A momentum-based method for the mass concentration measurement of pneumatically conveyed solid: design optimization

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Abstract. Mass concentration measurement of pneumatically conveyed solid is still challenging in industry. In our previous work (Liu G.Q., The 5th International Conference on Advances in Energy Resources and Environment Engineering, December 6-8, 2019, Chongqing, China.), a novel momentum-based method with more reliable measurement mechanism and simpler structure was developed and computationally validated with a one-end closed straight tube. In this paper, optimization on the structure of the metering tube is conducted to improve the measurement sensitivity represented by the conversion factor $k$. Tubes with a conical inlet are found to possess higher $k$ than that of the straight tube. Computational fluid dynamics (CFD) computations show that $k$ generally increases with decreasing half-cone angle at fixed radius and decreases with decreasing restitution coefficient of collision between particles and the tube walls.

1. Introduction

Though pneumatic transportation of bulk solids widely exists in industry, the measurement of the concentration of solid particles is still challenging. Various measurement techniques that have been developed in past decades can not work well in situ as in laboratory environment, due to reasons such as[1-4]: (1) non-uniform flow in large-diameter pipes, (2) disturbances like pipe vibration and particle contamination and (3) high sensitivity to secondary factors such as moisture content of solid particles that varies in wide ranges. In a previous work[5], we have proposed a momentum-based measurement mechanism that only relies on the essential flow parameters and is easy to implement. The mechanism was computationally verified with a straight metering tube. In current work, we seek to make optimization on the structure design of the metering tube to improve the measurement sensitivity which is represented by the conversion factor $k$. $k$ is enlarged by ‘collecting’ more particles into the tube through a conical opening, the diameter of which is larger than that of the straight part of the tube. Effects of the half-cone angle and the restitution coefficient of collision on $k$ are investigated and an optimized design of the tube structure is proposed.

2. Mechanism of measurement and computational setup

2.1. Measurement mechanism

As reported previously[5], a one-end closed tube with its opening facing towards a uniform gas-solid flow will see an increase in the fluid static pressure at its inner bottom end. The increment is proportional to the mass concentration of solid particles in the flow, as given by:
\[
\Delta p = \frac{1}{2} k c u_0^2
\]

where \( \Delta p \) is the difference between the fluid static pressure at the inner bottom of the tube and the fluid total pressure of the main flow, \( k \) is the conversion factor, \( c \) is the mass concentration of particles and \( u_0 \) is the velocity of the main flow.

In our previous computational fluid dynamics (CFD) computations, the maximum value of \( k \) for a straight tube was found to be around 1.5, smaller than the theoretical upper limit of 2. Since \( \Delta p \) originates from the drag force exerted by particles (especially those having entered the tube) on the fluid inside the tube, \( \Delta p \) and hence \( k \) can be enlarged if more particles ‘collide into’ the tube. A tube with a conical opening is a straightforward option. The conical opening is characterized by diameter \( D_0 \) and half-cone angle \( \theta \), as shown in figure 1.

![Figure 1. Schematic of the metering tube](image)

In this work, \( D_0 \) is fixed to \( \sqrt{2} D \) and hence \( k \) is expected to be enlarged by up to two times. On the other hand, particles colliding with the conical wall will lose certain amount of momentum. Therefore, \( e \), the restitution coefficient of collision, is expected to play an important role in affecting particle motion and hence \( k \).

2.2. Computational setup

The CFD computational setup follows that of our previous work[5]. Simulations are carried out with Fluent in two-dimensional with axisymmetric boundary condition set on the axis of the tube. SST \( k-\omega \) model was adopted to model turbulence. The main flow is with air at 25°C and \( u_0=15 \text{ m/s} \). Structured grid is used and refined in the vicinity of the tube. Details of the computation setup is given in table 1. Particle motion and interaction with the fluid phase are computed with DPM model. Transient computations with time step of 0.0001s are conducted.

Coefficient of restitution (both tangential and normal) for the impact of particles with the tube wall are set to 0.9 for standard cases and varied in other cases to investigate the effect of wall collisions on \( k \). Trap condition is applied to the bottom of the tube.

Table 1. Computational parameters.

| Variable / Parameter      | Unit       | Default value         |
|---------------------------|------------|-----------------------|
| computation domain        | -          | 1150mm × 100mm        |
| tube length, \( L \)       | mm         | 200                   |
| tube diameter, \( D \)     | mm         | 5                     |
| fluid velocity, \( u_0 \)  | m/s        | 15                    |
| fluid temperature, \( t_f \)| °C        | 25                    |
| fluid density, \( \rho_f \)| kg/m³     | 1.225                 |
| fluid dynamic viscosity, \( \mu_f \)| kg/m·s | 1.789×10⁻³ kg/m·s |
| particle density, \( \rho_p \)| kg/m³ | 1550                  |
3. Results and discussion

The conical wall affects the motion of particles through two basic mechanisms. The first is that fluid motion around the tube opening is changed due to the existence of the conical opening and motion of particles are thereby affected. The second mechanism is that particles colliding with the conical wall will not only lose certain amount of momentum, but also are ‘redirected’ either into or away from the tube depending on the half-cone angle $\theta$. To reveal how these mechanisms quantitatively affect $k$, computations under various $e$ and $\theta$ are conducted, with results shown in table 2.

Table 2. Computation results.

| case | $d_p$ ($\mu$m) | $\theta$=15° | $\theta$=6° | $\theta$=30° | $\theta$=90° | straight tube[5] |
|------|----------------|--------------|--------------|--------------|--------------|-----------------|
|      | $e$=0.9 | $e$=0.5 | $e$=0.2 | $e$=0.9 | $e$=0.9 | $e$=0.9 | $e$=0.5 |
| 1    | 1     | 1.01   | 1.01   | 1.01   | 1.03   | 1.00   | 1.01   | 1.01   |
| 2    | 20    | 1.78   | 1.50   | 1.33   | 1.62   | 1.44   | 1.47   | 1.39   |
| 3    | 40    | 2.60   | 1.83   | 1.59   | 2.76   | 1.95   | 1.67   | 1.5    |
| 4    | 60    | 2.83   | 1.90   | 1.49   | 3.01   | 2.06   | 1.68   | 1.53   |
| 5    | 90    | 2.71   | 1.77   | 1.46   | 3.02   | 1.85   | 1.69   | 1.48   |
| 6    | 105   | 2.49   | 1.63   | 1.37   | 2.74   | 1.66   | 1.54   | 1.36   |
| 7    | 120   | 2.24   | 1.46   | 1.25   | 2.45   | 1.43   | 1.37   | 1.21   |
| 8    | 150   | 1.85   | 1.18   | 1.04   | 1.96   | 1.07   | 1.10   | 0.98   |
| 9    | 200   | 1.33   | 0.87   | 0.78   | 1.43   | 0.69   | 0.76   | 0.73   |

3.1. Effect of the restitution coefficient

Figure 2 shows variation of $k$ versus $d_p$ at $e=0.9$, 0.5 and 0.2. $\theta$ is fixed at 15°, which is a moderate value, ensuring that particles colliding with the conical wall bounce and keep moving inwards (i.e. are ‘redirected’) into the tube. The general trends under varied $e$ are similar, i.e. $k$ firstly increases with $d_p$ due to increment of particle inertia, and then decreases since the stop distance of particles of higher inertia is longer than the tube length. Particles with $d_p$ as low as 1$\mu$m have negligible inertia and behave as part of the fluid phase itself such that $k$ is 1, as theoretically predicted.

Figure 2 shows $e$ has significant influence on $k$, especially for $d_p$ in the range of 40 to 105$\mu$m. The maximum value of $k$ is increased by approximately 75% when $e$ increases from 0.2 to 0.9. Therefore, the material of the tube especially the conical part must be carefully chosen to maximize $e$ and hence $k$. The material should be hard enough as well to resist corrosion of particles, and the inner surface of the cone should also be as smooth as possible.

It is seen that the curve for $d_p$ in between 40 and 105$\mu$m at $e=0.2$ is rather flat, similar as when a straight tube is used[5]. This phenomenon becomes less distinct when $e$ is increased, i.e. $k$ is more sensitive to particle inertia at higher $e$. The percentage of increment of $k$ at $e=0.9$ comparing to $e=0.2$, however, lies in a narrow range of 1.8 to 1.9 for $d_p$ in between 60 and 150$\mu$m.
3.2. Effect of the half-cone angle
Figure 3 shows $k$ under different half-cone angles. One extreme condition is $\theta$ at 90°, in which particles colliding with the ‘conical’ wall will directly bounce outwards and fly away from the tube. The conical opening was designed to ‘collect’ more particles into the tube to enlarge $k$. However, such a design will take minor effects when $\theta$ is too big and hence the second mechanism as mentioned at the beginning of this section fails. On the other hand, $k$ at $\theta=90^\circ$ for all investigated particle sizes are indeed higher than that of a straight tube (smaller $e$ of the later case is believed to have negligible effect on $k$, as shown in [5]). Therefore, the ‘conical’ wall at larger $\theta$ does help enlarge $k$, though not significantly. Such an effect is probably due to the first mechanism mentioned previously, as the ‘conical’ wall at larger $\theta$ helps creating an enlarged stagnation zone of fluid in front of the tube opening.

$k$ at $\theta=90^\circ$ and 30° does not differ remarkably, especially for $d_p \leq 20\mu m$ and $d_p \geq 120\mu m$. However, when $\theta$ is further decreased to 15° and 6°, $k$ is significantly enlarged, especially for $d_p \geq 40\mu m$. $k$ at $\theta=6^\circ$ is even larger than the 15° case for $d_p \geq 40\mu m$. At small $\theta$, particles still possess a large velocity component along the axial direction of the tube after colliding with the conical wall. Particles with moderate particle size have higher $k$. For smaller $d_p$, the forementioned second mechanism plays a less important role since fewer particles will collide with the conical wall due to their short stop distances.

Compared to the straight tube, $k$ of the tube with $\theta=6^\circ$ and $e=0.9$ is increased by nearly 100% for $d_p>40\mu m$. As previously mentioned, the expected of increment of $k$ is one time for $D_o=\sqrt{2}D$. Consequently, the newly proposed design of the metering tube is effective.
4. Conclusions
Optimization on the structure of the metering tube of a momentum-based measurement technique of solid concentration is conducted in this work. Tubes with a conical inlet are found to possess a higher conversion factor \( k \) than that of the straight tube, leading to improved measurement sensitivity. \( k \) is increased by nearly 100% under optimized design. \( k \) increases with decreasing half-cone angle and decreases with decreasing restitution coefficient of collision. \( \theta \) around 6°~15° and higher \( e \) are recommended for the optimization of design.

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