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Correlation analysis of three influencing factors and the dust production rate for a free-falling particle stream

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ABSTRACT

The effects of three factors (i.e., drop height h, hopper outlet diameter d_0, and material temperature T) on the dust generation rate derived from a free falling particle stream were investigated via full factorial experiments. The correlation between the three factors and dust generation rate was also analysed. Results show that T and h affect the first fugitive dust rate largely, whereas the second fugitive dust rate is mainly dominated by h and d_0. Through analysing the first fugitive dust percentage data, it is found that h and T should be considered first for higher temperatures and lower flow rates, whereas h and d_0 can be considered under contrasting conditions, and h should be controlled in the remaining two sets of conditions. Relationships between the influencing factors and total and first fugitive dust rates were developed via multiple regression to quantify the dust emission rates for different contact surfaces (rigid or water).

Nomenclature

d_0	Hopper outlet diameter (mm)
d_p	Mean diameter of particles (μm)
g	Gravitational acceleration (m/s^2)
h	Drop height (m)
$\dot{m}$	Mass flow rate (kg/s)
p	Significance value
r	Correlation coefficient
T	Material temperature (K)
x	Independent variable
y	Dependent variable
η_r	Total fugitive dust rate (mg/kg)
η_s	Second fugitive dust rate (mg/kg)
η_w	First fugitive dust rate (mg/kg)
β	Regression coefficient

Introduction

Handling operations that involve transportation of bulk materials, such as the processes of material transfer and dumping, are ubiquitous in the metallurgical, medical, cement, and food industries. Particle streams form with the free falling of materials. In the process that a particle stream falls and impacts onto a contact surface, particles with diameters less than 10 μm, commonly inhaled by workers and then deposited in the respiratory tract and lungs, are released to the ambient environment. Dust is thus a main contaminant, which may threaten physical health and even cause environmental pollution or explosions.

The above issue has been researched for decades. To control dust more effectively and to optimise ventilation systems, multiple influencing factors that affect the entrainment air, dust generation rate, and flow characteristics have been experimentally investigated. Hemeon (Hemeon, 1963; Hemeon & Burton, 1998) considered the particle diameter, density, and mass flow rate and initially proposed a single-particle analytical model with which to predict the entrained air flow rate. On the basis of Hemeon's theory, Tooker (1992) introduced a new concept of the entrainment efficiency factor and provided a more accurate empirical equation. Because different diameters of particles exist in industry,

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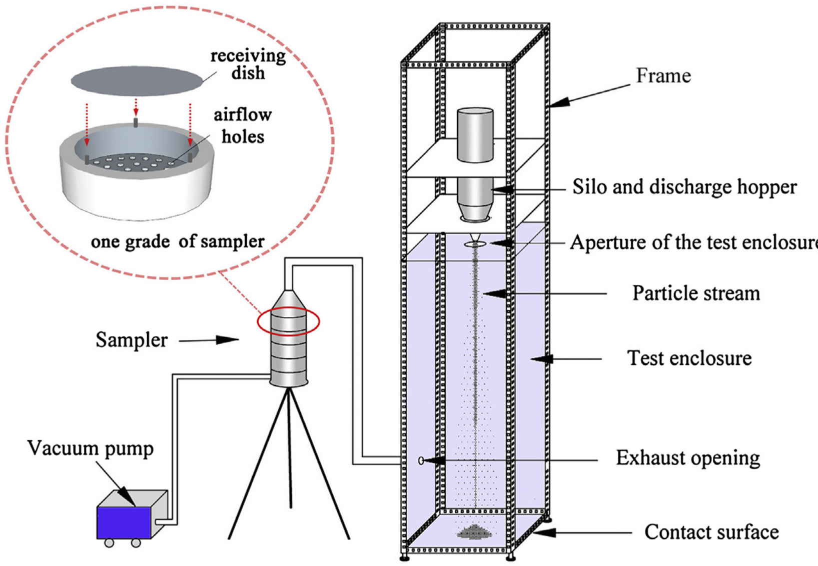

Fig 1. Sketch of the experimental setup.

the massive-particle model and the miscible plume model were proposed by Cooper and Arnold (1995). Several researchers have investigated the dust generation rate for the sake of controlling the dust emission more effectively. Cowherd, Grelinger, Englehart, Kent, and Wong (1989) explored an experimental apparatus in the analysis of the dust emission rate of 14 different types of materials. Plinke et al. (Plinke, Maus, & Leith, 1992; Plinke, Leith, Goodman, & Löffler, 1994; Plinke, Leith, Boundy, & Löffler, 1995; Plinke, Leith, Holstein, & Boundy, 1991) systematically studied several factors, such as the drop height, mass flow rate, moisture content, and particle size, by experiment to measure the dust generation rate during the material free-falling process. Liu, Wu, and Feng (2014) explored the relationship between the deflector curvature and quantity of dust produced. Heitbrink, Baron, and Willeke (1992) studied the dust generation rate of constant-mass aluminium by changing the contact surface at the end of the falling process. To describe the flow characteristics of the particle stream more precisely, Ogata, Funatsu, and Tomita (2000, 2001) studied glass particles falling from different heights with different mass flow rates and analysed the velocity distribution along the jet centreline. To investigate the characteristics of particle flow comprehensively, a two-phase model was proposed by Ansart et al. (Ansart, De Ryck, & Dodds, 2009; Ansart, De Ryck, Dodds, Roudet, Fabre, & Charru, 2009; Ansart, Letourneau, De Ryck, & Dodds, 2011). The effect of the drop height and hopper outlet geometries on the dust generation rate and velocity distribution was described through experimental and numerical simulation. High-temperature particle flow is common in many industrial fields, such as the production of aluminium carbon blocks and the transportation of high-temperature material in the iron-making process. Wypych, Cook, and Cooper (2005) conducted research on this aspect, which brought the temperature into consideration. Their results revealed that temperature is an essential factor for dust production.

The present paper explores the variation in PM_{10} (i.e., particles with aerodynamic diameters less than 10 μm) emission for different falling processes when the hopper diameter and drop height vary at different material temperatures. Correlation analysis is applied to evaluate the effects of the three factors. Furthermore, regressive equations for the dust emission rate and the multiple factors are used to predict the dust generation rate quantitatively under different conditions. The aim is to provide references for the dust control of the free-falling process affected by multiple factors in industrial practices.

Experimental

The present paper combines experimental and statistical analysis methods to describe the dust emission rate in a more comprehensive and detailed way. The amount of dust produced under different influencing factors is determined employing experimental methods. The experimental data are analysed by correlation analysis and regression analysis.

Experimental setup and procedure

Fig. 1 shows a schematic of the experimental apparatus. The test enclosure, with a square cross-section (0.6 m × 0.6 m) and a height from 0.78 to 1.58 m, is made from Perspex material to observe the particle flow and is sealed well with duct tape to prevent air leakage through the aperture. Three different hoppers, controlled by a sliding valve, are used to change the mass flow rate of the particle stream. It takes a short time to open the valve, and its effect on the particle stream can thus be minimized. Additionally, each hopper has a conical outlet of a semi-angle of 30° and is connected with a silo, the inside diameter and height of which are 0.1 m. The walls of the silo and hoppers are grounded through several wires to avoid a build-up of charge through friction. To vary the material temperature, the material is heated by an electric heating device and multi-point temperatures are measured to ensure uniform heating and to eliminate the effect of a temperature gradient. The silo and hopper are well insulated to ensure the material temperature at the outlet of the hopper matches the experiment conditions.

The hopper outlet is coaxial with the aperture of the test enclosure. When the contact surface is water (0.05 m depth), there is a plate with an aperture at the centre. The diameter of the aperture is determined as 200, 250, and 300 mm to match, respectively, the hopper outlet diameter d_0 of 6, 4, and 2 mm, and the flow of particle stream is unaffected. The distance between the plate and water surface is 0.02 m. A detailed configuration is shown in Fig. 2. The ambient environmental temperature is 293 K throughout the experiment.

The mass of the dust is measured by an eight-stage cascade impactor (FA-3, PuSen Electronic Instrument Factory, Changzhou,

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