Experimental Investigation of Heat Transfer with Ash Deposition in Ultra-Low Temperature WHRS of Coal-fired Power Plant

Rutgers University has made this article freely available. Please share how this access benefits you.
Your story matters. [https://rucore.libraries.rutgers.edu/rutgers-lib/56670/story/]

This work is an ACCEPTED MANUSCRIPT (AM)
This is the author's manuscript for a work that has been accepted for publication. Changes resulting from the publishing process, such as copyediting, final layout, and pagination, may not be reflected in this document. The publisher takes permanent responsibility for the work. Content and layout follow publisher's submission requirements.

Citation for this version and the definitive version are shown below.


Terms of Use: Copyright for scholarly resources published in RUcore is retained by the copyright holder. By virtue of its appearance in this open access medium, you are free to use this resource, with proper attribution, in educational and other non-commercial settings. Other uses, such as reproduction or republication, may require the permission of the copyright holder.

Article begins on next page
Experimental Investigation of Heat Transfer with Ash Deposition in Ultra-Low Temperature WHRS of Coal-fired Power Plant

Yuetao Shi1*, Chen Dai1, Zhihao Ma1, Zhixiong Guo2*

1School of Energy and Power Engineering, Shandong University, Jinan, China
2Department of Mechanical and Aerospace Engineering, Rutgers, the State University of New Jersey, NJ 08854, USA

*Correspondence authors: Z. Guo, Professor, guo@jove.rutgers.edu
Y. Shi, Associate Professor, shieddie@sdu.edu.cn

Abstract

Waste Heat Recovery Systems (WHRS) have been widely adopted in coal-fired power station boilers, though their heat transfer performance is poor under ultra-low tube temperature circumstances. In this study, we have carried out experiments to reveal heat transfer deterioration and its relation with ash deposition when probe tube temperature varies from 90°C to ultra-low 40°C. Results reveal that gas-side Nusselt number has two rapid drops as the probe outer wall temperature decreases. The first drop occurs when the wall temperature is about 32°C lower than the acid dew temperature, where the deposited ash thickens due to the condensed concentrated sulfuric acid and slight corrosion is observable. The second drop occurs when the wall temperature is about 10°C greater than the water dew temperature, where the corrosion becomes severe because the concentration of sulfuric acid decreases. For engineering applications, we suggest that the tube outer wall temperature be greater than the first drop temperature to deflate poor heat transfer and surface corrosion.
Keywords: Heat transfer; Dew temperature; Ash; Corrosion; Waste heat recovery

Nomenclature

\( A_{ar,zs} \) Converted ash content

\( A_{ar} \) Ash content of as received base

\( C_p \) Specific heat capacity (kJ \( \cdot \) kg\(^{-1} \) \( \cdot \) C\(^{-1} \))

\( d_e \) Characteristic diameter (m)

\( D_0 \) Outer diameter of the test probe (m)

\( D_i \) Outer diameter of inner tube (m)

\( d_0 \) Inner diameter of outer tube (m)

\( h \) Heat transfer coefficient (kw \( \cdot \) m\(^{-2} \) \( \cdot \) k\(^{-1} \))

\( H_{ar} \) Hydrogen content of as received base

\( L \) Insertion depth (m)

\( \dot{M} \) Mass flow rate (kg)

\( \text{Nu} \) Nusselt number

\( p \) Pressure (Pa)

\( Q \) Heat transfer rate (kJ)

\( Q_{net,ar} \) Lower heating value of coal (kJ \( \cdot \) kg\(^{-1} \))

\( Q_{gr,ar} \) Higher heating value of coal (kJ kg\(^{-1} \))

\( \text{Re} \) Reynolds number

\( R \) Volume percentage

\( S_{ar,zs} \) Converted sulfur content
<table>
<thead>
<tr>
<th>Greek Letters</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>Thermal conductivity coefficient (kw⋅m$^{-1}$⋅k$^{-1}$)</td>
</tr>
<tr>
<td>$\alpha_{fh}$</td>
<td>Coefficient for fly ash</td>
</tr>
<tr>
<td>$\nu_w$</td>
<td>Water kinematic viscosity (m$^2$⋅s$^{-1}$)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Excess air coefficient</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Abbreviations</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADT</td>
<td>Acid dew temperature</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy Dispersive Spectrometer</td>
</tr>
<tr>
<td>LPES</td>
<td>Low pressure economizer system</td>
</tr>
<tr>
<td>ORC</td>
<td>Organic Rankine cycles</td>
</tr>
</tbody>
</table>
1. Introduction

Coal is the primary energy source in China. According to BP statistical review of world energy in June 2016 [1], China accounted for 47.7% of world coal production and 50% of world coal consumption in 2015. Underground coal fires after coal mining or during coal mining cause disasters and serious pollution and health problems and recent studies [2, 3] have addressed the heat and mass transfer issues to compact underground coal fires. After coal extraction from mines, most of these coals were burned in boilers for various industrial processes. The exhausted flue gas from boilers at about 120~150°C is a tremendous energy source. Thus, use of waste heat recovery systems (WHRS) has attracted great interest all over the world [4].

In recent years low-pressure economizer systems (LPES) [5], which heat the
condensed water by the waste heat from flue gas, were adopted widely in power station boilers in China. Yang’s group has done a lot of researches on waste heat recovery system for flue gas [6-8]. In 2013 they conducted a techno-economic analysis of LPES [6]. In 2014 they proposed an optimized LPES system [7]. In 2015 they proposed a new system that can heat both the condensed water and the air needed to combust [8]. Besides LPES, organic Rankine cycles (ORC) [9, 10] have also received interests for their high efficiency and flexibility. Different working media were adopted to waste heat resources with different temperatures [11]. Flue gas cooler is the core equipment for both LPES and ORC systems, which can absorb heat from the exhausted flue gas for different usages. Unfortunately, flue gas cooler suffers from low-temperature corrosion and ash deposition if the flue gas temperature is reduced to acid dew temperature (ADT). Both will deteriorate heat transfer performance and shorten working life of the cooler. Thus, the ultimate temperature after the LPES or ORC system from coal-fired flue gas should remain higher than the ADT, which wastes tremendous energy under ADT.

Is there a limit for WHRS operation in coal-fired flue gas? If it does exit, to what degree can we reduce the flue gas temperature from ADT? These questions are closely related to corrosion and ash deposition under ultra-low temperature flue gas circumstances. There were some studies on low-temperature corrosion and ash deposition [12, 13]. Zhao’s group in Xi’an Jiatong University has performed some deep researches on coupling effect between low temperature corrosion and ash deposition. In 2013 they established an experimental system to lower the flue gas
temperature to about 40°C to analyze the relationship between ash deposition and corrosion rate [14]. In 2014 they investigated the coupling mechanism between low-temperature corrosion and viscous deposited ashes [15]. In 2016 they conducted a similar research in a biomass-fired circulating fluidized bed boiler instead of coal-fired boiler [16]. Recently, Shi et al. [17] published an experimental study to reveal the mechanisms on low temperature corrosion, but heat transfer performance and its influence were not involved in their study. It is necessary to understand the changing regularity and changing mechanism of heat transfer performance under low-temperature corrosion and ash deposition. This is the innovation and originality in this further study.

Therefore, we concentrate on the influence of low-temperature corrosion and ash deposition on heat transfer performance in this paper. The mechanism of heat transfer deterioration will be revealed, and the minimum wall temperature for long-term and safe operation of WHRS in coal-fired flue gas will be determined. This minimum wall temperature determines ultimately the limitation for waste heat recovery.

2 Description of experiments and methods

2.1 Experimental System

The whole experimental system was installed between the air preheater and the electrostatic precipitator of a 300MW power unit (see Fig. 1 in ref. [17]). The technical specifications of the boiler and coal quality were also listed in Table 1 in ref. [17]. Figure 1 in the present paper shows the detail of the experimental system, which is composed of three major parts: a constant temperature control system, a test probe,
and a measuring system. The probe is a tube heat exchanger and part of it is inserted into the flue gas duct. As shown in Fig. 1, water circulates between the constant temperature control system and the probe. The control system supplies the test probe with constant-temperature water. The water is heated in the test probe and flows back to a tank. The outer wall temperature of the test probe is controlled by the water circulation control system. This temperature represents WHRS tube surface temperature in flue gas duct.

Fig. 1 Experimental system.

1. makeup water valve; 2. water tank; 3. overflow port; 4. ditch; 5. circulating pump; 6 control valve; 7. flow meter; 8. flue gas analyzer; 9. flue gas duct wall; 10. flue gas analyzer; 11. test probe; 12. water side temperature measuring point; 13. mercurial thermometer; 14. recirculation valve; 15. temperature control device; 16. baffle; 17. water level indicator; 18. wall temperature measuring point; 19 data acquisition instrument.

The constant temperature control system contains a water tank, a temperature control device, three valves, a circulating pump, and a flow meter. The water tank can
supply sufficient water at set temperature to the test probe. The tank is divided into two zones – a mixing zone and temperature a control zone, by a baffle. There are two orifices located at the bottom of the mixing zone, which are connected to the makeup water and recirculation water, respectively. Here the makeup water at low temperature mixed with the recirculation water at a relative high temperature. The mixed temperature, which is about 5°C lower than the set value at the temperature control device, can be adjusted by operating the makeup water valve. A mercurial thermometer with accuracy of 0.1°C was inserted into the mixing zone. This helps the operator to adjust the makeup water valve accurately. The mixed water flows upwards and mixes thoroughly, then over the baffle to the temperature control zone. A temperature control device is installed in this zone, on which the value of temperature can be set. If the water temperature is lower/higher than the set value, the electrical heating rod in the temperature control device will be powered on/off to maintain water temperature at the set value. There also are two orifices in the temperature control zone. One locates at the bottom and connects to the pump. The other is the overflow orifice and locates at the top to prevent water flows out of the tank. The pump supplies water at set temperature through the control valve and flow meter to the test probe.
The structure of the test probe is plotted in Fig. 2. The test probe is of double-layer type and has an inner tube and an outer tube. The two layers are concentric. Thus, the test probe is a coaxial-pipe heat exchanger actually. As shown in Fig. 2, the supplied water initially enters the inner tube and then turns into the outer tube at the opposite end. The test probe was inserted into the gas duct horizontally, only the water inlet and outlet were left outside of the duct. The pressure inside the flue gas duct was negative and ambient air can leak into the gas duct from any tiny clearance, which may affect the experimental result heavily. Thus, the contact area between the duct and the probe was sealed tightly to prevent any air leakage. Hot gas from air preheater flows through the probe crossly. There were 6 different probes used in our tests. The structural data of these probes are listed in Table 1. It is seen from Table 1 that all the data in the length direction are same. It was not easy to keep the inserted probe horizontally when the insertion depth is large. Among different probes, the diameter of outer tube varies from 25mm to 48mm, while the diameter of inner tube varies from 10mm to 30mm.
Table 1. Structural dimension of test probes

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Unit</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length of the probe</td>
<td>$L$</td>
<td>mm</td>
<td>1200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insertion depth</td>
<td>$L_0$</td>
<td>mm</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation length</td>
<td>$L_b$</td>
<td>mm</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total length of inner tube</td>
<td>$L_i$</td>
<td>mm</td>
<td>1170</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter of outer tube</td>
<td>$D_o$</td>
<td>mm</td>
<td>25</td>
<td>30</td>
<td>34</td>
<td>38</td>
<td>42</td>
<td>48</td>
</tr>
<tr>
<td>Diameter of inner tube</td>
<td>$D_i$</td>
<td>mm</td>
<td>10</td>
<td>14</td>
<td>16</td>
<td>20</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Thickness of outer tube</td>
<td>$\delta_o$</td>
<td>mm</td>
<td>2</td>
<td>2.5</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Thickness of inner tube</td>
<td>$\delta_i$</td>
<td>mm</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

The absorbed heat by the cooling water inside the probe equals to the released heat by the hot flue gas to the probe. At the waterside, the inlet and outlet water temperatures of the probe were measured by K-type thermocouples. An electromagnetic flow meter rotameter was used to measure the water flux to the probe. With the water temperatures and flux, the absorbed heat by water can be gained.

The physicochemical property of ash deposited onto the probe surface is determined by the outer wall temperature of the probe. Meanwhile, the heat transfer performance of the probe, ash deposition and accumulation, and corrosion vary with the physicochemical trait of ash. Therefore, the outer wall temperature of the probe is introduced as the characteristic temperature in this work. The outer wall temperature...
along the inserted probe length may not be constant. It fluctuated within 1°C at appropriate water flux. So three thermocouples, whose locations are marked in Fig. 2, were set along each probe to measure outer wall temperature and the average reading was used in result analysis. All the measuring signals were sent to a data acquisition device and recorded automatically. Besides, the temperature, oxygen content, and SO$_2$ concentration of flue gas were measured and recorded by a flue gas analyzer. Monitoring of SO$_2$ concentration can justify whether coal quality was changed. During the experiment, coal quality and oxygen content should remain unchanged. All the monitored parameters and measuring instruments were listed in Table 3 in ref. [17].

2.2 Experimental Procedure

During the experimental tests, boiler load was remained at 300MW. The exhaust flue gas temperature is about 131.1°C. There are measuring holes that allow the test probe to insert into the flue gas duct. In order to reduce the error, the temperature difference between the inlet and outlet is controlled less than 2.5°C by adjusting the water flux. The difference of three wall temperature points is smaller than 1°C. Thus, the average value of three values can represent the outer wall temperature of probe. The main experimental procedure is stated as follows:

1) Turn on the power of the pump and the temperature control device. Set the water temperature to 95°C. Water circulates between the probe and the tank. Once the inlet temperature of the probe becomes stable and approximately equals to 95°C, insert the probe into the gas duct. Seal any clearance tightly.
2) Record the inlet and outlet temperatures of the probe, water flux, and outer wall temperatures by the data acquisition system. Once all the recorded data tend to stable, pull the probe out of the gas duct. Observe ash deposition on the probe and collect ash sample for further analysis by Scanning Electron Microscope (SEM) and Energy Dispersive Spectrometer (EDS). 3) Clear the deposited ash away from the probe. Repeat the above two steps while the inlet temperature was set from 90°C to 40°C, from high to low. The set value was reduced 5°C each time.

**3 Data processing**

3.1 Gas-side $Nu_g$ and water-side $Re_w$

Gas-side $Nu_g$ and water-side $Re_w$ should be calculated to analyze the heat transfer performance according to the experimental data. Gas-side $Nu_g$ is defined as

$$Nu_g = \frac{h_g \times D_0}{\lambda_g}$$  \hspace{1cm} (1)

where $D_0$ is the outer diameter of the test probe, $\lambda_g$ is the flue gas thermal conductivity, $h_g$ is the gas side heat transfer coefficient, which is obtained by

$$h_g = \frac{Q}{\pi D_0 L (T_g - T_w)}$$ \hspace{1cm} (2)

where $L$ is the insertion depth, $D_0$ is outer diameter of outer tube, $T_g$ is the flue gas temperature, $T_w$ is the probe outside wall temperature, $Q$ is the heat absorption rate by the cooling water. The heat absorbed can be calculated as

$$Q = C_p \times \dot{M} \times (T_{out} - T_{in})$$ \hspace{1cm} (3)

where, $\dot{M}$ is the mass flow rate of the cooling water, $T_{out}$ is the outlet water temperature, $T_{in}$ is the inlet water temperature, and $C_p$ is the specific heat at constant
Boiler load and coal quality remained stable during the experiment. Volume flux and temperature of the flue gas were stable too. Thus, the gas-side $Re_g$ remained constant during the experiment. The outer wall temperature of the probe depends on the circulation of the cooling water and the probe size under constant flue gas conditions. Water-side $Re_w$ is calculated by

$$Re_w = \frac{w_w \times (d_0 - D_i)}{\nu_w}$$

where $w_w$ is the water velocity at the annular flow area between the inner and outer tubes, $\nu_w$ is the water kinematic viscosity, and $d_o$ is the characteristic diameter of the annular area, $d_o$ is inner diameter of outer tube, and $D_i$ is outer diameter of inner tube.

3.2 Acid and water dew temperature points

During the experiment, the outer wall temperature $T_w$ of the testing probe drops from about 95°C to an ultra-low value about 45°C. It is necessary to know the acid dew temperature (ADT) and water dew temperature (WDT), because ash properties may change when $T_w$ passes through or is close to ADT/WDT. Ash deposition performance and heat transfer performance of the testing probe will be influenced by ash properties.

The acid dew temperature can be calculated as [18]

$$T_{ad} = T_{wd} + \frac{125 \times \sqrt{S_{ar.zs}}}{1.05^{\alpha_{a.r.zs}}} \quad (^\circ C)$$

where $T_{wd}$ is the water dew temperature, $\alpha_{a.r}$ is the coefficient for fly ash and equals to 0.9 for pulverized coal boiler, $A_{ar.zs}$ and $S_{ar.zs}$ are converted ash and sulfur contents that
can be calculated by

\[ A_{\text{ar, zs}} = \frac{A_{\text{ar}}}{Q_{\text{net, ar}}} \times 4190 \quad \% \]  \hspace{1cm} (6)

\[ S_{\text{ar, zs}} = \frac{S_{\text{ar}}}{Q_{\text{net, ar}}} \times 4190 \quad \% \]  \hspace{1cm} (7)

where \( Q_{\text{net, ar}} \) is the lower heating value of coal. Recently, we have also introduced the concept of engineering ADT (EADT) and studied the relationship between ash accumulation and EADT [19, 20].

\( T_{wd} \) equals to the saturation temperature and can be gained by the thermodynamic properties of water and steam once water vapor partial pressure \( p_{H2O} \) in the flue gas is known. \( p_{H2O} \) can be calculated by

\[ p_{H2O} = R_{H2O} \times p_{\text{total}} \quad (\text{Pa}) \]  \hspace{1cm} (8)

where \( p_{\text{total}} \) is the absolute pressure in the flue gas duct, which is 95,800Pa. \( R_{H2O} \) is the water vapor volume percentage and can be calculated by

\[ R_{H2O} = \frac{V_{H2O}}{V_y} \quad \% \]  \hspace{1cm} (9)

where \( V_{H2O} \) and \( V_y \) are the total water vapor and flue gas quantities, which can be calculated by

\[ V_{H2O} = 0.111H_{ar} + 0.0124W_{ar} + 0.016\alpha V_k^0 \quad (\text{Nm}^3/\text{kg}) \]  \hspace{1cm} (10)

\[ V_y = V_y^0 + 1.0161(\alpha - 1)V_k^0 \quad (\text{Nm}^3/\text{kg}) \]  \hspace{1cm} (11)

where \( \alpha \) is the excess air coefficient, \( V_k^0 \) and \( V_y^0 \) are the theoretical air and gas quantities respectively, \( H_{ar} \) is hydrogen content of as received base [21]. The calculation equations are below.
where \( O_2 \) is the oxygen content of gas at measuring point, and \( O_2 = 5.8 \) in the present analysis.

\[
\alpha = \frac{21}{21 - O_2} \tag{12}
\]

\[
V_k^0 = 0.251 \times \frac{Q_{net, ar}}{1000} + 0.278 \quad \text{(Nm}^3/\text{kg}) \tag{13}
\]

\[
V_y^0 = 0.248 \times \frac{Q_{net, ar}}{1000} + 0.77 \quad \text{(Nm}^3/\text{kg}) \tag{14}
\]

\[
H_{ar} = 0.07V_{ar} + 0.000165Q_{gr, ar} - 0.0285 \times (100 - W_{ar} - A_{ar}) \tag{15}
\]

where \( V_{ar}, W_{ar}, \) and \( A_{ar} \) are volatile, water and ash contents of coal of as received base respectively, \( Q_{gr, ar} \) is gross calorific value of coal. All the items except \( V_{ar} \) mentioned above are listed in Table 1. \( V_{ar} \) is obtained by

\[
V_{ar} = V_{ad} \times \frac{100 - W_{ar}}{100 - W_{ad}} \tag{16}
\]

According to the coal quality used in this study, the acid dew temperature and water dew temperature are calculated as 102.3°C and 39.6°C, respectively.

4 Results and Discussion

The profiles of \( Nu_g \) against \( Re_w \) at eight different probe outer wall temperatures are plotted in Fig. 3. The inner wall temperature of the probe was sensitive to \( Re_w \); and thus, it was hard to keep the outer wall temperature \( T_w \) stable with varying \( Re_w \). So \( Re_w \) was controlled such that the flow in the probe was not turbulent. It is seen that water-side \( Nu_w \) on the inner wall of the probe increases with \( Re_w \). It is seen that the eight curves can be basically grouped into three typical profiles depending on the wall temperature. There exists a laminar flow \( Re_w \) range (1,300 – 2,300) in which \( Nu_g \)
profiles are nearly flat since water-side Nusselt number for laminar fully developed flow region remains constant [22]. Although the flow is laminar in the low Re\(_w\) zone (<1300), the difference between the inlet and outlet water temperatures is larger than 2.5\(^\circ\)C because of small water flux. The temperature distribution is greatly uneven along the probe and the determination of the wall temperature with the average value in the three measuring points comes with greater error that affects the value of Nu\(_g\).

![Graph](image)

**Fig. 3** Nu\(_g\) vs Re\(_w\) at various wall temperatures for \(\Phi\) 48 test probe.

Figure 4 shows Nu\(_g\) against the wall temperature within the specific Re\(_w\) (1,300 – 2,300) range. In this range, both the experimental error, and the impact of cooling water on Nu\(_g\) are minimized. It is seen that the larger the outer diameter is, the larger the Nu\(_g\) is. This is because the boiler load, flue gas temperature and velocity were stable during the experiment. Thus, gas-side Re\(_g\) increases with increasing outer tube diameter. As shown in Fig. 4, the profile of Nu\(_g\) vs. \(T_w\) is of stepwise style, i.e., Nu\(_g\) remains constant within three specific temperature zones with two rapid drops in the
two narrow turning zones. $Nu_g$ approximately equals to 68, 52 and 37 for the testing probe of $\Phi 48$ when the outer wall temperature $T_w$ is in zone 1 ($T_w \geq 70^\circ C$), zone 2 ($54^\circ C < T_w < 66^\circ C$) and zone 3 ($T_w < 51^\circ C$), respectively. The two turning zones are located in $66^\circ C < T_w < 70^\circ C$ and $51^\circ C < T_w < 54^\circ C$, respectively.

Fig. 4 $Nu_g$ against $T_w$ with $Re_w$ in the range of 1300–2300.

The stepwise $Nu_g$ distribution is related to the deposited ash properties on the test probe. Ash deposition occurs inevitably on heat transfer surface while firing solid fuel. Photos of ash deposition for the $\Phi 48$ testing probe in zone 1 temperature range are shown in Fig. 5. The flue gas velocity in the gas duct at 300MW was about 15m/s. There was no ash deposition on the windward side of the probe (Fig. 5a) under such high velocity. On the leeside of the probe, there existed a thin layer of deposited ash because of gas flow vortex (Fig. 5b). Corrosion was not found on the wall after the deposited ash was removed (Fig. 5c). The outer wall temperature of the probe was high enough that little $SO_3$ condensed in the deposited ash. Thus, the deposited ash was dry, loose and easy to blow off. The fouling resistance coefficient was low and
heat transfer performance was very good as $Nu_g$ was higher.

Fig. 5. Photos of the Ф48 test probe in zone 1.
Photos of ash deposition for the Φ48 testing probe with wall temperature in zone 2 lower than 66°C are shown in Fig. 6. Though the flue gas velocity is unchanged, there is a thick layer of deposited ash on the windward side of the probe (Fig. 6a). The deposited ash on the leeside is humid and a little bit sticky (Fig. 6b). So it is difficult to clean out the deposited ash. Obvious corrosion is observed at the outer wall (Fig. 6c). Compared with $Nu_g$ in zone 1, $Nu_g$ in zone 2 is smaller because of thicker ash layer.

(a) windward side view of the testing probe

(b) leeside view of the testing probe
(c) leeside view with deposited ash scraped off

Fig. 6. Photos of the $\Phi 48$ test probe in zone 2.

Photos of ash deposition for the $\Phi 48$ testing probe in zone 3 temperature range are shown in Fig. 7. The deposited ash on both the windward and leeside side is very humid and accumulates together (Figs. 7 a and b). It adheres to the outer wall and was hard to clean. It is so sticky that one can print fingers on it. Severe corrosion is observed after deposited ash is scrapped off (Fig. 7c).
To view small particles clearly in the deposited ash, ash samples were collected for scanning electron microscope (SEM) analysis. SEM photos of ash samples from different zones are shown in Fig. 8. It is seen that the ash particles are loose and small for zone 1 (Fig. 8a). Ash particles separate from each other. Thus, the fouling resistance coefficient is low and $Nu_g$ is high. The adhesion force between particles should be very small. So it is easy to blow off the deposited ash. As the outer wall temperature drops, particle accumulation occurs. The deposited ash becomes denser
and larger (Figs. 8 b and c). In zone 3 (Fig. 8c), ash particles adhere to each other to form a thick ash layer clinging to the probe outer wall. It took great energy to scrape part of the ash layer off. This thick hard layer reduces heat transfer performance and leads to small $Nu_g$ for wall temperature in zone 3.
An energy dispersive spectrometer (EDS) was further employed for elemental analysis of the deposited ash. Ash samples were analyzed as required by Chinese National Standard - “Microbeam analysis-Quantitative analysis using energy dispersive spectrometry”. Point analysis was adopted because of its higher sensitivity, compared with line and face analysis. The relative errors for EDS analysis depend on the element weight percentage and are shown in Table 2.

<table>
<thead>
<tr>
<th>Relative error</th>
<th>Element weight percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5%</td>
<td>&gt;20%</td>
</tr>
<tr>
<td>&lt;10%</td>
<td>3%~20%</td>
</tr>
<tr>
<td>&lt;30%</td>
<td>1%~3%</td>
</tr>
<tr>
<td>&lt;50%</td>
<td>0.5%~1%</td>
</tr>
</tbody>
</table>

EDS spectra of ash samples in different temperature zones were displayed and
discussed in ref. [17]. From Fig. 3(b) in ref. [17] it is known that the major elements in the ash sample in zone 1 were O, Si, Al, and Ca. The chemical compound should be SiO$_2$, Al$_2$O$_3$, and Wollastonite, which are major incombustible matter of coal. For the ash sample from zone 2 (see Fig. 5b in ref. [17]), the weight percentage for S and Fe are 0.16% and 1.55%, respectively, whose chemical compound should be FeSO$_4$. This is why there exists slight corrosion on the probe in zone 2 (see Fig. 9b in ref. [17]). While for ash sample from zone 3, the weight percentage for S and Fe rise to 5.98% and 37.54%, respectively, which explains severe corrosion on the probe in zone 3 (Fig. 7c in the present paper).

Water vapor, SOx, and ash are important components in flue gas. SOx and water vapor can react into H$_2$SO$_4$ vapor. When the outer wall temperature is high enough, H$_2$SO$_4$ vapor adjacent to the outer wall is of gaseous state. H$_2$SO$_4$ vapor begins to condensate at acid dew temperature (ADT). ADT is a function of the partial pressure of H$_2$SO$_4$ vapor. Generally, local ADT drops with decreasing partial pressure of H$_2$SO$_4$ vapor [23]. When $T_w$ is slightly lower than the local ADT, the partial pressure of H$_2$SO$_4$ vapor decreases because part of the H$_2$SO$_4$ vapor condensates into liquid acid, leading to a decrease of the local ADT. Thus, the condensation may not continue and the condensed sulfuric acid is so rare that it has little influence on ash property. The deposited ash particles remains dry and separate from each other, just like that with temperature over ADT. Therefore, no accumulation and corrosion occurred on the probe, no large particles were detected in the SEM analysis, no Fe and S were found in EDS photos, and the deposited ash was easy to blow off. The component of
the deposited ash is just incombustible matter of coal. All the phenomena mentioned above are characteristics of zone 1.

With the $T_w$ drops farther from ADT, the H$_2$SO$_4$ vapor condensation produces more concentrated liquid acid. The deposited ash absorbs the liquid acid and increase the adhesion force between particles. When $T_w$ goes down to a certain temperature range, the adhesion force becomes strong enough for particles to accumulate when collision happens. With accumulation goes on, the probe surface will inevitably change from that partly covered by separated dry particles to that fully covered by accumulated humid particles. The temperature range that ash particles on the probe surface begin to accumulate is the turning zone 1 (66–70°C) shown in Fig. 4. The accumulated deposited ash is too sticky to clear off and the fouling thermal resistance increases. Thus, gas-side $Nu_g$ has a sudden drop at turning temperature zone 1.

Besides, chemical reaction between liquid acid, incombustible matter of coal and heat transfer surface occurs to produce FeSO$_4$; but the reaction is slow because of concentrated acid. Fe and S can be detected by EDS although their contents are rare. Those are characteristics of zone 2. In our experiments conducted, the turning temperature is about 32°C lower than the ADT.

As $T_w$ goes down from zone 2, it is much lower than the local ADT, but higher than the WDT. Massive H$_2$SO$_4$ vapor condensates to produce more and more concentrated acid. Oxygen content in the concentrated sulfuric acid is relatively high. Thus, passivation occurs on metal surface of tube bundle. Corrosion rate between metal and acid is low. But the concentrated sulfuric acid has a strong ability to absorb
water vapor from flue gas. It actually acts as desiccant. With absorption goes on, water content in the deposited ash becomes larger and larger. When $T_w$ goes down to a certain temperature range, sufficient water vapor is absorbed by the concentrated acid, and the concentrated acid turns into dilute acid with certain oxygen content [24]. The protection film on metal surface caused by passivation vanishes and corrosion accelerates. More and more FeSO$_4$ appears. It is loose and enlarges the thermal resistance in a short time. The sudden drop of heat transfer performance occurs within turning zone 2, which is about 10°C higher than the WDT.

In practical point of view, as long as the outer wall temperature is in zone 1, the deposited ash will be thin and easy to blow off. It does not impact heat transfer performance and introduces no corrosion on the tube heat transfer surface. In a limit case, the exhausted flue gas temperature can be reduced to the sum of the minimum value in zone 1 and a reasonable heat transfer temperature difference between tube wall and flue gas. Thus, the maximum limit for waste heat recovery can be determined.

5 Conclusions

Experimental studies have been conducted to investigate the heat transfer deterioration, ash deposition, and corrosion for tube heat transfer surface under ultra-low tube wall temperature circumstance for WHRS in boilers. The experimental result reveals that the gas-side $Nu_g$ experiences two rapid drops with decreasing tube outer wall temperature.

When $T_w$ was higher than 70°C, which was about 32°C lower than ADT, there
was no obvious ash deposition on the testing probe. $Nu_g$ was high and no corrosion was observed. As $T_w$ drops below 66°C but above 54°C ash deposits because of the condensed concentrated sulfuric acid and the deposition becomes thicker and stickier, which reduces heat transfer performance to a mediate $Nu_g$ and accompanies with slight corrosion. As $T_w$ further drops below 51°C, FeSO$_4$ content has a sharp increase because of increased corrosion, resulting in a further reduction in $Nu_g$ and severe corrosion. The present experiments observed two turning zones – the first one occurs when the wall temperature is about 32~36°C lower than the ADT, and the second one is about 10°C higher than the WDT.

To operate and design WHRS in practical boilers, it is critical that the tube outer wall temperature should be higher than the first turning temperature zone so that the heat transfer performance of the heat transfer tube bundle is not affected by ash deposition and sulfuric acid corrosion. The limit for waste heat recovery can be determined when the exhausted flue gas temperature is reduced to the sum of the minimum value in zone 1 and a reasonable heat transfer temperature difference between tube wall and flue gas.

Acknowledgment:

The authors acknowledge the financial support provided by the Chinese National Development and Reform Commission on Low-carbon Technological Innovation and Industrial Demonstration Project on Power Industry ([2003] 1819).

References


operating at both subcritical and supercritical conditions, Applied Thermal Engineering, 92 (2016) 1-7.


[23] P. Müller, Contribution to the problem of the action of sulfuric acid on the dew point...


Corrosion of carbon steel pipes and tanks by concentrated sulfuric acid: A review,

List of Figures

Fig. 1 Experimental system.

Fig. 2 Structure and dimension of the test probe.

Fig. 3 $Nu_g$ vs $Re_w$ at various wall temperatures for Φ48 test probe.

Fig. 4 $Nu_g$ against $T_w$ with $Re_w$ in the range of 1300~2300.

Fig. 5 Photos of the Φ48 test probe in zone 1.

Fig. 6 Photos of the Φ48 test probe in zone 2.

Fig. 7 Photos of the Φ48 test probe in zone 3.

Fig. 8 SEM photos of the ash samples in different zones.