Online Measurement System of Pulverized-Coal Concentration in Power Plant

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Abstract. Measurement for pulverized-coal concentration is important to the safe and economic operation in power plant. This paper presents an on-line measurement system for pulverized-coal concentration based on the method of ultrasonic attenuation in the gas-solid two phase flow. According to the non-liner error of the ultrasonic transducer, multiple reflections signal from the two ultrasonic transducer is used to calculate the concentration, the result of which is displayed on LabVIEW. The experiment result shows that the multiple reflections signal can reduce the non-liner error and improve the accuracy of the measurement.

1. Introduction
The importance of pulverized-coal in power plant has given considerable impetus to the development of analytical techniques to provide information about concentration, such as electrostatic sensor technology [1], light scattering [2], and light microscopy [3]. Each technique has its own advantages and limitations, and consequently has a specific application. Ultrasonic wave has been applied widely for its high penetrability and precision [4-6]. Nevertheless, ultrasonic attenuation has been applied to the measurement of liquid-solid concentration [7-8], rarely to gas-solid concentration. The non-liner error exist in the ultrasonic transducer, and it often shows that the initial signal amplitude will change by the time. The amplitude change will seriously restricted the accuracy of measurement. With the problem in hand, multiple reflect signal is used to reduce the influence. And then, the concentration data will be displayed on computer through the LabVIEW [9]. This paper is intended to introduce the measurement system based on ultrasonic attenuation, and it is verified by the experiments.

2. Methodology
Epstein [10] found theoretical model that ultrasound propagate through two phase flow by analyzing Navier-Stokes function in hydromechanics based on law of conservation of mass. After that, Allegra and Hawley [11] developed this model and expanded its scope of application. The model is called ECAH model [12-13] in memory of those people who have made outstanding contributions to it. The derivation process of the ECAH model, as follows. The solid must meet requirements that the solid media is of elastic isotropic heat-conducting. The wave equations are obtained from a stress-strain relation, conservation laws and thermodynamic equation of state, wave equations can be written as
\[
\begin{align*}
(\nabla^2 + k_c^2)\phi_c &= 0 \\
(\nabla^2 + k_T^2)S &= 0 \\
(\nabla^2 + k_s^2)\phi_s &= 0
\end{align*}
\] (1)

where

\[
\begin{align*}
k_c &= \omega / c + i\alpha_L \\
k_s &= (\omega p / \eta_s)^{0.5} \\
k_T &= (1 + i)(\omega p c / 2\lambda)
\end{align*}
\] (2)

where \(k_c\) is compressional wave number, \(k_T\) is thermal wave number, \(k_s\) is shear wave number, \(\alpha_L\) is the attenuation coefficient, \(\omega\) is the angular frequency, \(p\) is the density, \(\eta_s\) is the coefficient of shear viscosity, \(c\) is the velocity, \(\lambda\) is the thermal conductivity and \(i = \sqrt{-1}\).

The wave equations can be solved in spherical coordinates and six equations are obtained by utilizing the boundary conditions at the surface of the particle. The equations can be solved for the coefficient \(A_n\). In condition that the effect of the individual particles can be additive, the attenuation can be written as [14]

\[
\alpha = -\frac{12\phi}{k_i^2 D^2} \sum_{n=0}^{\infty} (2n+1) \text{Re} A_n
\] (3)

where \(\phi\) is the volume fraction of the solid phase, \(D\) is the diameters of solid phase.

McClements simplified the model on account of the complexity of the coefficient \(A_n\). What he thinks is that the coefficient can be ignored but \(A_0\) and \(A_1\) [15] when the diameters of solid phase is far less than the wave length. The coefficient \(A_0\) and \(A_1\) can be written as

\[
A_i = \frac{ik_i R}{3p k_i^2} \left( \rho k_i^2 - \rho i k_i^2 \right)\left( \frac{\beta}{\rho C_p} - \frac{\beta}{\rho C_T} \right)^i
\] (4)

\[
A_1 = -\frac{2ik_i R}{3} \times \frac{p - \rho}{3\rho + 4R^2(\rho - \rho)\lambda^2} \left[ 2R^2 + 3R(1 + i)\delta + 3\delta^2 \right]^{1-i}
\] (5)

where

\[
H = \left[ \frac{\delta}{\delta + (1-i)R} \left( \frac{\lambda}{\lambda} \right)^i \tan z' \left( \tan z' - z \right)^i \right]^{i}
\] (6)

\[
z' = (1+i)R / \delta_i
\] (7)

\[
\delta = \frac{2\lambda}{\rho \omega c_p}, \quad \delta_i = \frac{2\lambda}{\rho \omega c_p}, \quad \delta_c = \frac{2\mu}{\rho \omega}
\] (8)

where the simple with superscript and none refer to the properties of the continuous phase and the emulsion droplets, respectively, \(T\) is the temperature, \(\beta\) is the thermal dilatation, \(c_p\) is the specific heat at constant pressure.

The coefficient \(\alpha\) can be derived from an intensity balance for an infinitesimally thin layer of suspension:

\[
dl = -i\alpha \cdot 2\cdot \Delta s
\] (9)
By integration, it can be written as

\[ \alpha = \frac{\ln(I / I)}{2 \cdot \Delta s} \]  (10)

where \( I' \) and \( I \) are the radiation intensities transmitted in the absence and presence of particles, respectively, and \( \Delta s \) is the path length.

Finally, the expression of volume fraction of the solid phase can be written as

\[ \varphi = -\frac{24 \cdot \Delta s}{k^2D^3\ln(I / I)} \Re(A_i + 3A_s) \]  (11)

### 3. Measuremental System

#### 3.1. Hardware Design

Figure 1 illustrates the hardware structure of the system. The generation source is sinusoid burst wave which is supplied from arbitrary waveform generator (AWG). The ultrasonic measuring section consists of two piezoelectric transducers, the center frequency of which is 170 KHz, acting as emitter and receiver. The signal received is amplified by signal-amplifier and enter into the four-order active band pass filter. In order to collect and process data in real time, high-speed data acquisition is used to collect the signal to which is analyzed by computer after A/D conversion.

![Diagram of the system](image)

Figure 1. The hardware structure of the system.

#### 3.2. Software Design

In order to facilitate extending and debugging, the measuring system is building with modular design. The whole software is made up of six circulation module, it were event capture module, UI processing module, data acquisition module, data processing module, logging module and display module, respectively. Each module is independent of each other and they are parallels-operating. Upcoming articles will describe the data acquisition and data processing module.

1) **Data acquisition**

USB-1210 (adlinktech) is used as data acquisition device. It is convenient for quick development of applications with the help of DAQPilot.

First, as can be seen in figure 2, PLT Create Channel VI is used to create new task with local virtual channel information; The Sample Clock VI can assign samples per channel, sampling (update) rate per channel, and conversion (update) source properties; PLT Trigger VI is used to Sets whether the trigger occurs when the analog signal crosses the level; PLT Start Task VI is used to starts measurement or generation by transitioning the task to the running state;
Second, as can be seen in figure 3, after the device initialization, PLT Read VI is used to acquire data. In order to realize continuous measurement, PLT Read VI is called circularly. The real-time data is sent to data display module by notifier (real-time performance), and the real-time data is sent to data processing module by queue (data integrity).

Finally, as can be seen in figure 4, when the data acquisition task is finished, PLT Stop Task VI is used to stop the task, and PLT Clear Task is used to clear the task, release resources.

2) Data processing
Figure 5 illustrates the multiple signal received by the ultrasonic transducer. Generally, the primary signal amplitude is used to calculate the ultrasonic attenuation, but the result may be inaccuracy because of the non-linear error of the ultrasonic transducer. Experiments found that the primary signal and secondary signal have the same change direction in the results of the non-linear error. So this paper uses the ratio of amplitude of primary to secondary signal to present the ultrasonic attenuation.

The flowchart of data processing is shown in figure 6.

![Flowchart of data processing](image)

**Figure 6. The software structure of the system.**

4. Experimental Results and Analysis

In order to evaluate the performance of the measurement system, measurements with different concentration were conducted. For testing, glass beads were chosen, the concentration of which is controlled by the vibrating feeder. And the mass flow is calculated by the weighting sensor data. The result of figure 7 is calculated by the primary signal, and the result of figure 8 is calculated by the ratio of the primary signal to the secondary signal. The R-Square of the fitting curve is 0.9264 and 0.9888, respectively. Obviously, the different particle volume fraction is clearly distinguishable and the correlation between particle volume fraction (measured by ultrasonic attenuation) and mass flow (determined from load cell) remains linear over an extensive range.

![Graph showing experimental data and fitting curve](image)

**Figure 7. Primary signal.**
The results show that the ratio of the primary signal to the secondary signal can reduce the non-linear error of the ultrasonic, and the measurement system is accuracy.

5. Conclusion
The method of ultrasonic attenuation in the gas-solid two phase flow, ECAH model, is used to calculate the concentration of pulverized-coal, and it is proved to be a powerful tool for on-line concentration. According to the non-linear error of the transducer, multiple ultrasonic wave signal is used to reduce the error, and it shows the good result. The experimental results show that the measurement system is of accuracy, stabilization and reliability. It is certain that ultrasonic instrumentation will continue to develop and that the technique will become a powerful tool for measuring the concentration of pulverized-coal. The particle size distribution is also an important property of the pulverized-coal, and more ultrasonic frequency is needed based on the ECAH model, it will be a good challenge in the future.

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7. References
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