Flow Measurement and Instrumentation 40 (2014) 185–191

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Pulverized coal flow metering on a full-scale power plant using electrostatic sensor arrays

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ARTICLE INFO

Available online 7 July 2014

Keywords:
Pulverized coal
Gas–solid two-phase flow
Particle velocity
Mass flow rate
Fuel distribution
Electrostatic sensor
Cross-correlation

ABSTRACT

On-line continuous monitoring of pulverized coal in fuel injection pipes will allow power plant operators to optimize fuel conveying conditions and ultimately to achieve higher combustion efficiency and lower atmospheric emissions. This paper presents the design, implementation and trials of a prototype instrumentation system for the on-line measurement of pulverized coal on a full-scale power plant. An array of three identical arc-shaped electrostatic electrodes is housed in a sensing head to derive particle flow signals. Pulverized coal flow parameters such as velocity, mass flow rate and fuel distribution among the injection pipes from the same pulverizing mill are obtained by processing the signals and fusing the resulting measurements. On-plant demonstration trials on 560 mm bore pneumatic conveying pipes feeding a 600 MW boiler were undertaken following system evaluation tests on a 50 mm bore laboratory test rig. Experimental results demonstrate that reliable monitoring of pulverized coal flow parameters is achieved and that the system is able to track both transient and long-term fluctuations of pulverized coal flow in fuel injection pipes under real power plant conditions.

1. Introduction

Despite the increasing use of renewable energy (solar, wind power, etc.), pulverized coal (or pulverized fuel, PF) remains to be a primary energy source around the world. Real-time data about variations in PF supply will allow power plant operators to achieve safer and more economic fuel handling and will ultimately lead to improved fuel combustion performance and reduced pollutant emissions. Therefore, the development of a reliable instrumentation system that is capable of continuously measuring PF flow parameters and is easy to install and maintain is of great interest to the power generation industry.

Substantial effort has been invested in developing technologies that may offer solutions to the measurement challenges and much progress has been made in the past two decades. Common inferential methods include acoustic emission, digital imaging, electrical capacitance, electromagnetic waves, mechanical vibration, optical and thermal techniques, etc. [1–2]. Such methods essentially use either passive detection of certain physical properties of particles or injection of external energy that is modulated by particles to derive the flow parameters [2]. Most of the proposed methods can only offer satisfactory measurement performance under laboratory or strict flow conditions. Therefore, reliable on-line continuous measurement of PF flow is still a technically challenging area due to its dilute nature, extremely complex dynamics and industrial restrictions [3]. The electrification of particulate material in pneumatic conveying pipes is a well-known phenomenon. Electrostatic sensors, which are passive without any injection of energy (in any form) to the flow, make good use of this phenomenon to measure the flow parameters by sensing the fluctuation of the electrostatic field due to the charged particles. Because electrostatic sensors respond only to moving particles, the signals enjoy a high degree of immunity from the physical properties and accretion effects of particles in pipes, which adversely affect other technologies [2–3]. The electrostatic sensing technique offers a prospective solution to measuring key parameters of PF flow [4–5] due to its unique advantages such as low cost, simple structure and easy installation. The development of electrostatic sensors for the measurement of gas–solid flow in a pneumatic conveying pipe began from more than half a century ago [6]. A mathematical model of the circular electrostatic sensor was reported by Yan et al. [7]. Xu et al. [8–9] analyzed the frequency response, bandwidth, spatial sensitivity and spatial filtering effect of circular electrostatic sensors. Intrusive electrostatic electrodes were studied by Shao et al. [10] and Krabicka and Yan [11] through both finite-element modeling (FEM) and

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http://dx.doi.org/10.1016/j.flowmeasinst.2014.06.001
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experimental assessment on a 94 mm bore horizontal pipe feeding PF to a 4 MW industrial furnace. Zhang et al. [12] studied the impact of sampling frequency and integral time of the electrostatic signal on correlation velocity measurement based on FEM analysis. Qian and Yan [13] implemented a multi-channel electrostatic sensor system to measure velocity, particle concentration and flow stability of biomass and biomass blends on a 50 mm bore laboratory-scale test rig. They used an array of four circular electrodes to measure the cross-sectionally averaged particle velocity and four arrays of four arc-shaped electrodes to measure the localized particle velocities on a horizontal pipe. Preliminary industrial-scale tests of PF flow and coal-biomass mixture flow were also conducted on a 150 mm bore pipe using the same sensor design and data fusion techniques [14]. An integrated instrumentation system, incorporating electrostatic and capacitive sensors and data fusion algorithms, was reported by Zhang et al. [15] for the volumetric concentration measurement of biomass/coal/air three-phase flow in a 100 mm bore pneumatic pipe. Zhou and Zhang [16] presented a non-invasive measurement method of visualizing the flow pattern and charge distribution of glass beads and PF under dense-phase flow conditions on 25 mm bore gravity-fed and 100 mm bore pneumatic conveying rigs. However, most of the above research is conducted under laboratory conditions and a very few systems have been evaluated in a full-scale power plant environment [17].

In this study, an instrumentation system for on-line flow metering of PF is designed and implemented, which has taken into considerations the difficult nature of PF flow, harsh industrial environment and power plant installation requirements. Systematic evaluation tests of a 50 mm bore sensing head were conducted on a laboratory scale test rig. A system comprising four independent electrostatic sensing heads was installed and evaluated on 560 mm bore PF pipes from the same pulverizing mill on a 600 MW PF-fired boiler unit.

2. Measurement principles

Various intrusive and non-intrusive electrostatic sensors of different shapes and dimensions have been used as the sensing units of particle flow measurement systems [7,10,13,14]. However, non-intrusive installation is desired in most industrial applications. The arc-shaped electrode is particularly suitable for industrial installation due to its non-intrusiveness and flexibility in installation and is thus adopted in this research. Fig. 1 shows the structure of a 3 mm wide stainless steel arc-shaped electrode with a 60° central angle flush mounted on the inner pipe wall along with its simulated sensitivity distribution using FEM. As shown in Fig. 1, the electrode is more sensitive to particles in its vicinity. Therefore, the sensor with arc-shaped electrodes should be installed on a vertical pipe where particle velocity profile and distribution across the pipe are relatively homogeneous [2]. Multiple sensors may have to be installed on a horizontal pipe in view of the likely inhomogeneous distribution of particles and irregular velocity profile across the pipe.

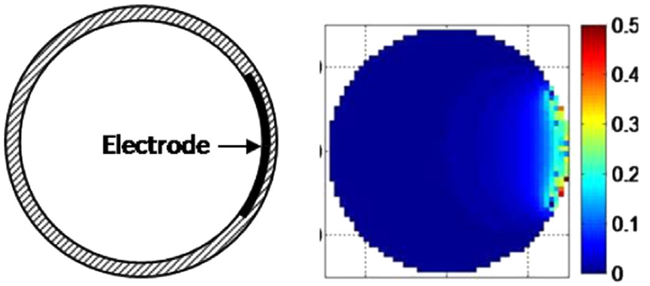

Fig. 1. Cross section of an arc-shaped electrode and its spatial sensitivity distribution.

Cross correlation is a well-established method that has been widely used to determine the fluid velocity by calculating the flow transit time between the upstream and downstream sensors [2,4,6,10,12–14]. Electrostatic sensors combined with cross correlation signal processing algorithms are superior to all other known sensors for the velocity measurement of pneumatically conveyed particles under steady flow conditions [7]. However, inhomogeneous distribution of particles and irregular velocity profile with the volumetric concentration of particles in a PF pipe being 0.1% or less lead to significant fluctuations in the measured flow parameters and sometimes spurious readings due to an ill-defined correlation peak [18]. To minimize this problem, an array of electrodes is employed to conduct multiple measurements simultaneously, so that more reliable flow parameters can be obtained by fusing all the measurements. Fig. 2 shows the block diagram of a three-electrode correlation velocimetry system.

Unlike the conventional two-electrode system, a third electrode with the same geometric structure and dimensions is added to the system. The use of three electrodes in the sensing unit is a trade-off among fast system response, measurement reliability and compactness of the sensing head. As the sensor array consists of three equally spaced identical electrodes, three correlation velocities are obtained by permutation of the signals. If one more sensor is added to the array, the signal processing time will be doubled, and as a result the system response performance will deteriorate. The three-sensor system will still be functioning when one of the sensors fails to function or an ill-defined correlation peak is obtained from one or two pairs of the signals under very difficult flow conditions. As the main body of the electrostatic sensing head that is used in the power plant is made of stainless steel, the three-electrode system is much lighter in weight and relatively easier to install than a system with more complex structure. The three correlation functions from the three signals are given by

$$R_{12}(\tau)=\frac{1}{T}\int x_1(t)x_2(t+\tau)dt \tag{1}$$

$$R_{23}(\tau)=\frac{1}{T}\int x_2(t)x_3(t+\tau)dt \tag{2}$$

$$R_{13}(\tau)=\frac{1}{T}\int x_1(t)x_3(t+\tau)dt \tag{3}$$

where $x_1(t)$, $x_2(t)$ and $x_3(t)$ are the three electrostatic signals and T is the integration time. For each pair of electrodes, three velocities of the particles are determined from the known spacing (L) and the transit time (τ)

$$v_{12}=\frac{L}{\tau_{12}} \tag{4}$$

$$v_{23}=\frac{L}{\tau_{23}} \tag{5}$$

$$v_{13}=\frac{2L}{\tau_{13}} \tag{6}$$

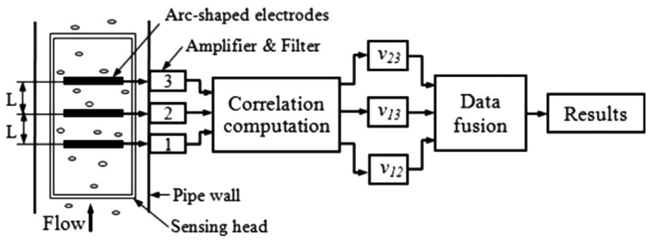

Fig. 2. Block diagram of the three-electrode correlation velocimetry system.