

OPEN ACCESS

Digital image processing based mass flow rate measurement of gas/solid two-phase flow

To cite this article: Ding Song *et al* 2009 *J. Phys.: Conf. Ser.* **147** 012048

View the [article online](#) for updates and enhancements.

Related content

- [Comparison of differential pressure model based on flow regime for gas/liquid two-phase flow](#)
- [Mass flow measurement of pneumatically conveyed solids using electrical capacitance tomography](#)
- [Velocity measurement of pneumatically conveyed solid particles using an electrostatic sensor](#)

Recent citations

- [Particle volume flow rate measurement by combination of dual electrical capacitance tomography sensor and plug flow shape model](#)
Chit Oo Maung *et al*



IOP | ebooks™

Bringing together innovative digital publishing with leading authors from the global scientific community.

Start exploring the collection—download the first chapter of every title for free.

Digital image processing based mass flow rate measurement of gas/solid two-phase flow

Ding Song¹, Lihui Peng¹, Geng Lu¹, Shiyuan Yang¹, Yong Yan²

¹ Tsinghua National Laboratory for Information Science and Technology, Department of Automation, Tsinghua University, Beijing, 100084, China

² University of Kent, Canterbury, Kent CT2 7NT, U.K.

lihuipeng@tsinghua.edu.cn

Abstract. With the rapid growth of the process industry, pneumatic conveying as a tool for the transportation of a wide variety of pulverized and granular materials has become widespread. In order to improve plant control and operational efficiency, it is essential to know the parameters of the particle flow. This paper presents a digital imaging based method which is capable of measuring multiple flow parameters, including volumetric concentration, velocity and mass flow rate of particles in the gas/solid two phase flow. The measurement system consists of a solid state laser for illumination, a low-cost CCD camera for particle image acquisition and a microcomputer with bespoke software for particle image processing. The measurements of particle velocity and volumetric concentration share the same sensing hardware but use different exposure time and different image processing methods. By controlling the exposure time of the camera a clear image and a motion blurred image are obtained respectively. The clear image is thresholded by OTSU method to identify the particles from the dark background so that the volumetric concentration is determined by calculating the ratio between the particle area and the total area. Particle velocity is derived from the motion blur length, which is estimated from the motion blurred images by using the travelling wave equation method. The mass flow rate of particles is calculated by combining the particle velocity and volumetric concentration. Simulation and experiment results indicate that the proposed method is promising for the measurement of multiple parameters of gas/solid two-phase flow.

1. INTRODUCTION

Pneumatic conveying as a tool for the transportation of a wide variety of pulverized and granular materials has become widespread in many industrial fields. A well known example is pulverized coal in electrical power generation where the dilute-phase flow conditions give a typical solids/air mass ratio of 0.5:1 kg/kg to 5:1 kg/kg (equivalent to volumetric concentration of 0.05% to 0.5%) in the pneumatic pipelines (Hu et al., 2006). However, it is the mass flow rate of solids that is of primary interest to operators of a pneumatic conveyor (Yan et al., 1996).

It has long been recognized that the on-line measurement of gas/solid two-phase flow is a technically challenging area. Much work has been carried out in the field of gas/solids two-phase flow measurement over the past three decades. In general, the measurement methods can be classified into two categories, direct method and indirect method. The direct methods such as the thermal methods (Moriyama et al., 1985), the active charging and detecting method (Zhang, 1988), and the passive charge detecting method (Masuda et al., 1994), are capable of providing the mass flow rate directly.

However, besides the mass flow rate, the indirect method also provides other parameters such as particle velocity and volumetric concentration, which are useful for the monitoring of pneumatic conveying systems.

Recently, optical methods have attracted a lot attention because of their non-intrusive nature in the sensing process. Carter and Yan (2003) use a CCD camera for online particle size distribution and concentration measurement. Song et al. (2006) proposed a digital image processing based method for the measurement of particle velocity. This paper focuses on the mass flow rate measurement by using a single cost-effective digital camera.

2. MEASUREMENT PRINCIPLE

As depicted in Fig.1, the measurement system consists of a cost-effective solid state laser for illumination and a CCD camera for particle image acquisition. The principle of the proposed method is to capture particle images with adjustable exposure time. Clear images with shorter exposure time are used to determine the volume concentration, and the blurred images with longer exposure time are used to derive the particle velocity. The mass flow rate of particles is then deduced according to the following equation:

$$M_s(t) = \rho_s A V_s(t) \beta_s(t) \quad (1)$$

Where $V_s(t)$ and $\beta_s(t)$ are the particle velocity and cross-section averaged volumetric concentration, respectively, ρ_s is the true density of the solids material, and A is the cross sectional area of the pipe.

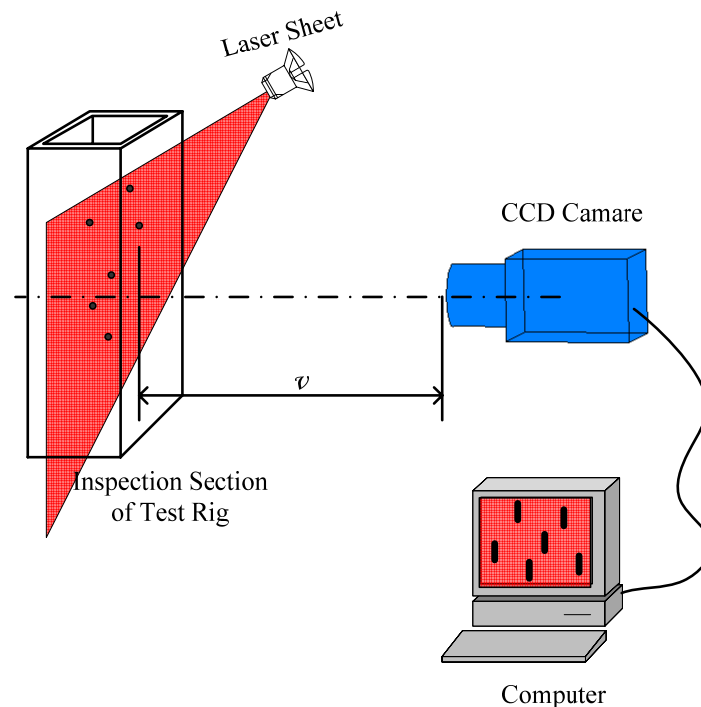


Fig.1 Principle of the measurement system

2.1 Velocity Measurement

To deduce the velocity of particles, the key point is to obtain from the blurred image the motion length due to the exposure time of the camera. A method based on the point spread function (PSF) has been

reported (Song et al., 2006). However, this method is sensitive to the noise in the image. The travelling wave equation (TWE) can be used to solve this problem (Cai et al., 2003). In addition, the travelling wave equation (TWE) method is easy to compute because the image processing is in the space domain. Without losing generality, we use $w(x, y, t)$ representing the gray scale of pixel (x, y) at time t in a moving image. Suppose the image keeps a linear uniform motion at a velocity of V_p pixels per second in x direction and its gray scale does not change during the motion, therefore,

$$\frac{\partial w(x, y, t)}{\partial x} \cdot \frac{\partial x}{\partial t} + \frac{\partial w(x, y, t)}{\partial y} \cdot \frac{\partial y}{\partial t} + \frac{\partial w(x, y, t)}{\partial t} = 0 \quad (2)$$

Assume that the image moves only in x direction at a velocity of V_p pixels per second, so $\frac{\partial x}{\partial t} = V_p$ and $\frac{\partial y}{\partial t} = 0$. Equation (2) now becomes

$$\frac{\partial w(x, y, t)}{\partial t} + V_p \frac{\partial w(x, y, t)}{\partial x} = 0 \quad (3)$$

Suppose $f(x, y)$ is the initial value (image) of $w(x, y, t)$ when $t = 0$, i.e.

$$f(x, y) = w(x, y, 0) \quad (4)$$

Equations (3) and (4) can be modelled with a 1-D travelling wave equation as follows

$$\begin{cases} \left(\frac{\partial}{\partial t} + V_p \frac{\partial}{\partial x} \right) w(x, y, t) = 0 \\ w(x, y, 0) = f(x, y) \end{cases} \quad (5)$$

The D'Alembert solution to equation (5) (Zhang et al., 2003) is

$$w(x, y, t) = f(x - V_p t, y) \quad (6)$$

According to the aforementioned analysis, $g(x, y, \tau)$, the so-called motion blurred image, is the total exposure of moving image on the CCD chip and can be obtained by integrating its instantaneous image $w(x, y, t)$ over the exposure time τ during which the camera shutter is open. In other words,

$$g(x, y, \tau) = \int_0^\tau w(x, y, t) dt \quad (7)$$

Multiplying the Equation (7) by V_p and differentiating both sides yields

$$\begin{aligned}
 V_p \frac{\partial}{\partial x} g(x, y, \tau) &= \int_0^\tau V_p \frac{\partial}{\partial x} w(x, y, t) dt \\
 &= \int_0^\tau -\frac{\partial}{\partial t} w(x, y, t) dt = -w(x, y, t) \Big|_0^\tau \\
 &= f(x, y) - f(x - V_p \tau, y) \\
 &= f(x, y) - f(x - \sigma, y)
 \end{aligned} \tag{8}$$

where $\sigma = V_p \tau$ is defined as the motion blur length and can be obtained by calculating the autocorrelation function of the row vectors of $\frac{\partial}{\partial x} g(x, y, \tau)$. The lens model (Song et al., 2006), which links the motion blur length σ to the particle velocity V_s , can be described as:

$$V_s = \frac{(u - f)\sigma e}{f \tau} \tag{9}$$

where u , v and f are the object distance, image distance and focal length of the lens system, respectively, τ stands for the exposure time of the CCD camera, and e is the size of each pixel.

2.2 Concentration Measurement

The volumetric concentration of solids represents the total quantity of moving solids within a pneumatic pipeline and is defined as the cross sectional area occupied by the moving solids normalized with respect to the pipe cross sectional area. The key task is to identify the particles from the acquired clear images under short exposure time. In fact, the acquired images are far less clear than their static counterparts because of the motion of particles and the non-uniformity of the illumination. For this reason, the background image is first obtained and then used to subtract from the original image. A simple thresholding method (Otsu, 1979) is used for the image segmentation, which is the key step to identify the particles from the dark background.

Otsu's algorithm assumes the image contains two classes of pixels (e.g. foreground and background) and finds the optimum threshold separating the two classes so that their combined spread (within-class variance) is minimal (Liu et al., 1993). As a method to select a threshold automatically from a gray level histogram, the Otsu method directly deals with the problem of evaluating the goodness of thresholds. An optimal threshold is selected by the discriminant criterion, namely by maximizing the discriminant measure (or the measure of separability of the resultant classes in gray levels).

Once a binarized image is available the sizes of particles can be determined. The system software calculates A_s which represents the sum of the area of all particles in the binary image. The volumetric concentration of β_s is calculated from:

$$\beta_s = \frac{A_s}{A} \tag{10}$$

where A represents the total area of the CCD camera scope.

3. RESULTS

Experimental tests were performed on a pneumatic conveying test rig (Carter et al., 2003; Peng et al., 2008) as depicted in Fig.2. The inner diameter of the pipeline is 40mm. A 1.3Mega pixel progressive scan CCD camera was installed on the inspection section to capture particle images. The camera works in two modes - short exposure time mode and long exposure time mode. Motion blurred images for particle velocity measurement were captured under the long exposure time mode. On the other hand, clear images for the volume concentration measurement were captured under the short exposure time mode. The superficial air velocity and mass flow rate of particles were varied by controlling the power of the vacuum system and the frequency of the vibrating feeder, respectively.

Sago particles with the diameter of approximately 3.2 mm were used as a test material. The true density of the particle is $1.329 \times 10^3 \text{ kg/m}^3$. Fig.3 and Fig.4 show some examples of particle images captured for different exposure times. The short exposure time (50 μs) was set to obtain the average volume concentration. Fig.3 shows the clear image and its thresholded version which was processed using the Otsu method. Long exposure time (1ms) was set to obtain motion blurred image for particle velocity measurement. The blurred images are illustrated in Fig.4. The Mass flow rate of solids was deduced using equation (1). Results obtained are summarized in Table 1.

Glass particles of 0.4mm in diameter and $2.213 \times 10^3 \text{ kg/m}^3$ true density were also tested. Table2 outlines the results.

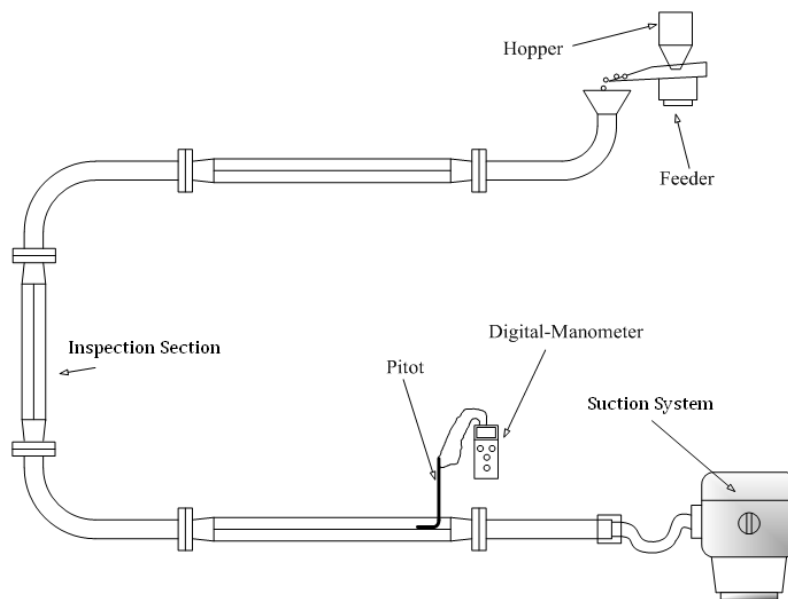


Fig.2 Schematic diagram of the test rig

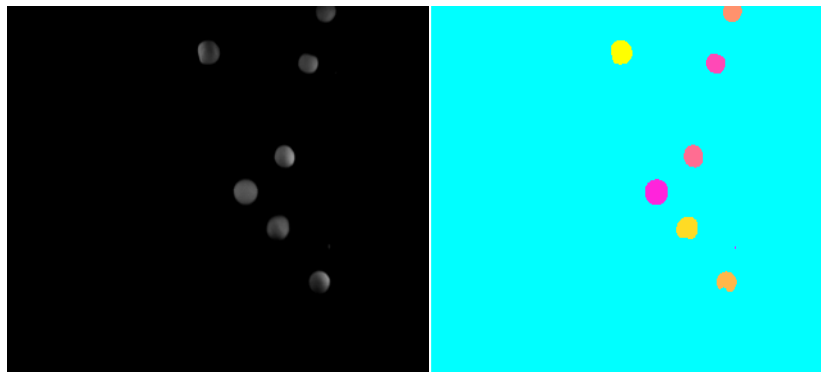
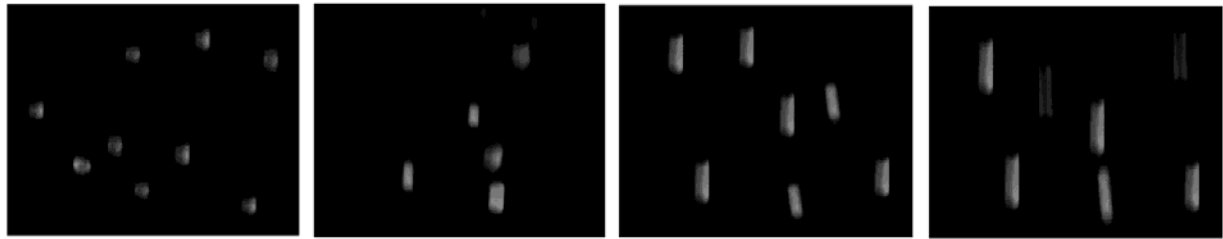


Fig.3 Clear image and its thresholded version



Air velocity=7m/s

Air velocity=9m/s

Air velocity=11m/s

Air velocity=13.3m/s

Fig. 4 Motion blurred images for different air velocities (CCD exposure times=1ms)

Table 1. Mass flow rate measurement results using sago particles as a test material

Total mass (kg)	Measurement time (s)	Air velocity (m/s)	Measurements (kg)							
			1	2	3	4	5	6	Mean value (kg)	Standard deviation (kg)
2	120	7	1.835	1.965	2.253	1.796	2.092	1.781	1.946	0.173
2	120	9	2.182	2.096	1.865	1.968	2.163	1.802	2.041	0.163
2	120	11	2.223	2.152	1.873	1.902	1.825	1.854	1.953	0.163
2	120	13.3	1.914	1.963	2.123	2.208	2.107	1.907	2.063	0.134
2	180	7	2.172	2.302	1.875	1.869	1.924	2.197	2.078	0.181
2	180	9	2.249	1.853	1.864	1.832	2.092	1.867	1.958	0.157
2	180	11	2.155	1.896	1.874	2.106	1.909	1.865	1.947	0.135
2	180	13.3	1.874	2.166	1.968	2.201	2.136	1.985	2.032	0.135
2	300	7	2.091	2.135	2.093	1.833	1.891	2.103	2.037	0.122
2	300	9	1.826	2.271	1.864	1.934	2.202	1.921	2.024	0.159
2	300	11	2.123	1.865	1.832	1.968	2.168	2.244	2.044	0.157
2	300	13.3	1.909	2.124	2.214	1.934	1.936	2.21	2.026	0.154

Table 2. Mass flow rate measurement results using glass particles as a test material

Total mass (g)	Measurement time (s)	Air velocity (m/s)	Measurement value (g)							
			1	2	3	4	5	6	Mean value (g)	Standard deviation (g)
500	120	7	550.57	545.85	519.16	481.36	500.93	463.27	510.19	34.94
500	120	9	532.58	510.51	439.91	445.59	481.37	500.45	485.07	36.75
500	120	11	528.69	465.93	494.82	479.20	505.50	556.81	505.16	33.29
500	120	13.3	533.71	491.74	462.42	542.99	531.15	540.37	517.06	32.61
500	180	7	553.44	477.08	519.78	446.03	553.04	517.28	511.11	42.56
500	180	9	551.46	464.34	550.94	474.80	499.99	518.72	510.04	37.13
500	180	11	533.47	491.61	452.93	451.56	524.94	508.19	493.78	35.24
500	180	13.3	505.76	505.15	480.61	528.87	515.74	485.02	503.53	18.26
500	300	7	520.20	539.60	495.37	482.20	488.42	461.49	497.88	27.95
500	300	9	466.21	480.13	504.31	476.59	455.92	511.82	482.50	21.67
500	300	11	528.66	484.93	547.67	458.69	497.99	552.50	511.74	37.31
500	300	13.3	475.53	494.47	535.61	471.27	462.31	490.26	488.24	26.11

4. CONCLUSIONS

A method for the mass flow rate measurement of pneumatic conveyed particles through digital imaging is proposed. By controlling the exposure time of a CCD camera, both a clear image and a motion blurred image are obtained, respectively, and these images are then used to derive the particle velocity, the volume concentration, and the mass flow rate. The experimental tests on the pneumatic conveying test rig have produced favourable results supporting that the proposed digital imaging method is a viable approach to mass flow rate measurement. Future work will focus on the enhancement of the real-time performance of the system and the practical design and implementation of a prototype system for field trials.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the National Natural Science Foundation of China for providing financial support under the framework of two-base research project between Tsinghua University, China and University of Kent, U. K. (contract number 60440430641). The authors are also grateful to Tsinghua Basic Research Foundation for supporting the project under the contract No. JC2007026.

NOMENCLATURE

A	the cross-section area of the pipe	[m ²]
A_s	sum of the area of all particles in the binary image	[m ²]
e	the size of CCD pixel	[m]
f	focal length of the lens system	[m]
$f(x, y)$	original image	[-]
$g(x, y, \tau)$	motion blurred image during the exposure time	[-]
$M_s(t)$	mass flow rate	[kg/s]
u	object distance of the lens system	[m]
V_s	particles velocity	[m/s]
V_p	particle image velocity	[pixel/s]
$V_s(t)$	solids velocity of the two-phase flow	[m/s]
$w(x, y, t)$	instantaneous exposure of the moving object at time t	[-]
x, y	dimensions of image array	[-]
$\beta_s(t)$	volumetric concentration	[-]
ρ_s	density of the solids material	[kg/m ³]
σ	motion blur length	[-]
τ	exposure time of the CCD camera	[s]

REFERENCES

- Cai, L. D. (2003). "Travelling wave equations and restorations of motion blurred images," *Acta Automatica Sinica*, 29, pp. 466-471.
- Carter, R. M., Yan, Y. (2003). "On-line particle sizing of pulverized and granular fuels using digital imaging techniques," *Measurement Science & Technology*, 14(7), pp. 1099-1109.
- Hu, H. L., Xu, T. M., Hui, S. E., Zhou, Q. L. (2006). "A novel capacitive system for the concentration measurement of pneumatically conveyed pulverized fuel at power stations," *Flow Measurement and Instrumentation*, 17(2), pp. 87-92.

Liu, J. Z. et al. (1993). "The automatic thresholding of gray-level picture via 2D Otsu method," *Acta Automatica Sinica*, 19(1), pp. 101-105.

Masuda, H., Matsusaka, S., Nagatani, S. (1994). "Measurement of powder flow rate in gas–solids pipe flow based on the static electrification of particles," *Advanced Powder Technology*, 14(5), pp. 5241-5254.

Moriyama, T., Fujii, S., Abe, K., Kobayashi, M, (1985). "Mass flowmeter using heat transfer for dense phase solid gas two-phase flow, " 'Int. Conf. on Fluid Control and Measurement, Tokyo, 1985, September.

Peng, L. H., Zhang, Y., Yan, Y. (1993). "Characterization of electrostatic sensors for flow measurement of particulate solids in square-shaped pneumatic conveying pipelines," *Sensors and Actuators A: Physical*, 141(1), pp. 59-67.

Otsu, N. (1979). "A threshold selection method from gray-level histograms," *IEEE Transactions on Systems, Man, and Cybernetics*, 9(1), pp. 62-66.

Song, D., Peng, L. H., Zhang, Y., Yang, S. Y. (2006). "Simulation studies on the on-line concurrent measurement of velocity and size distribution of pneumatically conveyed particles through digital imaging," 'The 5th International Symposium on Measurement Techniques for Multiphase Flows, Macau, China, December 10-13.

Yan, Y. (1996). "Mass flow measurement of bulk solid in pneumatic pipelines," *Meas. Sci. Technol.*, 7(12), pp. 1687-1760.

Zhang, J., Chen, H. R., Rong, G. (2003). "Motion blurred image restoration based on wave equation," *Journal of Tsinghua Science and Technology*, 45(7), pp. 1003-1007.

Zhang, X. L. (1988). "The development and test of FG-1 type flowmeter for pulverized materials," 'Proc. First Int. Conf. on Measurement and Control of Granular Materials, Shenyang, China, September.