On-line Measurement of Pneumatic Conveying of Pulverized Coal in pipes

JIA Zhi-hai¹, FAN Xue-liang¹, LI Jun-feng¹, CAI Xiao-shu¹, LIU Ji-ze², CONG Xiao², JIA Jing-chen²

1.University of Shanghai for Science & Technology, Shanghai, 200093, China
2.Zouxian Power Plant, Huadian International Electric Power Co. Ltd. ,Zoucheng, 273522, China

jzhihai@163.com

Abstract. Running conditions of pulverized coal pipes and mills are of greatly effecting on the combustion and safely operation of utilities in coal-fired power plants. However, there are less effective ways to on-line measure or diagnose the pipes or mills. Based on light fluctuation method, the on-line measurement of size and concentration of pulverized coal were presented in this work. Moreover, the velocity of pulverized coal in pipes was measured by cross correlation method. A novel on-line monitoring system was designed with above measurement principles. The on-line monitoring system was applied to measure pulverized coal pipes and mills in-situ in a 1000MW ultra supercritical unit. The unit had 48 pulverized coal pipes and adopted three–layer opposed firing pattern. The experimental results showed the on-line monitoring system can simultaneously measure the size, concentration and velocity of pulverized coal in different coal pipes accurately and quickly. Using these parameters, the running condition of pulverized coal pipes and mills can be diagnosed. Therefore, this work provided a practical method and instrument for on-line monitoring technology of pulverized coal pipes and mills.

1. INTRODUCTION

Pneumatic conveying is based on the physical principle that air, under certain conditions, is able to convey heavy materials. The importance of efficient pneumatic conveying of particulate materials is widely accepted in many industries. Pulverized coal flowing in pipes is a typical phenomenon of pneumatic conveying. Detailed information on the flowing particles other than the mass flow rate, such as the particle size, concentration and the local velocity, is recognized as important to process optimization and control as well as to improvement in the understanding of multiphase flow fundamentals. A common requirement exists for the continuous on-line measurement of these parameters. Much research work has been carried out in the field of pulverized coal flow metering and a wide range of techniques. Many authors tried to use different methods to on-line measurement of pneumatic conveying of pulverized coal in pipes. A number of methods have been proposed for sizing, concentration and mass flow rate, including those based on capacitance method, electrostatic method, differential pressure, acoustic emission, imaging method and so on.

Capacitance transducers are the early technique to measure mass flow rate. In general, these transducers are designed to determine the capacitance arising from the average permittivity of the mixture of conveyed and conveying phases flowing within the sensing volume of the capacitor electrode. For example, Beck et al(1990) designed a capacitance sensor to monitor mass flow
measurement in pneumatic conveyors with very low solids loading. Later, electrostatic method was adopted to measure the parameters of pulverized coal. Yan and Li et al (1996, 2000, 2001) tested the velocity of particles with cross correlating two signals derived from a pair of electrostatic sensors. They designed a electrostatic sensors to evaluate the mass flow measurement of pneumatically conveyed solids. Digital imaging is becoming increasingly attractive because of the availability of low-cost high performance imaging devices and computing hardware. An advantage of using the imaging approach is that non-intrusive real-time measurement of many individual particles can be measured concurrently and continuously. Some researchers had done much work in this field, such as Carter and Yan (2003, 2005), Li and Tomita(2000), Nishino and Hiroyuki(2000). They studied the mass flow measurement of particles, velocity and volumetric concentration of particles using the digital imaging sensors. Some measurement equipments based on these methods have had development to measure various flow parameters. However, few systems have achieved commercial success to date.

In recent years, optical techniques have become one of the major contenders for being on-line multiphase flow measurement methods, such as Black and McQuay’s work (1996). One of their main advantages is that they are nearly free of interference by most environmental factors, such as temperature, humidity and electrostatics. On the other hand, they are highly sensitive to change in either the concentration or the size of the measured particles. Therefore, optical techniques have been recognized as more appropriate method to on-line measure particle parameters. Teipel (2002) used laser light diffraction spectrometry technique to determine particle size distribution. Cole et al (2001) used Mie scattering theory to measure hypersonic microparticle characteristics. Recently, Xu and Cai et al (2004, 2005) studied the forward scattering theory and designed an advanced coal measurement sensor to measure the pulverized coal characteristic parameters.

However, gas-particle two-phase flow is an unsteady and complicated nonlinear dynamics system. A detailed understanding of the behavior of particles is important for design, optimization, and operation of the pneumatic conveying system. Most of the proposed methods are still on the stage of laboratory research and few of them are commercialized and practically used in industry. There are still less effective ways to on-line monitor or diagnose the pulverized coal pipes. It is clear that an instrumentation system must be developed that can measure these important parameters online.

This paper presents a new solution for the measurement of size, concentration and velocity of particulates within a gas-solid pneumatic conveying pipeline using laser light fluctuation and cross-correlation method. An advanced on-line pulverized coal monitoring system was devised and applied to measure pulverized coal pipe in-situ in a 1000MW ultra supercritical unit and measurement results was going to be discussed.

2. MEASUREMENT PRINCIPLES
2.1 Measurement of the size and concentration of pulverized coal
When a bouquet of parallel single wavelength laser light passed through the measured particles, due to the scattering and absorption of light, the transmitted light intensity will decay. According to Lambert-Beer’s Law, the transmitted light intensity can be described as

$$\ln \left( \frac{I}{I_0} \right) = -\frac{\pi}{4} LD^2 NE(\lambda, m, D)$$

(1)

Where $I$ and $I_0$ are the transmitted and incident light intensity respectively, $L$ is the path that the measuring beam traverses through the sensed volume, $D$ is the mean diameter of particles ; $N$ is the concentration of particles per unit volume, $E(\lambda, m, D) =$ the coefficient of decay light and related with wavelength of laser light $\lambda$, relative refraction index $m$, and $D$. The coefficient of decay, $E$, can be calculated according to Mie scattering theory.

If the cross-sector area of light beam is $A$, then the volume of measurement zone is equal to $AL$. The equ. (1) can be modified into
\[
\ln \left( \frac{I}{I_o} \right) = -\frac{\pi}{4A} nD^2 E(\lambda, m, D)
\]

(2)

Where \( n \) is the number of particles through the measurement zone, \( n = NAL \).

Further researches showed the beam diameter \( A \) had complex relation with the size and concentration of pulverized coal. When \( A \) diminished to a certain extent, the number of particles through the test zone was stochastic and varied with the measurement time. That resulted in the transmitted light intensity increasing. Because the transmitted light intensity \( I \) was caused by the number of the particles and size of pulverized coal, it contains the information of the concentration and size of pulverized coal. Therefore, through analyzing the transmitted light intensity, the size and concentration of pulverized coal can be acquired by inversion algorithm.

In most cases, the fluctuation of the transmitted light intensity can be mostly ascribed to the variation in the number of the sensed particles. If the particle/beam size ratio is much smaller than 1, the “boundary effect” can be neglected. Then, the mean transmitted light intensity \( \bar{I} \) and its variance \( \sigma^2 \) can be calculated with equ. (3) and equ. (4).

\[
\bar{I} = I_o e^{-\tau}
\]

(3)

\[
\sigma^2 = (\Delta I)^2 = I_o^2 \Phi(\tau) / \bar{N}
\]

(4)

Where \( \tau \) is the absorption coefficient of particles, \( \tau = -\ln(\bar{I} / I_o) \), \( \bar{N} \) is the average number of the particles in the measurement zone, and \( \bar{N} = nL \), \( \bar{n} \) is the average concentration of the particles, \( \bar{n} = \tau / L \Phi(\tau) \) is a single-peaked Shifrin function.

\[
\Phi(\tau) = 2\pi e^{-2\pi} \int_0^\pi \chi(\tau, \Psi) d\Psi
\]

(5)

\[
\chi(\tau, \Psi) = \sin(\Psi) \exp \left[ \frac{\tau(\Psi - \sin(\Psi))}{\pi} - 1 \right]
\]

(6)

Hence, the projection area of the particle of pulverized coal is

\[
S_1 = \frac{(\Delta I)^2}{I_o^2} \left[ A - \frac{\tau}{\Phi(\tau)} \right]
\]

(7)

or the average size of the particle is

\[
D = \sqrt{4S_1 / \pi}
\]

(8)

and mass concentration of pulverized coal is

\[
W = \frac{\pi}{6} \rho \bar{n} D^3
\]

(9)

Where \( \rho \) is the density of pulverized coal.

2.2 Measurement of the velocity of pulverized coal

The cross-correlation method is a technique widely used for measurement of flow rate, which may also be applied to measure the velocity of the flowing particles: two measuring light beams are aligned at a short distance, \( l \), along the flowline and the time lag between the upstream and downstream transmission signals, \( \tau \), is determined by extremum point estimation of the cross-correlation function, then the local flow velocity, \( v \), is given as follows:

\[
R_{12}(\tau) = \lim_{\tau \to 0} \frac{1}{T} \int_0^T y_1(t) y_2(t - \tau) dt
\]

(10)

The cross-correlation function \( R_{12}(\tau) \) and transmit time \( \tau \) can be calculated with FFT. Then the velocity of pulverized coal can be acquired with equ. (11).
\[ v = \frac{l}{\tau} \]  

(11)

3. PROBE STRUCTURE AND INSTALLATION

In this work, a novel on-line monitoring system based on the laser light fluctuation method and cross-correlation method has been developed for on-line measurement of pneumatically conveyed solid particles, as shown in Fig. 1. It is of great significance to consider how to enable enough flexibility and easy install/uninstall processes for the intrusive probe. The laser diode, the optical fibers, the photodetectors and the preamplifier circuit are all integrated into a rugged package at the probe tip, making the install/uninstall process quite convenient. In addition, the intrusive probe is made of ceramics to ensure excellent work reliability and resistance to abrasive erosion by flowing particles. This makes the probe appropriate for in-line measurement of hard solids, even with a high flow rate. To prevent contamination and blockage of the beam aperture by the flowing solids, a purging air flow is injected into the probe, which also helps with probe cooling. When used for continuous measurement of long duration, little maintenance work is required besides occasional self-calibration with no particle load.

The instrument can measure simultaneously the concentration, size and velocity of pulverized coal. It works as follows: a light beam produced by a laser diode traverses through the sensed volume and undergoes attenuation due to absorption and scattering by the sensed particles; the transmitted light is received by an optical fiber and then falls onto a photodetector, giving rise to a series of voltage signals, which are pre-amplified and sent to the AD unit whose output is analyzed by a computer. A compact portable type or a stationary type of the instrument is available upon request. The former consists of an intrusive probe for user-defined sizes compatible with a certain application, a pre-amplifier/AD unit with a USB output port and an optional laptop. The instrument is capable of simultaneously driving 48 individual probes.

Experiments were carried out in a 1000MW ultra supercritical unit in Zouxian power plant, China. The boiler adopted three–layer opposed firing pattern. The supercritical boiler had six double charge-discharge coal ball mills and a mill provided pulverized coal to eight pipes. The total coal pipes are 48. The measurement probes installed in pulverized coal pipes in situ were shown in Fig. 2.

The running parameters of pulverized coal are as follow: diameter of pipe: \( \Phi 480 \times 10\text{mm} \); operating temperature: 70–100°C; primary air flow velocity: 18–25m/s; concentration of pulverized coal (coal/air): 0.45–0.61kg/kg; probes working environment: working temperature <100°C, working pressure <6kPa; surrounding working environment: temperature 0–40°C.

4. MEASUREMENT RESULTS AND DISCUSSION

The measurement probe was installed on the coal pipes at Zouxian coal-fired power plants for medium
term in situ tests. Real-time, on-line monitoring of pulverized coal flow in transport pipes may provide an indication of how to retain the proper air/fuel balance at each burner as well as control and diagnosis of mills running. A real-time experiment results by the on-line monitoring system of pulverized coal were shown in Tab. 1.

**Tab.1** A real-time measurement data for D and B layers

| Pipes | D layer |    |    |    | B layer |    |    |
|-------|---------|----|----|----|---------|----|----|
|       | C (kg/m³) | S (µm) | V (m/s) | C (kg/m³) | S (µm) | V (m/s) |
| 1     | 0.67    | 19.25 | 20.00 | 0.65 | 19.60 | 15.62 |
| 2     | 0.66    | 13.62 | 18.23 | 0.57 | 20.10 | 21.79 |
| 3     | 0.61    | 29.90 | 27.82 | 0.65 | 39.18 | 20.00 |
| 4     | 0.65    | 57.87 | 23.00 | 0.68 | 20.14 | 19.84 |
| 5     | 0.59    | 49.83 | 20.19 | 0.65 | 36.08 | 20.79 |
| 6     | 0.66    | 10.97 | 15.47 | 0.64 | 15.94 | 19.23 |
| 7     | 0.63    | 40.56 | 16.78 | 0.62 | 39.28 | 15.91 |
| 8     | 0.65    | 14.50 | 18.52 | 0.57 | 25.94 | 15.07 |

Note: C-Concentration; S-Size; V-Velocity

The D and B layers are the lower opposite layers of the three layer burners. From the table 1, the measured parameters are in general accord with the outlet parameters of mills. That proved the monitoring system has the characteristic of high accuracy. In addition, the parameters of pulverized coal have the characteristic of fluctuation. For example, the concentration of pulverized coal from D layer varied from 0.59~0.67kg/m³, however, 0.57~0.68kg/m³ from B layer. These parameters provided valuable data to monitor the running condition of coal pipes and mills.

In order to further study the characteristics of pulverized coal, the long-time measurement was carried out for D1 and B1 coal pipes. The measurement results were shown in Fig. 3, Fig. 4 and Fig. 5. For the 1000MW ultra supercritical unit, the concentration of pulverized coal from D1 and B1 coal pipes from the same mill varied from 0.55~0.70kg/m³. That proved that the primary air velocity had an effect on the concentration of pulverized coal. Because the primary air velocity was unsteady, that resulted in the concentration of pulverized coal varies, but the mean concentration was steady.

![Fig.3 The concentration of pulverized coal](image1)

![Fig.4 The size of pulverized coal](image2)

The size of pulverized coal has relation with safe and steady combustion. According to the Fig. 5, the size of particles from the mill varied from 10~60µm and the size was small in general. The sizes of D1 and B1 coal pipes were 31.25µm and 32.31µm, respectively. The pulverized coal was measured by off-line instrument, particle imaging analyzer, and the mean size was 34.65µm. The on-line...
monitoring system’s error was less than 10% and satisfied the accuracy of measurement in situ. Moreover, the smaller the mill produced the size of pulverized coal, the higher the pulverized coal contained volatile content and calorific value. If the concentration of pulverized coal is higher than critical concentration (1.2~2.0kg/m$^3$), the explosion will be caused. According to the measurement results, the size of pulverized coal was in a safe level and assured the boiler safe running.

The mass flow rate is of great important to monitor the running operation of pipes and boiler. The flow velocity directly related to mass flow. The velocity of pulverized coal in D1 and B1 pipes was shown in Fig. 5. Because of turbulence effect, the flow velocity of particulates varied with air flow. Their mean velocities were less than primary air velocity. The difference of mean velocity between the D1 and B1 pipe was small and the mean velocity was 20.63m/s. Therefore, the boiler lay in balanced combustion.

Through testing the 1000MW ultra supercritical unit with the on-line monitoring system, the unit lay in a good running status.

5. CONCLUSIONS

Through monitoring the running condition of pulverized coal pipes and mills of the 1000MW Ultra supercritical unit, the following conclusions can be made.
(1) The on-line monitoring system can measure accurately the concentration, size and velocity of pulverized coal. A novel on-line monitoring system of pulverized coal was provided to test in situ.
(2) It is different that the concentration, size and velocity of pulverized coal from the different pipes of the same mill. Using the fluctuation signals, the running status of mill can be evaluated.
(3) It is helpful for boiler by monitoring these parameters and helpful to know the running status of pulverized coal pipes.
(4) The on-line monitoring system has the advantage of high accuracy, simplicity, reliability, and low cost and it is convenient to install/uninstall in pipes.

ACKNOWLEDGEMENTS

The authors like to thank National Natural Science Foundation of China (No.50706029), 863 plan of china (2006AA03Z349) and Shanghai special fund for choosing and cultivating young scholars.

REFERENCES

Beck M S, Green R G, plaskowski A B, Scott A L.(1990). Capacitance measurement applied to a pneumatic conveyor with very low solids loading, 1(7): 561-564.

Black D L, McQuay M Q, Bonin M P. (1996). Laser-based techniques for particle-size measurement: A review of sizing methods and their industrial applications. Progress in Energy and Combustion Science, 22(3): 267-306.

Cai X S, Li J F, Ouyang X, Zhao Z J, Su M X. (2005). In-line measurement of pneumatically conveyed particles by a light transmission fluctuation method. Flow Measurement and Instrumentation, 16 (5): 315–320.
Carter R M, Yan Y. (2003). On-line particle sizing of pulverized and granular fuels using digital imaging techniques. Measurement Science and Technology, 14(7): 1099-1109.

Carter R M, Yan Y, Cameronb S D. (2005). On-line measurement of particle size distribution and mass flow rate of particles in a pneumatic suspension using combined imaging and electrostatic sensors. Flow Measurement and Instrumentation, 16(5): 309–314.

Cole J B, Jagadeesh G, Takayama K. (2001). Optical measurement of hypersonic microparticles using Mie scattering. Proceedings of SPIE-The international Society for Optical Engineering, Vol. 4183, pp552-555.

Li H, Tomita Y. (2000). Particle velocity and concentration characteristics in a horizontal dilute swirling flow pneumatic conveying. Powder Technology, 107(1-2): 144–152.

Ma J, Yan Y. (2000). Design and evaluation of electrostatic sensors for the mass flow measurement of pneumatically conveyed solids, Flow Measurement and Instrumentation, 11(3): 195–204.

Nishino K, Hiroyuki K, Kahoru T. (2000). Stereo imaging for simultaneous measurement of size and velocity of particles in dispersed two-phase flow. Measurement Science and Technology, 11(6): 633-645.

Teipel U. (2002). Problems in Characterizing Transparent Particles by Laser Light Diffraction Spectrometry. Chemical Engineering & Technology, 25(1): 13–21.

Xu F, Cai X S, Ren K F. (2004). Geometrical Optics Approximation of Forward Scattering by Coated Particle. Applied Optics, 43(9):1870—1879.

Yan Y. (1996). Mass flow measurement of bulk solids in pneumatic pipelines[J]. Measurement Science and Technology, 7(12): 1687-1706.

Yan Y. (2001). Guide to the flow measurement of particulate solids in pipelines, Part I: Fundamentals and principles. Powder Handling and Processing, 13 (4): 343–352.