent relation with the dimensionless drop height. The empirical equation about η_r is derived. It is found that the second fugitive dust still emits under the condition that the particle stream impacts into the water surface when the hopper outlet diameter is from 1 to 8 mm. Reducing the expanding level and the impaction intensity of the particle flow is considerably important when the contact surface is in the transitive regime and the dispersive regime, respectively.

1. Background

In many industries, such as metallurgy, medical, cement, and food, it is normal to have handling operations involving the transportation of bulk materials in which dust emission may often be observed. Dust is one of the main contaminant sources in industrial buildings, which may affect workers' mental and physical health, lead to serious environmental pollution, and even cause explosion.

A particulate stream can be formed during the free falling of bulk materials. In the process of particle free falling, air is entrainment into the particulate stream as the particle flow accelerates and expands. Some of the particles, especially the smaller ones, break away from the particle stream into the surrounding environment and thus form the first fugitive dust. The free falling stream impacts onto a contact surface releasing the entrained air, and smaller particles are rebounded away from the particle stream, forming the second fugitive dust. The first fugitive dust and the second fugitive dust compose the total dust during the free falling of the particle stream. (Fig. 1).

Previous research efforts in this field have been going on for decades, and the objectives focus on the flow characteristics of particle stream and dust loading. There are two aspects concerning the flow characteristics of particle stream: the quantity of the entrainment air and the particle motion. Regarding the entrainment air, Hemeon [1] firstly proposed the formula for the quantity of entrainment air of a free falling particle stream, based on the assumption that the work done on the air by a stream of falling particles is the sum of friction forces produced by a single particle in free-fall and the velocity pressure acts as the total pressure. On the basis of Hemeon's theory, Tooker [2] investigated fugitive dust generation from enclosed bulk materials handled during transfer operations and stated that the total pressure was the sum of the velocity pressure and the system resistance pressure. Cooper and Arnold [3] conducted the study under two extreme conditions, with particle streams made up of very massive particles and extremely fine particles with cohesion, respectively. Liu [4] validated the former equations and drew the conclusion that Cooper's was more in agreement with the case in reality. Esmaili [5] presented the behavior of the coarse particle stream and obtained the equations of the entrainment air flow within a certain particle diameter range. Li [6] established the semi-empirical model of induced airflow velocity by using the Pi theory and similitude experiments. The rapid development of computer technology provides more motivations for the numerical development of free falling particulate stream. Uchiyama [7–9], Liu [10], and Ansart [11] predicted the volumetric flow rate of entrained air with numerical analysis and researched the physical field variables. As

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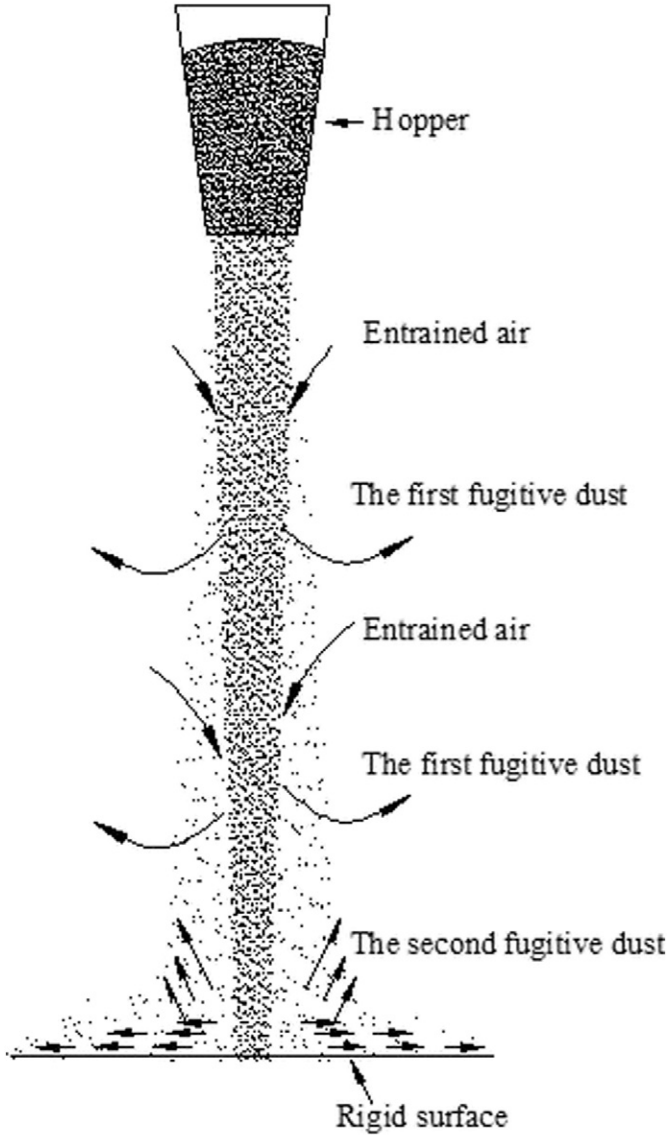

Fig. 1. Schematic of dust emission from a free falling particulate stream onto the rigid surface.

a conclusion, they succeeded in describing the particle flow both with and without empirical parameters. Regarding the particle motion in the stream, great efforts have been made, including the variation of the cross section diameter [5,12–13], the characteristics of the velocity distribution [5,8,13–15], the characteristics of rupture and clustering [16–18], and capillary-like fluctuations at the interface of falling granular jets [19]. All of these research findings contribute to a thorough understanding of the characteristics of the free falling particle stream.

To analyze the characteristics of dust loading, many researchers studied the dust emitted from free falling particle streams. Chatten [20] developed an experimental setup that was used to predict the dustiness for 14 types of materials. Plinke [21–24] examined factors that affect the amount and size distribution of dust emission produced by falling granular material in still air and obtained empirical equations of impaction and dust generation rate. Wypych [25] believed that temperature difference might cause the dust generation rate to increase by an order of magnitude. Liu [26] explored the relationship between the deflector curvature and quantity of dust produced. Heitbrink [27] studied the dust generation rate of constant mass alumina. Changing the contact surface at the end of the fall provided an indication of whether dust generation occurred during the free fall or on contact surface.

The particle dispersion of a free falling particle flow is quite complex. To further control the dust emission, more mechanisms related to particle dispersion and dust generation should be explored. It is considerably necessary to identify the flow regimes corresponding to the characteristics of particle flow in free-fall. It is also expected that the main dust source can be determined exactly and the first fugitive dust or the second fugitive dust therefore can be reduced by improving the flow or impact condition. Many studies could be found on the characteristics of particle flow in the field of combustion, including dispersion modes [28], the undisturbed length, the dispersion length [29], and the diameter of the granular jet core and thickness of the boundary layer [30], while a quantitative description of those characteristics was not involved in free falling particle flow. In the present work, detailed researches regarding the flow regimes and dust emission in a free falling particle stream are performed. The free falling process of the particulate flow is recorded by a high-speed camera, and the generative dusts in the range of 0 to 10 μm are sampled by using a cascade aerosol sampler.

2. Experimental method and materials

The experimental arrangement (Fig. 2) is similar in design to that used by Ansart [11] and Heitbrink [27]. Three primary components of the test rig are the silo and hopper arrangement, the test enclosure, and the dust collection system. The silo and hopper arrangement is mounted on a steel frame that can be raised and lowered to alter the drop height of the free falling materials. The silo has an internal diameter of 10 cm and height of 10 cm and it is connected with a hopper, which has a conical outlet of a semi-angle of 30°. The hoppers with different diameter outlet are used. The walls of the silo and the hoppers are grounded through several wires to avoid a buildup of charge through friction. The hopper outlet is coaxial with the aperture of the test enclosure, and the aperture is with a diameter of 5 cm. The test enclosure has a square cross section (60 cm by 60 cm) and a height from 78 cm to 158 cm. Moreover, it is made from Perspex material to observe the flow regimes and the dust pattern of the free falling particle stream during the tests. The four sides of the test enclosure walls are sealed well with ducting tape to prevent air leakage through the aperture. An 8-grade cascade aerosol sampler is used to measure the dust, the aerodynamic diameter distributions of which are in the range of 0 to 10 μm. The sampling rate is 28.3 L/min. The aerosol sampler connects the test enclosure with an exhaust pipe of 1.5 cm internal diameter.

A high-speed camera (Phantom V9.1) is used to track a 30-cm-long section of the stream as it falls from the hopper to the bottom of the test enclosure (0.28 mm per pixel, 300 images per second). The exposure time of every image is 3.3×10^{-3} s. A black background is used to isolate the particles from the background. An LED light located in front of the test rig illuminates a plane in the particle stream (Fig. 3), and the position of the particles is recorded. For each case, two 15 second videos, which correspond to a total of 4500 individual frames, of the flow are captured once the falling stream has fully developed. Image processing software PCC2.14 is used to analyze the images. Due to the particle flow process, which is done randomly, the measured lengths observed from the images under the same flow regime could be different. The lengths of 100 photographs in each case are measured and the mean values are obtained (precision of ± 0.0001 m). The mean values can be used as the average lengths for different flow regimes. Calibration is undertaken before measurement of flow regime.

In the test rig, the particle stream is dropped from the outlet of the hopper through a sliding valve. It only takes a very short time to open the sliding valve, thus, the effect on the particle stream can be minimized. The conditions for different diameters of the hopper outlet, the drop height, and the contact surface can be seen in Table 1. The particle stream falls either onto a rigid flat surface or into water (5 cm depth). In this study, the mass flow rate is determined by measuring the time necessary to drop a known mass of material. Flow rate varies from 0.0058×10^{-2} g/s to 1.1921×10^{-2} g/s by changing the hopper