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Real-time solid flow velocity measurement based on a microwave sensor

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Abstract

Measurement and control of bulk solid flows become increasingly important in industries, such as large-scale production, coal transportation and food processing, although rapid and accurate velocity measurement is still a challenging task in these applications. This paper presents a new velocity measurement method based on a microwave sensor operated at 10.525 GHz and investigates the factors that affect velocity of bulk solid flows and the velocity of the solid particles in order to quantify the flow and improve the efficiency of transportation. In this method, a microwave Doppler Signal Analyser is adopted to calculate the average velocity of bulk solid flows and obtain the instantaneous velocity of a single solid flow. The influence of air friction, pipe collision and particle interactions is also analysed with experiments. The measurement results show that the average velocities of bulk solid flows range from 0.6 to 1.6 m/s, and the interaction between solids play a major effect on solid movements. The effect of pipe wall friction should also be considered. Besides, the mass flow rate and the total mass of bulk solid flow can be calculated. The mass flow rate ranges from 0 kg/s to 0.21 kg/s in the entire experiment.

Keywords

Velocity, mass flow rate, microwave Doppler, sensor, real-time

Introduction

Owing to its convenience, environmental protection and automation, pneumatic transportation of bulk solids has been widely used in chemical engineering processes (Jaworek and Krupa, 2010), coal transportation, food processing and drug quality-control. As one of the most important parameters of the transportation, accurate flow velocity of solids has a crucial impact on measurement and control systems (Yan and Ma, 2000).

Over the past decades, a large number of flow velocity meters have been introduced to meet the needs of industrial production. Generally, the existing flow velocity meters are achieved through three methods: (i) cross correlation method (Wang et al., 2013; Zhang, 2008), which can be realized with capacitive sensors, electrodynamic sensors (Ghazali et al., 2001), acoustic sensor (Gratiot et al., 2000; Thorne and Hanes, 2002), optical sensors (Malara et al., 2017) radiometric sensors (Zubkov and Kuba, 2005) or capacitive sensors (Fuchs and Zang, 2006); (ii) spatial filtering method (Hrachet et al., 2008; Penirschke and Jakoby, 2008; Wu and Zhang, 2007; Xu et al., 2007), which can be realized with capacitive sensors, optical sensors and (iii) laser Doppler method. Among them, the cross correlation method has a poor spatial sensitivity with restricted signal processing, while the spatial filtering method is very complex. Furthermore, laser Doppler method is expensive. In the previous work, movements of bulk solid flows have been detected based on electrical capacitance sensors (Che et al., 2017; Wang et al., 2015; Zhao et al., 2012). Although this technique can detect the deposition of solids, it is not sensitive enough and unable to detect individual solid particles suspended in air as the particles are too small. Therefore, there is a need to develop a new method for the measurement and analysis of bulk solid flows.

Nowadays, due to the rapid development of microwave technology, diversified microwave sensors are emerging for industrial applications. With these sensors, consistent real-time velocity measurements can be achieved. Besides, with the Doppler method (Greve et al., 2013; Neumann et al., 2009; Weber et al., 2002), non-intrusive point velocity measurement with fine temporal resolution and high accuracy is feasible. Based on these characteristics, a microwave Doppler sensor is adopted to measure the flow velocity of solids. Simplicity, low cost and easy installation of microwave Doppler sensor make it attractive for routine use in hostile environments.

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The microwave Doppler sensor will also bring significant benefits for industrial analysis, efficiency improvement, quality control and validation.

As it is well known, Doppler radar is a common technique to measure velocities of objects (Wang et al., 2011; Zarifi and Daneshmand, 2015; Zarifi et al., 2016). Many researchers have also concluded that the microwave method has great potential to measure the velocity of bulk solid flows (Hamid and Stuchy, 1975; Isa and Wu, 2006; Stuchly et al., 1977). However, the influence factors, such as locations of the antenna, air friction, pipe collision and particle interactions, have not been well analyzed, which may have a direct effect on velocity measurement, and greatly limit the industrial application of the microwave method. Despite numerous theoretical and experimental investigations, no general models are available that reliably predict two-phase process and the influence factors. A reason for this is that two-phase flow includes all the complexities of single-phase flows like non-linearities, transition to turbulence and instabilities plus additional two-phase characteristics like motion and deformation of the interface, non-equilibrium effects and interactions between phases. The prediction of this is made by one of three approaches: empirical correlations, analytical models (Funahashi et al., 2018; Liu, 2014; Michaelides and Michaelides, 2007; Quibén and Thome, 2007; Tokan, 2014) or phenomenological models. Many empirical relationships have been obtained over the last half century. This paper performs experimental studies with empirical information used to investigate the effects of locations of the antenna, air friction, pipe collision and particle interactions on gas-solid two-phase flow.

In this paper, a microwave Doppler sensor suitable for velocity measurement in process industry has been developed, and associated signal analysis method is described. The influence factors are verified through a range of experiments including bulk solid flows and single solid flows. Besides, a correlation as the functions of particle concentration and velocity is proposed to measure the mass flow rate for practical industrial application. The remainder of the paper is organized as follows. In Section 2, the determination of instantaneous single solid flow velocity is derived from the Doppler principle and the short-time average velocity of bulk solids is obtained from the combination of FFT (Fast Fourier Transform Algorithm) and Doppler spectrum analysis. In Section 3, the microwave Doppler sensor system is introduced. In Section 4, the velocity measurements of single and bulk solid flows are made through experiments and the factors that affect the bulk solid flows in a pipe are analysed. A method for mass flow estimation based on the velocity measurement using the microwave Doppler sensor is also presented. Finally, conclusions are drawn in Section 5.

Microwave Doppler analysis

Microwaves with frequencies between 300 MHz and 300 GHz are usually characterized by transmission, absorption and reflection through media. The strength of reflection depends on the ratio of the object size to the incident wavelength. When the size of the object is larger than the microwave wavelength, a direct reflection occurs. However, when the particle size is much smaller than a wavelength, scattering occurs so that part of the microwave energy is reflected back to the source direction, part is transmitted into the particle, and part of scattered towards other directions, and further to other particles. In such a manner, multiple reflections and scattering would occur and the movements of particles concerned would contribute to the velocity measurement of the objects. In this paper, this principle is applied to the velocity measurement of bulk solid flows (Cai et al., 2009).

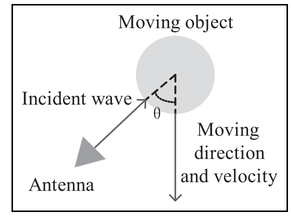

Figure 1. Diagram for illustrating Doppler principle.

Single solid microwave Doppler analysis

When microwave energy is reflected from a moving object, a frequency shift is resulted. Such a frequency shift is proportional to its velocity, and it is known as Doppler frequency shift (Nguyen et al., 2014; Shourcheh and Rezazadeh, 2016). Hence, the measurement of Doppler frequency shift will give the velocity information of the moving object.

Referring to Figure 1, when a sinusoidal microwave is radiated from an antenna towards a moving object at an angle θ, the Doppler frequency shift f_d of the reflected wave back to the antenna is given by

$$f_d = \frac{2v}{\lambda} cos\theta \tag{1}$$

where v is the velocity of the moving object, λ is the wavelength of the radiated wave. Hence, when f_d is measured, the moving velocity can be obtained as

$$v = \frac{f_d \lambda}{2cos\theta} \tag{2}$$

Equation (2) is well suited for the movement of a single object. However, for multiple objects moving at different velocities and different directions, such as in bulk solid flows, the detected Doppler signal $S_r(t)$ has multiple frequency components. The waveform is generally noted as $h(t)$, which may consist of a number of waves of different frequencies.

$$S_r(t) = h(t) \tag{3}$$

To analyse the detected Doppler signal, Fast Fourier Transform (FFT) is needed to observe and analyse the waveform in frequency domain (Lu and Guo, 2011) for a short sampling time. The detected Doppler waveform is sampled at a sampling frequency f_s or period $T_s = 1/f_s$. The k-th sampled is noted as

$$h_k = h(t_k) \tag{4}$$

where

$$t_k = kT_s \tag{5}$$

To implement the FFT (Press et al., 1988), N sampling points of data are used. With N numbers of input, it is evidently able to produce no more than N independent numbers of output. So, instead of trying to estimate the Fourier transform $H(f)$ at all values of f in the range $-f_c$ to f_c where f_c is the Nyquist critical frequency, only at the discrete values are calculated at.

$$f_n = \frac{n}{N} f_s \tag{6}$$

with $n =$ -N/2,…N/2.

With the discrete Fourier transform of the N points h_k, $H(n)$ can be written as

$$H_n = \sum_{k=0}^{N-1} h_k e^{2\pi ikn/N} \tag{7}$$

with $H_{-n} = H_{N-n}$.

The corresponding FFT spectrum of h_k for $k = 0$ to (N-1) is H_n for $n = 0$ to (N/2-1) at frequency f_n, that is

$$H_n = \mathrm{FFT}(h_k) \tag{8}$$

With reference to equation (1), the velocity corresponding to f_n is

$$v_n = \left(\frac{\lambda}{2\cos\theta}\right) f_n \tag{9}$$

Bulk solid flows microwave Doppler analysis

In industrial transportation, large numbers of solids move in the pipe with different velocities, microwave radiation are scattered by different particles with different velocities (magnitude and direction) in the pipe. Scattering is considered as an elastic process, in which wavelength or frequency of the electromagnetic radiation is not substantially changed. As the pipe is vertically oriented, all solids move under the gravitational force either individually or together with other solids. In the case of a horizontal pipe – which is, however, not the case in our study – the situation that some particles may move while others may be static may occur. In this case, different Doppler shifts may be obtained and those still particles would produce zero Doppler shift (i.e. $f_n = 0$.). The bulk solids are considered as a whole, and the randomness of the interaction tends to be averaged out by the large number of scattering events, so that the final path of the radiation appears to be a deterministic distribution of intensity and its time variation. Hence, with the spectral distribution, a $|H_n|$ weighted average velocity is proposed, and it is the average velocity over a time duration of NT_s; as a result, all the solids that are moving or static are all considered in the measurement. The average velocity is defined as

$$v_{avg} = \frac{\lambda}{2\cos\theta} \frac{\sum_{n=0}^{(\frac{N}{2}-1)} f_n |H_n|}{\sum_{n=0}^{(\frac{N}{2}-1)} |H_n|} \tag{10}$$

For pneumatic transportation, there exist reflections from the pipe walls during the measurement. However, the reflected signals do not yield Doppler effect, hence, the reflections from the pipe walls do not contribute to the velocity calculation.

Similarly, the $|H_n|^2$ weighted velocity can be defined and it is referred to as the dominant velocity.

$$v_{dom} = \frac{\lambda}{2\cos\theta} \frac{\sum_{n=0}^{(\frac{N}{2}-1)} f_n |H_n|^2}{\sum_{n=0}^{(\frac{N}{2}-1)} |H_n|^2} \tag{11}$$

The dominant velocity may be the main velocity of the moving objects. If the difference between the average velocity and dominant velocity is small, the velocity spread of the moving objects is low. If the difference is large, it indicates that the objects move at many different velocities. This may be a useful indicator in assessing a flow with multiple objects, such as solid flows.

In the FFT spectrum, the lowest frequency component is

$$f_{\min} = \frac{f_s}{N} \tag{12}$$

and the highest frequency component used for velocity calculation is

$$f_{\max} = \left(\frac{N}{2} - 1\right) \frac{f_s}{N} \approx \frac{f_s}{2} \tag{13}$$

These correspond to the lowest and highest velocity components of

$$v_{\min} = \frac{\lambda f_s}{2N\cos\theta} \tag{14}$$

and

$$v_{\max} = \left(\frac{N}{2} - 1\right) \frac{\lambda f_s}{2N\cos\theta} \approx \frac{\lambda f_s}{4\cos\theta} \tag{15}$$

As the v_{max} is independent of N, for slow moving objects, it would be more suitable to use a large N and small f_s, so as to measure small velocity. For fast moving objects, it would be more suitable to use large f_s and large N, to obtain the large velocity, and to get measurement in a longer range.

Microwave Doppler sensor system

A microwave Doppler system consisting of microwave measurement hardware and its associated signal analysis software with the implementation of above equations is set up. An 80 cm long polyvinyl chloride (PVC) pipe with an inner diameter of 54 mm and outer diameter of 60 mm, as shown in Figure 2

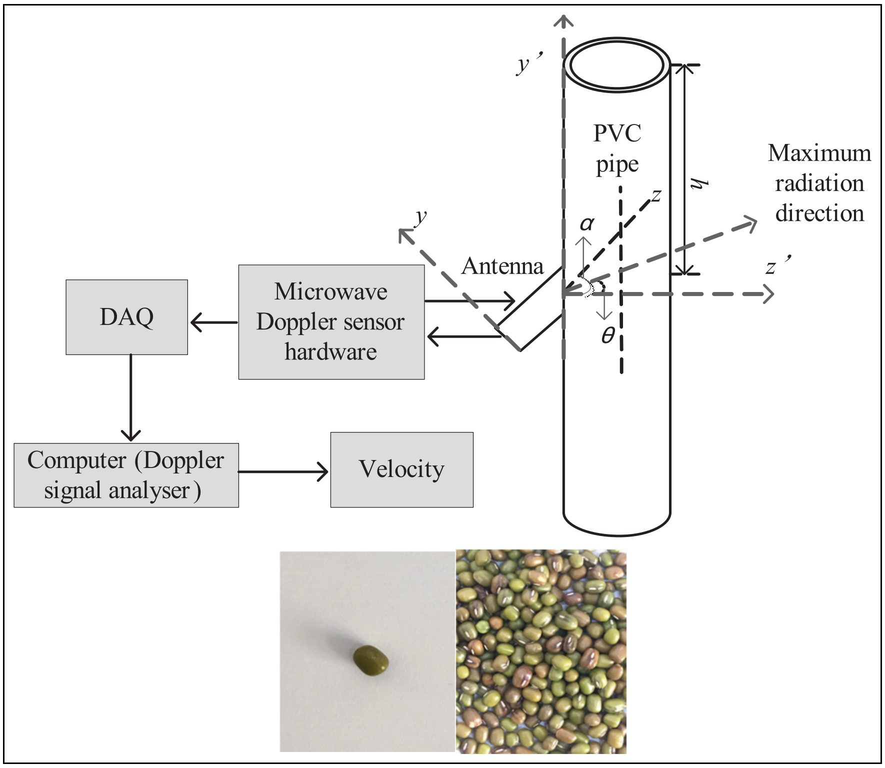

Figure 2. A diagram of the microwave Doppler system and test materials.

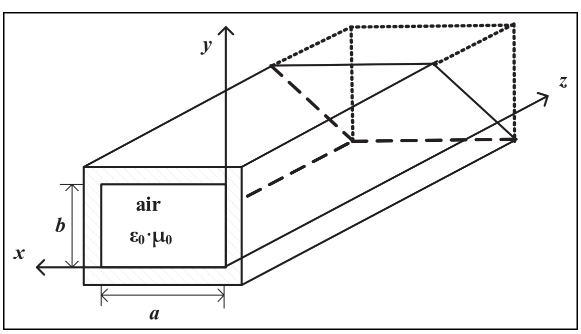

Figure 3. Tapered rectangular waveguide antenna.

is used. Green beans, as shown in Figure 2, are used as bulk solids because they are nearly spherical and easy to handle. The average diameter of the solids is 4~5 mm, which is smaller than the wavelength $\lambda = 2.82$ cm of microwave signal. In this size regime, the degree of scattering varies as a function of the ratio of the particle diameter to the wavelength of the radiation, along with many other factors including polarization, angle and coherence. The method in the paper can only be used to measure solids of certain size; as a rule of thumb, the particle size is similar or less than wavelength/10. The bulk solids are dropped randomly into the PVC pipe and the amplitude of the reflected voltage signal is sampled and processed to determine the characteristics of the flow.

For the microwave measurement hardware, a tapered rectangular waveguide antenna is used as the microwave Doppler sensor, as shown in Figure 3. The long side is in *x*-axis with a length of $a = 1.6$ cm, and the short side is in y-axis with a length of $b = 1.0$ cm while the variation in *z*-axis is tapered. The rectangular waveguide antenna is installed on the measuring pipe with an angle of $\alpha = 45°$ between the waveguide axis and the normal direction of the cross section, as shown in Figure 2. The maximum radiation direction of the antenna measured deviates $(\alpha–\theta) = 30°$ from the axial direction *z*-axis.

When the microwave Doppler system was powered up, it produces a 5 mW, 10.525 GHz microwave signal. The signal is radiated through the tapered rectangular waveguide antenna towards moving bulk solid flows, and the reflected signal is produced and captured by the same antenna. The viewing angle between the electrical axis of the antenna and the direction of the average velocity of the bulk solid flows is 45°, as shown in Figure 2. The antenna is attached to the PVC pipe located at a distance of 38 cm from the point where the bulk solids are released. The Doppler signal output after a microwave mixer is sampled at 1 kHz and transferred into a computer for processing using the equations above via an NI data acquisition (DAQ) card (National Instruments, 2007).

Experimental tests and results

Single solid tests

In the experiment, as the solids are dropped in the PVC pipe randomly, their directions of motion are unpredictable. The probability of collisions with the pipe wall is very high. To analyse the effect of the PVC pipe wall, a single solid is

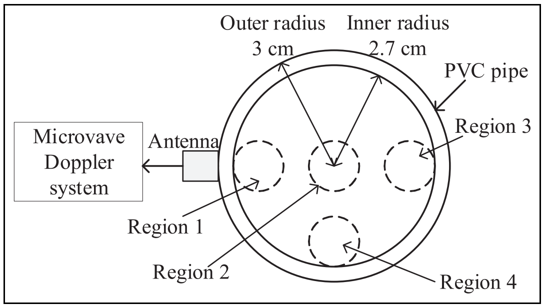

Figure 4. Velocity measurement in different regions.

released repeatedly in different regions from the top of the PVC pipe, which is placed at a distance of 38 cm from the antenna, as depicted in Figure 4. Region 1 is in the pipe near to the antenna. Region 2 is in the centre of the pipe and regions 3 and 4 are in the pipe also near the wall but away from the antenna.

With the division of typical regions above, single solid measurements are made repeatedly on all of these four regions. When single solids are dropped from the top of the pipe, typical sampled voltage signals are shown in Figure 5(a)-(d) respectively. With the repetition 10 times, the maximum voltages observed in Regions 1~4 are 2.23 V, 2.83 V, 1.73 V and 1.70 V, respectively. As Region 1 is closer to the antenna compared to the other 3 regions, the antenna can detect stronger signal when solids are released in Region 1 than Region 3 and 4. Solids with higher velocities have smaller response time between peak and trough, as shown in Figure 5.

The velocities of solids change when they are released in different regions because of the influence of the pipe wall. Solids dropped in the centre of the pipe appear to have higher velocities, which are less likely to bump onto the pipe wall. Solids released in Region 1 are smaller Velocities than those in Region 2 and a slightly larger than those in Regions 3 and 4. Solids released in Region 3 and 4 have similar velocities. Since Regions 1, 3 and 4 are near the pipe wall, the solids have higher probability to bump onto the wall, resulting a reduction in velocity.

The average measured velocities for single solids are shown in Table 1. The results also show that the location of antenna has less effect on the velocity measurement with respect to the positions where solids fall.

The average velocity of single solid flow released in Region 2 is the highest in all regions. However, it is still smaller than the free-fall velocity of solids released at the same height, which is 2.729 m/s. The difference between the average velocity in Region 2 and theoretical velocity could be due to the influence of air resistance. Differences between the relative errors in Region 2 and Regions 1, 3 and 4 are 2.2%, 8.4 %, 9.7 % and 9.6 %, respectively. Compared to the relative error of 2.2 % in Region 2, the effect from the PVC pipe wall is very significant. This effect would increase in bulk solid flows where many solids start to flow at the same time.

Bulk solid flows

In the experiments of bulk solid flows, a total of 80 solids (millet) with an average diameter of 1.5 mm are chosen to measure the average velocity. The bulk solid flows are released vertically into the PVC pipe for 100 times. The results show that the average flow velocities of bulk solids

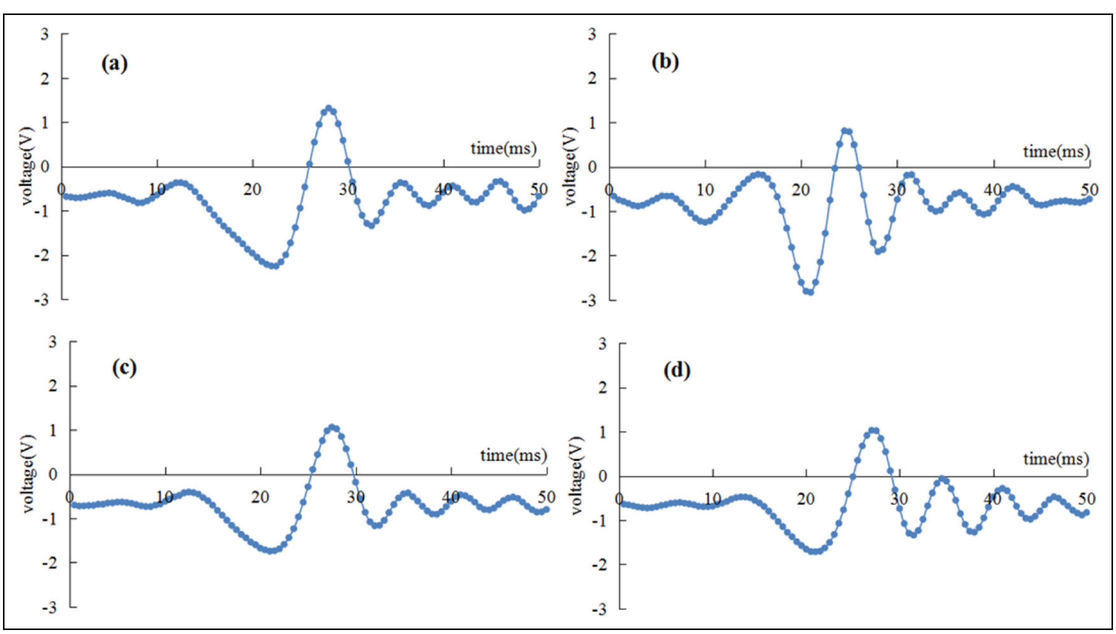

Figure 5. Single solid flow released (a) in region 1; (b) in region 2; (c) in region 3; (d) in region 4.

Table 1. Velocities of singe solid flow in different regions (10 times).

Region	1	2	3	4
Free fall velocity (m/s)	2.729	2.729	2.729	2.729
Velocity(m/s)	2.497	2.628	2.607	2.543
Velocity(m/s)	2.640	2.598	2.439	2.466
Velocity(m/s)	2.441	2.610	2.553	2.371
Velocity(m/s)	2.400	2.778	2.370	2.527
Velocity(m/s)	2.523	2.728	2.349	2.428
Average value	2.500	2.668	2.464	2.466
Relative error	8.4%	2.2%	9.7%	9.6%
Standard deviation	0.082	0.072	0.101	0.063

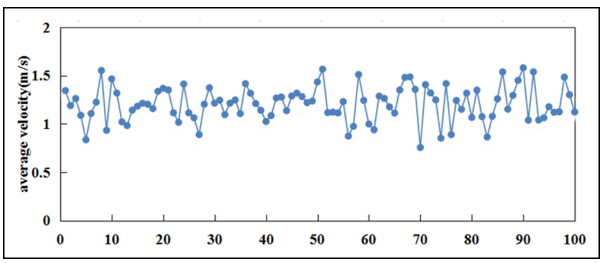

Figure 6. Average velocity of bulk solid flows.

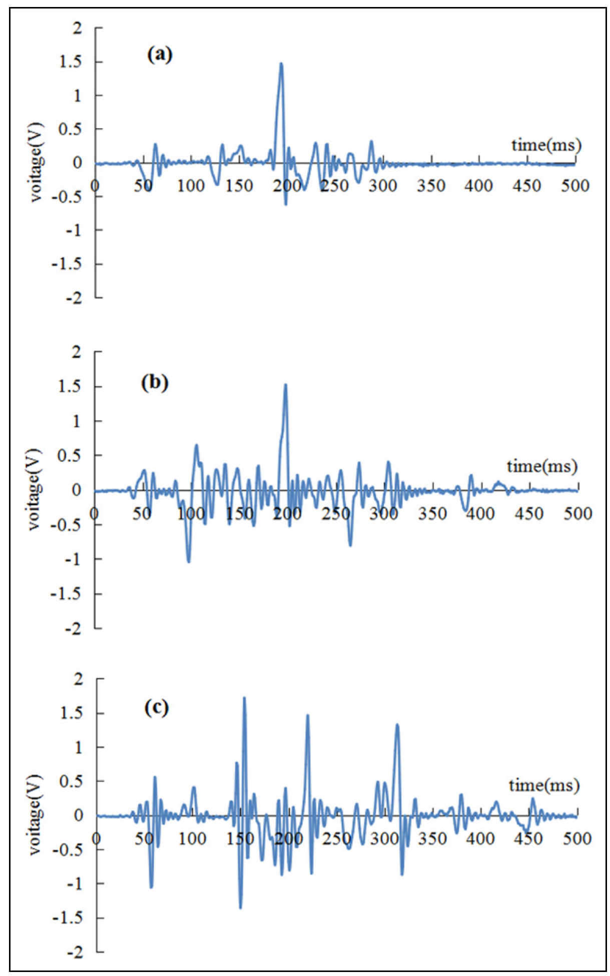

Figure 7. Voltage signal response at velocities of (a) 0.6 m/s; (b) 1.2 m/s; (c) 1.6 m/s.

range from 0.6 to 1.6 m/s, which is shown in Figure 6. Three typical voltage signals corresponding to three different flow velocities are shown in Figures 7(a)–(c). A larger flow velocity corresponds to a rapid signal variation. The average value for 100 tests in Figure 6 is 1.21 m/s. Compared with the theoretical velocity of 2.729 m/s, the average velocity of bulk solid flows is much less than the theoretical value.

Even though 80 solids are released at the same time, the bulk solids have different average velocities ranging from 0.6 m/s to 1.6 m/s. As solids are in bulk and random in flow direction, they not only collide with each other but also with the wall during the motion, which change their velocities. As it can be seen from the analysis above, the effect of the interactions between solids are much larger than the influence of pipe wall.

However, the bulk solid flows are not always of irregular shapes. For modeling of scattering with a wavelength larger than the solid size, the exact shape of the scattering centre is usually not very significant and can often be treated as a sphere of equivalent volume. So, other materials such as sand of irregular shapes could also be used in the experiment, and in fact the test shows that the average velocity of bulk sand is similar to that of millet.

To prove that the microwave Doppler sensor can be applied to industrial transportation, the microwave Doppler sensor is adopted in the measurement together with a microwave tomography sensor. Microwave Doppler sensor is used to measure the average velocity of bulk solid flow and microwave tomography sensor is used to measure the concentration of bulk solids in the flow.

The controlled test is observed over a period of 40 s. At first, there is no solid flowing in pipe. The voltage signal received by microwave Doppler sensor is 0, so is the velocity calculated from the voltage signal. Shortly, a voltage signal starts to increase as the solids gather and flow. The average velocities $v(t)$ at different times are recorded as shown in Figure 8(a), which ranges between 0 m/s and 0.5 m/s. Their corresponding concentration values $\beta(t)$ (percentage content for per unit volume) are shown in Figure 8(b), and the

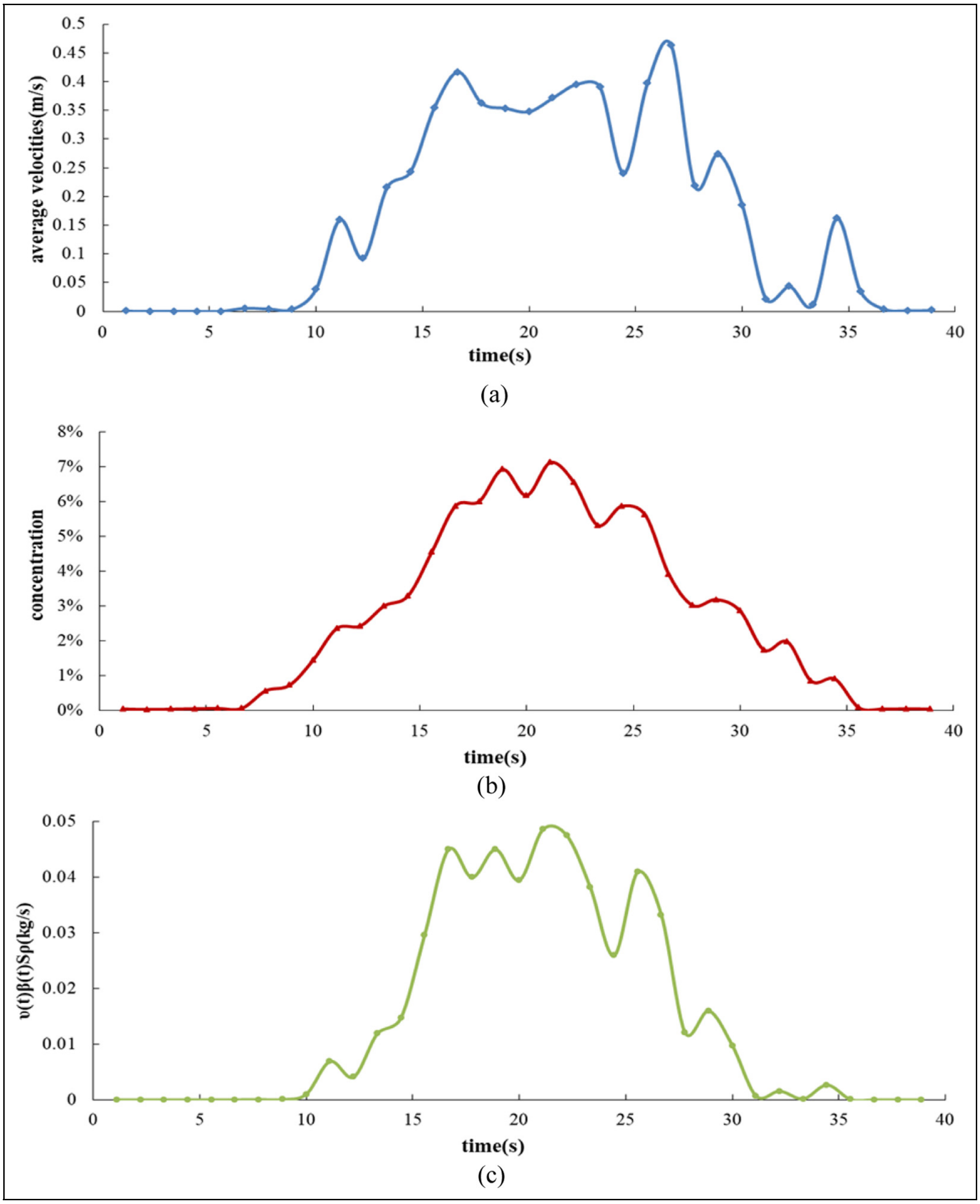

Figure 8. (a) Average velocities; (b) concentration and (c) relative mass flow rate of bulk solid flows.

Table 2. Measurement mass and relative errors.

	Actual mass (kg)	Measurement mass(kg)	RELATIVE ERROR
1	2	2.092	9.16%
2	2	1.740	−13.01%
3	3	3.213	7.09%
4	3	3.038	1.26%
5	3	2.893	−3.55%
Average value	2.60	2.590	1.61%

product of $\upsilon(t)$, $\beta(t)$, S and ρ are shown in Figure 8(c). At the end of the transport, the average velocity returns to 0 m/s again. The flow volume concentration ranges from 0% to 10% in the entire experiment.

The mass flow rate $M(t)$ for the flow can be estimated using the 'velocity-concentration' method, that is

$$M(t) = \mathrm{A}\upsilon(t)\beta(t)S\rho \tag{16}$$

where

$S = 22.9$ cm^2 is the cross-sectional area of pipe, $\rho = 0.803$ g/cm^3 is the density of bulk solids, and A is a modeling constant.

After integrating the curve in Figure 8(c) and the prior knowledge that

$$\int_0^{40} M(t)dt = 3kg \tag{17}$$

it can be obtained that A = 4.2 for the operating system. Hence, equation (16) can be expressed as

$$M(t) = 4.2v(t)\beta(t)S\rho \tag{18}$$

With equation (18), the mass flow rate can be calculated, which ranges from 0 kg/s to 0.21 kg/s in the entire experiment. Besides, the total mass of bulk solid flow can be calculated. Five further tests are thus carried out as listed in Table 2. For each test, the flowing mass estimated by using equation (18) is also given in Table 2 together with the measurement error. In average, the 'velocity-concentration' method can give an accurate estimate. The results also show that microwave Doppler system is a potential tool for the determination of the velocity of bulk solid flows.

In practice, bulk solid flows are dense in common and the flow state is not always steady. The output velocity may change with time under unsteady solid flow conditions. In this study, the microwave Doppler measurement method is proven to be applicable to steady as well as unsteady solid flows.

Discussion and conclusions

A new velocity measurement and analysis method for bulk solid flows based on a microwave sensor has been presented. In this approach, the instantaneous velocities of single solid flows and the average velocities of bulk solid flows can be measured with the microwave Doppler principle and short-time FFT. The measured velocities for single solid flows in air using the method are closed to their free-fall velocity calculated in the ideal vacuum environment with a difference of 2.2%–9.6% for different flowing positions one the pipe cross-section. The experiments carried out show that there exists a significant difference between the velocities of single solid flow and bulk flows, ranging from 2.3 m/s to 2.8 m/s and 0.6 m/s to 1.6 m/s, respectively. This indicates that the interaction between solids in bulk flows and that between solids and pipe walls can cause the flow velocities to reduce significantly in bulk flow.

Besides, the mass flow rate and the total mass of bulk solid flows can be calculated using the proposed mass flow calculation method. The experiments also show that the measured errors of flowing mass are within 13.01%. The study shows that microwave sensor is potentially applicable to measurement of velocities and the determination of the mass flow rate of bulk solid flows.

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