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Investigation of the parameters important in the measurement of small particle impact forces

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ABSTRACT

Impact forces in pneumatic conveying bends are becoming more significant in industry, and in research centres, as the size of pneumatic conveying pipeline bores increase to achieve high product throughput with the greater efficiency possible from a dense phase conveying system. This paper continues the authors' work in investigating this issue by undertaking a detailed comparison of the equations given for contact time and maximum contact force, from a range of literature with applications to various impact events both practical and theoretical. These predictions are also compared: to experimental results presented previously by the authors, to further results from an electrical resistance measurement system, and to a limited extent to experimental results from existing literature. The equations that are most reliable consider the elasticity of the particle and the elasticity of the impact surface, as well as the particle size, and also reflect a weak dependence on impact velocity. Whilst the electrical resistance measurement method has provided a useful verification of a number of theoretical predictions, its application is limited and is not suitable for the majority of particles that are conveyed pneumatically. Future work will expand on the particles tested using this method, and will also work on understanding better the influence of the force sensor on contact time and maximum force measurement.

1. Introduction

This work summarises the initial investigations into the factors important in the measurement of small particle impact forces. The origins of this work lie in the authors' experiences working with industrial partners to improve the efficiency of their pneumatic conveying systems and an investigation of the literature that identified an issue with impact forces in pneumatic conveying systems [1–4]. Pneumatic conveying systems benefit greatly from the use of bends to allow considerable flexibility in conveying route, but as these systems increase in pipe bore, and there is a trend towards dense phase conveying systems, there is a consequential increase in the forces of impact at these bends [5]. Klinzing et al. [5] have long recognised the relationship between the impact and friction forces and the mass of plugs in these systems.

The authors' first work in investigating these issues further [6] illustrated the complexity of measuring these forces on pneumatic conveying systems, and the decision was made to investigate single particle impacts with a view to better understand the contact dynamics. The analysis of impacts between particles and a contact surface is well represented in the literature [7–27], and the majority of these sources can be traced back to the work of either Goldsmith [28] or Johnson [29]. Goldsmith [28] begins with a stereomechanical analysis, that is a consideration of the impulse–momentum relation during the impact of rigid bodies, then proceeds to discuss Hertzian contact between two spheres or cylinders, or between a sphere or cylinder and a flat surface, which takes into consideration the deformation of the colliding bodies. Johnson [29] is primarily concerned with contact mechanics and therefore focuses his analysis on Hertzian contacts for impact situations involving elastic bodies, but also includes an analysis of non-Hertzian contacts.

The work of the authors represented above [7–29] has involved the investigation of subjects including the coefficient of restitution, the time of contact, the maximum impact force, or the impulse, with a view to gaining greater understanding of the mechanics of an impact which is relevant to particle degradation, surface erosion or energy transfer between the particle and the surface. As discussed above, this work is concerned primarily with impacts in pneumatic conveying systems. Therefore, this work presents a summary of the literature investigated, detailing the various formulations for the variables discussed previously, and comparing these to each other as well as some experimental measurements made of these variables, considering only particles and surfaces that would be expected in pneumatic conveying systems.

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2. Experimental setup

The experimental apparatus developed to measure the impact characteristics between a single particle and an impact surface has undergone several iterations, the details of which have been published previously [30–33]. In summary, the measurement system is based upon the use of force sensors of the piezoelectric type. These sensors work on the principle that a deflection of the piezoelectric element induces charges of opposite sign on the two faces. As force is to be measured on three axes, there are three piezoelectric elements in the force sensors used [34].

In order to ensure the transmission of the force from oblique impacts it is important that the top and bottom surfaces of the force sensors are clamped flat against surfaces that have been ground flat and polished. The force sensors that have been selected for this application are Kistler Type 9017B, which are three-component sensors that allow measurement in the x-, y- and z-directions as shown in Fig. 1. More detail on the correct mounting of these sensors has been discussed in Cowell et al. [31]. For the experimental data discussed in this paper, only one of these force sensors is used, and only the results in the z-direction are discussed, since the particles are assumed to impact at an angle normal to the contact surface.

The future configuration of the measurement system, including the number of force sensors mounted underneath the impact plate, is dependent on several variables, mostly importantly the mass and stiffness of impact plate, as discussed in Cowell et al. [33]. This arrangement must also take into account the difficulty of ensuring that particles, travelling at velocities typical of pneumatic conveying systems, reliably hit the target.

The data acquisition system for up to three sensors is shown schematically in Fig. 2. The three force signals (F_x, F_y, F_z) from each of the three force sensors are summed in the summing box (Kistler Type 5431), then these three signals (one for each direction) are passed through the charge amplifier (Kistler 5073 [35]) whereupon the surface charge is converted into a voltage. These voltage signals are acquired using a National Instruments PXIe-6124 data acquisition card. The maximum sampling rate is (4 MS/s) per channel which means one reading every 0.25 μs. The schematic in Fig. 2 shows the full measurement system including up to three force sensors, but, as discussed above, only the z-direction results are discussed here. The RS-232C connection between the PC and the charge amplifier allows setting the coefficients for the charge amplifier. After the in-situ dead weight calibration of the force sensor, and once the sensitivity coefficients have been set within the data acquisition system, the data acquisition system is able to monitor the z-direction force, plus the two voltage signals used in the electrical resistance circuit shown in Fig. 3. This circuit, described in detail in Cowell et al. [32], is broadly similar to that used by Calvit [11] to determine the contact time between steel balls and silver coated blocks of polymer material.

The effect of changing the mass of the impact surface was also investigated in this work by substituting the original frame [31] with a ball of the same size as the impacting ball or a cylindrical structural steel bar of 38.3 mm in diameter and 502 mm in length. The cylindrical structural steel bar was either supported by a wire placed at the midpoint of its length or by wires at either end. It was also possible to measure the contact time without the force sensor.

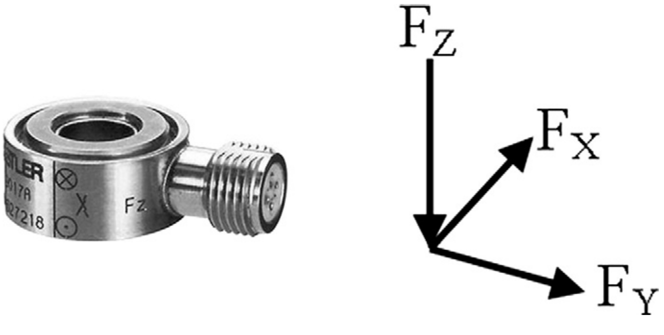

Fig. 1. Load washer showing coordinate axes for force measurement (Kistler AG [34]).

The data acquisition is controlled by a LabVIEW® Virtual Instrument (VI) that includes the relevant data acquisition commands and file writing commands to write the data acquired from the force sensor and the voltage signals to file.

Two groups of materials are presented here for consideration in this paper. The first group, are those that have been used for experiments described in previous papers [30,31]. The second group of materials is taken from the work of Joseph et al. [25], and is intended to provide a wider range of comparison for the parameters determined from the various theoretical equations discussed in this paper. Whilst the properties of the first group have been provided previously [31,32] a full list of materials is provided in Table 1 for clarity. More details about the silica glass and Nylon 6,6 material can be found in Cowell et al. [31].

It is clear from previous work [31] that the elastic modulus is an important parameter in these tests; therefore, the materials were chosen such that there was a significant difference in this value. It is interesting to note that Joseph et al. [25] chose similar materials for their tests despite undertaking their study on particles impacting against a wall in a viscous fluid. The elastic modulus for the steel used for the impact surfaces in this work was assumed to be 207 GPa. The three impact surfaces used, the original frame [30], a Newton's cradle steel ball, and a cylindrical steel bar, all had different masses. It is difficult to quantify the effective mass of the original frame, hence the reason for the alternative impact surfaces. The Newton's cradle steel ball's mass is given in Table 1, and the cylindrical steel bar's (diameter 38.3 mm and length 502 mm) mass is 4.55 kg.

3. Theoretical equations

This section presents theoretical equations from selected published works on the prediction of impact force and contact time between a particle and an impact surface, several of which have been discussed in the authors' previous work [31,32]. This discussion will commence with published work that makes predictions for both of these variables, quotes several papers that give a maximum force equation and finally concludes with papers that make predictions for contact time alone.

The theoretical approach undertaken for elastic impacts by the publications quoted is based on Hertzian Theory. Using the notation in [7], this theory relates the pressure distribution for a contact between a particle and a wall by:

$$\left(\frac{p_{el}}{p_{\max}}\right)^2 = 1-\left(\frac{r_k}{r_{k,el}}\right)^2, r_k \le r_{k,el} \tag{1}$$

where:

$$p_{\max} = \frac{3F_{el}}{2\pi r_{k,el}^2} \tag{2}$$

and:

$$r_{k,el} = \left(\frac{3R^* F_{el}}{2E^*}\right)^{1/3} \tag{3}$$

Antonyuk et al. [7] define the effective modulus of elasticity as:

$$E^* = 2\left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right)^{-1} \tag{4}$$