A Momentum-Based Method for the Mass Concentration Measurement of Pneumatically Conveyed Solid: Computational Verification

Guanqing Liu*

1China Huaidian Research Institute of Science and Technology. Beijing, 100170, China

*Corresponding author’s e-mail: liugqthu@gmail.com

Abstract. A momentum-based method is proposed to measure the mass concentration of solids in pneumatic pipelines. The mechanism relies on the fact that particles flowing with the fluid will exert drag force and thus induce pressure increase on the fluid phase when they decelerate as approaching a static object or space in the flow domain. The pressure increase is expected to increase with the mass concentration of particles and the fluid velocity, and is also affected by the particles size and density. A conversion factor that indicates the extent to which particle momentum is converted to the fluid static pressure increase was defined. Computational verification of the mechanism was carried out with pulverized coal flow around a one-end closed tube with its opening facing towards the incoming flow. The pressure increase was quantitatively comparable to the fluid dynamic pressure when the solid-to-fluid mass ratio was of the same order of magnitude. The conversion factor was found insensitive to particle size over a wide range, which is advantageous since particle size distribution are usually not known in advance. Compared to most existing techniques, current mechanism is more robust and economic in industry field measurements.

1. Introduction

Pneumatic transportation of bulk solids widely exists in industry. The concentration of solid particles is a crucial parameter for better performance and operation of relevant industrial processes. Taking coal-fired power plant as an instance, pulverized coal particles are conveyed by so-called primary air to the boiler furnace through tens of pipes. Balance of coal flow between these pipes, though difficult to realize, is a necessity to achieve higher combustion efficiency and lower production of NO and NO₂. Better control and adjustment of coal flow can be carried out only when the mass flow rate or solid concentration of each pipe is measured and monitored. Various measurement mechanisms and techniques have been proposed and developed in past decades, such as laser-based, gamma-ray-based, electrostatic-based and electric capacitance tomography (ECT) and so on[1-4], but none of them is mature enough to be widely applied. The main drawback of light-based techniques is that the solid concentration is too high for light to transmit and it is very hard to keep the observing windows and lenses clear. As for ECT, on the other hand, the measurement is sensitive to moisture content in the air-coal mixture, which may vary in wide ranges in majority of power plants (e.g. in China) as the type and quality of supplied coals are rarely stable or predictable. Besides, as the measurement should be implemented on each pipe of a single boiler (over twenty to forty pipes totally), the investment based on the current price of forementioned techniques is too high and the benefit can hardly be justified. Therefore, it is quite essential to develop cost-effective, robust and reasonably accurate solid concentration measurement techniques. In this paper, a mechanism that only depends on the basic
physical properties (e.g. velocity, density, particle size) and flow characteristics of the gas-solid mixture is proposed and computationally verified.

2. **Mechanism of measurement and computational setup**

Pitot tubes are widely used to measure velocity of pure fluid flow. When there are solid particles present in the flow, however, the metering holes of the pitot tube may easily be blocked. According to our experience, on the other hand, before the pitot tube failed to work, the measured pressure difference can be substantially higher than that produced by pure fluid flow, due to the presence of solid particles. Such a phenomenon can be utilized to measure particle concentration.

2.1. **Measurement mechanism**

Assuming the main flow is uniform and the opening of a one-end closed tube (i.e. the metering tube, as schematically shown in Figure 1) is facing towards the incoming flow. For single-phase flow, fluid inside the tube is stagnant with static pressure equal to the total pressure of the main flow:

\[ p_{s,0} = p_0 + \frac{1}{2} \rho_f u_0^2 \]  

where \( p_0 \), \( \rho_f \) and \( u_0 \) are the static pressure, density and velocity of the main fluid respectively. \( u_0 \) can be measured by certain solid-independent techniques that are not affected by the existence of solid particles.

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

For gas-solid flow with mass concentration of particles given by \( c \), some particles will ‘collide’ into the tube due to inertia. These particles will decelerate due to drag force exerted by the stagnant fluid, which in turn leads to the increase of the fluid’s static pressure. If the tube is long enough, particles will halt before colliding with the end of the tube which maximizes of the ‘conversion’ of particle momentum to the fluid pressure increment, otherwise only portion is converted. Thus we have:

\[ \Delta p = p_s - p_{s,0} = k(\rho_f, \rho_p, d_p) \frac{1}{2} c u_0^2 \]  

with \( k \) defined as the ‘conversion’ factor, which is a function of the gas and solid density as well as the particle diameter \( d_p \).

For simplicity, following assumptions are made before further derivation: (1) particles inside the tube do not collide with the side wall of the tube, nor do they collide with each other, (2) fluid inside the tube is stagnant, (3) particles start to decelerate at the opening of the tube, (4) particles are single-sized, spherical and Stokes law of drag applies.

The number of particles that are flying (moving) at moment \( t \) can be given by the product of the flight duration \( T_r \), the cross section of the tube \( A \), fluid velocity \( u_0 \) and particle number concentration \( n \):

\[ N = T_r A u_0 n \]
Assuming a particle starts deceleration at \( t=0 \) with \( u(0) = u_0 \), its velocity at moment \( t \) is then given by [5]:

\[ u(t) = u_0 e^{-\lambda t} \tag{4} \]

where \( \lambda = 18\mu(\rho_p d_p^2)^{-1} \).

The total impulse exerted by a single particle on the fluid through drag force over time \( 0 \sim T \) is thus given by:

\[ I_d = \int_0^T \pi \mu d_p u(t) dt = \frac{\pi \rho_p d_p^3 u_0}{6} (1 - e^{-\lambda T}) \tag{5} \]

The corresponding pressure increase contributed by all particles is:

\[ \Delta p = \frac{NI_d}{T/A} = \frac{T/A}{T/A} \frac{\pi \rho_p d_p^3 u_0}{6} (1 - e^{-\lambda T}) = \frac{\pi \rho_p d_p^3 n}{6} u_0^2 (1 - e^{-\lambda T}) = cu_0^2 (1 - e^{-\lambda T}) \tag{6} \]

In an extreme condition where the tube is long enough to allow particles to halt before impacting the ending of the tube, equation (6) simplifies into:

\[ \Delta p = cu_0^2 \tag{7} \]

On the other hand, if these particles are simply gas molecules as the fluid phase, we have:

\[ \Delta p = \frac{1}{2} cu_0^2 \tag{8} \]

Equations (7) and (8) have defined two extreme conditions where particles are either with high inertia and the tube is substantially long, or with near-zero inertia and behaving like gas molecules. As for real conditions, we can define a general form as:

\[ \Delta p = \frac{1}{2} kcu_0^2 \tag{9} \]

where \( k \) is termed as the ‘conversion’ factor.

2.2. Computational setup

The CFD simulations are carried out with Fluent 14.0 in two-dimensional with axisymmetric boundary condition on the axis of the tube and SST \( k-\omega \) model was adopted. As the diameter of the conveying pipe (usually above 0.5m) is substantially larger than that of the tube, and to reduce computational cost, the width of the flow domain is set to twenty times of the tube radius and shear-free wall boundary condition is applied to the side edge of the domain. Uniform air flow with temperature of 25°C enters the domain with \( u_0=15 \text{ m/s} \). Structured grid is used and refined in the vicinity of the tube. Details of the computation setup is given in table 1. Particles are released at the velocity inlet of the domain and modeled by DPM model coupled with the fluid flow. Unsteady computations with time step of 0.0001s are conducted until the static pressure at the tube bottom reaches stable state.

Tangential and normal coefficients of restitution for the impact of particles with the side wall of the tube are set to 0.5 for standard cases and varied in other cases to investigate the effect of wall collisions on \( k \). Trap condition is applied to the end wall since in real applications particles will halt and accumulate making rebound hardly happen.

| 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/m$^3$ 1.225
fluid dynamic viscosity, $\mu_f$ kg/m·s 1.789×10$^{-5}$ kg/m·s
particle density, $\rho_p$ kg/m$^3$ 1550
particle mass concentration, $c$ kg/m$^3$ 0.5

3. Results and discussion

3.1. Fluid flow and particle motion

Figure 2 shows the fluid trace lines around the tube opening, without/with particles present in the flow. In the later case, particles are with diameter of 90μm. Fluid swirl motion and reverse flow are seen near the opening of the tube in both cases. Beyond a certain distance (with similar scale as the tube radius) into the tube, fluid is nearly stagnant. The presence of particles does not significantly affect the fluid motion.

Particles with $d_p=1.0\mu m$ have low inertia and can not ‘penetrate’ deep into the tube. They mostly move into the tube with a short distance and then move out following the fluid’s reverse flow. Particles with moderate sizes straightly flow into the tube, slow down under the fluid drag force but stop before colliding with the tube end. Particles that are sufficiently big can not substantially decelerate and finally impact with the tube end. A small portion of particles may collide with the side wall of the tube.
3.2. Variation of the conversion factor with particle diameter

Figure 3 shows the variation of $k$ with $d_p$ for cases with $e=0.5$. As theoretically predicted in previous sections, $k$ is close to 1.0 for small $d_p$. $k$ firstly increases with increasing $d_p$ and reaches a maximum of approximately 1.5, and then decreases with $d_p$ until below 1.0 for $d_p$ larger than about 145μm. The maximum can be approached only when particles are big enough and the tube is substantially long. For a tube with moderate length, $k$ will decrease as $d_p$ exceeds a certain range, due to that the particles can not stop before the tube ending and only portion of their momentum are converted into the pressure increase of the gas.

The curve is rather flat for $d_p$ ranging from approximately 20μm to 105μm. This is advantageous for industry applications since particle size distribution (PSD) are usually not known in advance. As a matter of fact, PSD of pulverized coal powders vary frequently with coal types and the operation condition of mills etc. Therefore, a more precise and robust measurement can be achieved if the size of particles majorly locates inside the insensitive region of the $k$-$d_p$ curve.

The theoretical upper limit of $k$ (i.e. 2) is not reached in current computations. This was suspected to be partially due to that particles may collide with the side wall of the tube and their momentum are reduced due to normal impact and tangential friction. However, as shown in table 2, the comparison between cases 6a and 6b, 9a and 9b showed that this is not true. Besides, either numerical reduction of fluid viscosity (case 5c versus 5a) or increase of particle density (case 5b versus 5a) induced major changes to $k$. 
Figure 3. Variation of the conversion factor with particle diameter.

Table 2. Computation results.

| case | \(d_p\) (μm) | \(\Delta p\) (Pa) | \(k\) | \(e\) (side / bottom) | comments |
|------|--------------|-------------------|-------|----------------------|----------|
| 1    | 1            | 196.5             | 1.01  | 0.5 / 0              |          |
| 2    | 10           | 205.2             | 1.16  | 0.5 / 0              |          |
| 3    | 20           | 218.1             | 1.39  | 0.5 / 0              |          |
| 4    | 40           | 224.3             | 1.50  | 0.5 / 0              |          |
| 5a   | 60           | 225.8             | 1.53  | 0.5 / 0              |          |
| 5b   | 60           | 224.6             | 1.51  | 0.5 / 0              |          |
| 5c   | 60           | 225.2             | 1.53  | 0.5 / 0              |          |
| 6a   | 90           | 223.3             | 1.48  | 0.5 / 0              |          |
| 6b   | 90           | 227.6             | 1.56  | 0.9 / 0              |          |
| 7    | 105          | 216.3             | 1.36  | 0.5 / 0              |          |
| 8    | 120          | 207.8             | 1.21  | 0.5 / 0              |          |
| 9a   | 150          | 195               | 0.98  | 0.5 / 0              |          |
| 9b   | 150          | 196.3             | 1.00  | 0.9 / 0              |          |
| 10   | 200          | 180.8             | 0.73  | 0.5 / 0              |          |
| 11   | 250          | 171.2             | 0.56  | 0.5 / 0              |          |

\(\rho_p=2300\text{kg/m}^3\) \(\mu_i = 9\times10^{-6}\text{kg/m}\cdot\text{s}\)

4. Conclusions

A momentum-based method is proposed to measure solid concentration in pneumatic pipelines. We defined a conversion factor \(k\) to indicate the degree to which particle momentum is converted to increase in hydrostatic pressure. The computational verification was carried out with a one-end closed tube facing towards the incoming flow. The pressure increase at the tube internal end as compared to pure fluid flow was monitored and \(k\) was calculated. \(k\) is found to firstly increase with particle diameter \(d_p\) to a maximum value in between 1 and 2 and then decreases with \(d_p\), as theoretically predicted. \(k\) is found insensitive to \(d_p\) over a wide range, and this can be advantageous for field measurements since particle size distribution is usually not known in advance. As particle size may vary for different industry circumstances, the tube shall be designed accordingly and more complex geometry may be adopted.

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