Experiment of Thermal Conductivity of Coal-fired Boiler Ash

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Abstract. In order to study the problem of ash deposition and slagging on the heating surface of coal-fired boiler, the ash specimens with different thickness are prepared in this paper, and the unsteady state method is used to test the thermal conductivity of the ash. The results show that the average thermal conductivity of the ash specimen is 0.3114W/(m·K), and the thermal conductivity of the ash does not change with the thickness. This paper provides important parameters for the study of heat transfer of boiler heating surface.

1. Introduction

Ash deposition and slagging on the heating surface of coal-fired power station boiler will affect the safety and economic operation of power plants. Therefore, there is a need to monitor the ash and slagging status of the heating surface online. However, the accurate measurement of the thermal conductivity of the ash is the premise of studying the online monitoring of the ash thickness. Generally, the determination methods of thermal conductivity include theoretical calculation and experimental testing [1, 2], with the development of measuring methods and measuring instruments, experimental testing is the main method to study the thermal conductivity of materials [3].

Jin et al. [4] used frozen-thawed sandy soil in the Qinghai-Tibet Plateau Engineering Corridor as the research object, the thermal conductivity of freeze-thaw sand was tested by thermal parameter analyzer according to transient plane source method, the empirical formula of the relationship between the thermal conductivity of sand and its dry density and natural water content were also given. Hu et al. [5] measured the thermal conductivity of clay and sandy soil in the Yangtze River region by the principle of non-steady state method. Tang et al. [6] used unsteady state method to test the thermal conductivities of the three unsaturated soils, and studied the relationship between the thermal conductivity of unsaturated soils and the water content and temperature.

At present, researchers have done a lot of research on measuring thermal conductivity. However, there is a lack of research on the thermal conductivity of coal-fired boiler ash. Therefore, this paper tests the thermal conductivity of coal-fired boiler ash based on unsteady heat conduction process, which provides important parameter for studying the heat transfer of the heating surface of boiler.

2. Test Principle and Test Device

2.1. Test Principle

Thermal conductivity test methods include steady-state method and unsteady-state method [7]. The steady-state method is simple in principle, high in accuracy, good in repeatability and easy to realize. However, the experiment process needs a long time and requires high environmental requirements [1].
Compared with the non-steady state method, the experimental process takes a short time and requires fewer environments, but the experimental principle and calculation formula of the non-steady state method are complicated [1]. Therefore, this paper comprehensively considers the actual requirements and the thermal conductivity of ash simples are tested by the unsteady method.

The specimen size is limited, according to the basic theory of the unsteady state heat conduction process; length and width of the specimen are more than 6 times its thickness [8]. The effect of heat dissipation from the side on the center temperature of the specimen is negligible, and the temperature difference between the center position of the upper and lower surfaces of the specimen can be equivalent to the temperature difference between the upper and lower surfaces of the infinite plate.

The test principle of the unsteady state method in this paper is shown in Figure 1(a) [9]. Specimen a, b and c are made of the same material with the same length and width, and their thicknesses are $h_a$, $h_b$ and $h_c$ respectively. The ash specimen b with the thermal conductivity is measured. This article uses multiple tests, the length and width of specimen b are all greater than 6 times of its thickness. A uniform plane resistance heater is placed between specimen b and specimen c. The plane resistance heater is supplied with a direct-current power supply.

The thermocouple 1 is placed in the middle of the upper surface of specimen a, which used to test the temperature $t_1$ of the upper surface of specimen a. The thermocouple 2 and the thermocouple 3 are placed in the middle of the upper surface and lower surface of specimen b respectively, which is applied to test the temperature $t_2$ of the upper surface of specimen b and the temperature $t_3$ of the lower surface. The thermocouple 4 is placed in the middle of the lower surface of specimen c, which is taken to test the temperature $t_4$ of the lower surface of specimen c.

Since the plane resistance heater contacts the upper surface and the lower surface of the specimen, which are the same materials, ignoring the heat absorption of the plane resistance heater itself, so the heat flux can be calculated by

$$q_0 = \frac{U^2}{2RF}$$

where, $U$ is heating voltage, V; $R$ is heater resistance, $\Omega$; $F$ is heater area, $m^2$; $q_0$ is heat flux of the plane heater through to the lower surface side of the specimen b, $W/m^2$.

The temperature is uniform at the initial time $\tau=0s$, the lower surface of the specimen b is heated by a constant heat flux density $q_0$. Under the condition that the thermal properties of the material are constant, at $\tau>0$, the temperature rise from the surface $x$ can be expressed as

$$\theta(x, \tau) = \frac{2q_0}{\lambda} \sqrt{a \text{ierfc}(\zeta)}$$

where, $\theta(x, \tau)$ is the temperature rise from the surface $x$ at time $\tau$, K; $\lambda$ is the thermal conductivity, W/(m·K); $a$ is the thermal diffusivity, $m^2/s$; ierfc ($\zeta$) is the variable $\zeta$ integral of the Gaussian error complement function.

In equation (2), $\zeta$ can be calculated by
\[ \zeta = \frac{x}{2\sqrt{a \tau}} \quad (3) \]

The variable \( \zeta \) integral of the Gaussian error complement function can be simplified as following

\[ \text{ierfc}(\zeta) = \int_{\zeta}^{\infty} \text{erfc}(\xi) \, d\xi \quad (4) \]

If \( x = 0 \text{m} \) and \( \tau > 0 \text{s} \), the first integral of the Gaussian error complement function of the variable \( \zeta \) needs to be solved as following

\[ \text{ierfc} \left( \frac{x}{2\sqrt{a \tau}} \right) = \frac{1}{\sqrt{\pi}} \quad (5) \]

If \( x = 0 \text{m} \) and \( \tau = \tau_i \), the temperature rise at this surface can be expressed as

\[ \theta(0, \tau_i) = \frac{2q_0}{\lambda} \sqrt{\frac{a \tau_i}{\pi}} \quad (6) \]

From equation (2) and equation (6), the ratio of \( \theta(h_b, \tau_j) \) and \( \theta(0, \tau_i) \) can be calculated as following

\[ \frac{\theta(h_b, \tau_j)}{\theta(0, \tau_i)} \sqrt{\frac{\tau_i}{\tau_j}} = \sqrt{\pi} \text{ierfc} \left( \frac{h_b}{2\sqrt{a \tau_i}} \right) \quad (7) \]

where, \( \theta(h_b, \tau_j) \) is the temperature rise from the surface \( h_b \) and the time is \( \tau_j, \text{K} \).

From equation (7), the Gaussian error complement function can be calculated by, as following

\[ \text{ierfc} \left( \frac{h_b}{2\sqrt{a \tau_j}} \right) = \frac{1}{\sqrt{\pi}} \frac{\theta(h_b, \tau_j)}{\theta(0, \tau_i)} \sqrt{\frac{\tau_i}{\tau_j}} \quad (8) \]

According to equation (3), we have

\[ \zeta' = \frac{h_b}{2\sqrt{a \tau_j}} \quad (9) \]

The thermal diffusivity at the average temperature corresponding to the test temperature range \( [t(0, \tau_i), \ t(h_1, \tau_i)] \) is calculated from equation (9), as following

\[ a = \frac{h_1^2}{4\zeta'^2 \tau_j} \quad (10) \]

The thermal conductivity is calculated by equations (6) and equation (10) as following

\[ \lambda = \frac{2q_0}{\theta_{0,\tau_i}} \sqrt{\frac{a \tau_i}{\pi}} \quad (11) \]

2.2. Test Device

The test device is shown in Figure 1(b). The test device is composed of a touch screen control system, a data acquisition system, an adjustable direct-current power supply, and a plane resistance heater. The touch screen is placed in the center, and the left and right sides of the test device can be tested for thermal conductivity. There is considering the difference of the equipment, the experiment is carried out on the left side of the test device.
The data is transmitted to the touch screen control system through the data acquisition system, and real-time display on the touch screen. The temperature measurement device in the test device uses a T-type thermocouple with a diameter of 0.1mm, and the measurement accuracy is 0.1°C [9].

3. Specimen Preparation and Test Process

3.1. Specimen
The simples are prepared from the ash of a coal-fired boiler, due to the test device restricts the size of the ash specimens, so, the length and width of the ash specimen are both 150mm, and the thickness of specimen b is 8mm, 15mm and 18mm in this paper, and the maximum allowable error range is 5%. The ash specimens are shown in Figure 2, and its preparation process can be described as follows:

(a) Original ash (b) Grinded ash (c) Naturally specimen (d) Polished specimen

Figure 2. Ash specimen.

(1) Grind the larger ash particles into smaller ash particles;
(2) According to the volume ratio of ash: cement = 3:1, put the small ash particles into the mold, and add the cement in the above ratio to the mold;
(3) Add an appropriate amount of water to the mold, stir evenly, smooth the surface of the specimen, place the mold in an environment with a temperature of 20°C to let it naturally solidify, until the specimen is completely dry;
(4) Take out the ash specimen, and smooth the surface of the formed ash specimen with sandpaper. Repeat the above process to complete the ash specimen preparation.

3.2. Test Process
The test process can be described as follows:
(1) Ash specimens a, b and c, thermocouple 1, 2, 3, 4 and plane resistance heater are placed on the left side of the test device;
(2) Enter the specimen thickness and heating voltage of the plane resistance heater;
(3) Start heating the specimen;
(4) The test device automatically performs data processing and calculates the thermal conductivity of the ash specimen.
Repeat the above test process to test the thermal conductivity of ash specimens of different thickness in turn.

4. Results and Analysis
The ash specimens with different thicknesses were tested in this paper, and the thermal conductivity changes with the test data are shown in Figure 3. It can be seen from Figure 3 that the thermal conductivity of the ash specimen continuously changes.
Figure 3. Test line of thermal conductivity of ash specimens with different thickness. When the ash specimens of different thicknesses reach thermal equilibrium, the curve does not maintain the level, fluctuates up and down around an average value. The main reason is that the plane resistance heater does not stop heating, which makes the temperature field of the ash specimen maintain dynamic equilibrium within a certain range. As the temperature field of the slag specimen tends to be stable, the thermal conductivity also reaches the steady state value. When the temperature field of the ash specimen keeps in a dynamic balance within a certain range, the average value of the thermal conductivity is used as the thermal conductivity of the ash specimen with a certain thickness at this time. It can be calculated that the average thermal conductivity of 8mm ash simple is 0.3030W/(m·K), the average thermal conductivity of 15mm ash simple is 0.3139W/(m·K); the average thermal conductivity of 18mm ash simple is 0.3174W/(m·K). The test results show that the thermal conductivity of the ash specimen does not change with the thickness. In this paper, the average thermal conductivity of ash specimens with different thicknesses is used as the thermal conductivity of ash and slagging. Therefore, the average thermal conductivity of ash and slagging is 0.3114W/(m·K).

5. Conclusions
(1) Different thickness of ash specimens require different time to reach thermal equilibrium, the smaller the thickness of the ash specimens, the easier it is to achieve thermal balance.
(2) The test data has good consistency; the thermal conductivity of the slag specimens between different thicknesses is small. The thermal conductivity of the ash specimen does not change with the thickness. Therefore, the average thermal conductivity of ash and slagging is 0.3114 W/(m·K).

Acknowledgement
This work is supported by the National Key Research and Development Program of China (Grant No. 2017YFB0602703).

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