Experimental Research on H-type Elliptical Finned Tubes in Low Temperature Boiler Gas Flue

Lei Ma¹,³, Fei Li², Jiayou Liu¹,⁴, Zhimin Li¹,⁴, Fengzhong Sun¹,*

¹ School of Energy and Power Engineering
Shandong University
Jinan 250000, China
² College of Physics Science and Technology
Jinan University
Jinan 250000, China
³ Jinan Institute of Measurement and Testing
Jinan 250000, China
⁴ Shandong University of Science & Technology
Taian 271000, China

Abstract — Low pressure economizer, which works at relatively low temperatures, is now commonly-used in coal-fired boilers to enhance waste heat recovery. However, too low temperature of the flue gas will deteriorate the ash deposition and finally influences heat transfer characteristics and resistance characteristics of heat exchange tubes in low pressure economizer. In order to study the change regulations of heat transfer characteristics and resistance characteristics of heat exchange tubes usually used in low pressure economizer in low temperature flue gas, a field experiment is carried out with typical H-type elliptical finned tubes in the flue pipe of a 250MW fluidized-bed combustion boiler. Based on the observation and analysis, the ash deposition can be divided into three conditions: mere ash deposition condition, acid-ash coupling deposition condition, and water-ash coupling deposition condition. The change regulations of heat transfer and resistance characteristics of typical H-type elliptical finned tubes in acid-ash coupling deposition condition and water-ash coupling deposition condition are obtained, and the influence of tube bundle arrangement is illustrated. Finally, some suggestions on the design of tube bundle arrangement are provided for practical application.

Keywords - low pressure economizer; ash deposition; H-type elliptical finned tube; heat transfer characteristics; resistance characteristics

I. INTRODUCTION

Nowadays, many countries, such as China and India, are still heavily dependent on coal-based energy supply [1]. The use of fossil fuels leads to environmental problems, which have severe influences on the human health and the sustainability of ecosystems. Hence, it is of great significance to improve the efficiency of coal-fired power plants [2]. One of commonly-used methods to improve efficiency of coal-fired boiler is using low pressure economizer to enhance the waste heat recovery [3]. Therefore, the research on the efficiency of heat exchangers in low pressure economizer is of great importance.

The temperature of the outer wall of heat exchange tubes is a key factor that can influence the efficiency of heat exchange tubes used in low pressure economizer, because extremely low temperature may cause sulfuric acid vapor and water vapor contained in the flue gas to condense on the outer wall of tubes to form liquid film, resulting in serious ash deposition and corrosion. Shi et al. [4] conducted experiments to investigate heat transfer characteristics of double pipe in the flue gas environment with dust and acid, and proposed the definition of engineering acid dew temperature of flue gas by analyzing the differences of heat transfer characteristics under different temperatures of outer wall, illustrating that heat transfer characteristics of heat exchanger can be influenced by outer wall temperatures. Nuntaphan and Kiatsiriroat [5] investigated the effect of fly-ash deposit on thermal performance of a cross-flow heat exchanger having a set of spiral finned-tubes as a heat transfer surface, with the inlet temperature of cold water stream being kept constant at 5°C. Wang et al. [6] performed ash deposition experiments with anti-dew point corrosion materials at temperature below dew point and analyzed microstructures of the composition of ash deposition by X-ray diffraction (XRD) and Energy Dispersive Spectrometer (EDS), illustrating that the ash deposition layer could be divided into non-condensation zone, main condensation zone and secondary condensation zone. He et al. [7] performed a three-dimensional numerical study on acid condensation characteristics of H-type finned tube bank with 10 rows of tubes, which led to a conclusion that among seven influence factors studied, Reynolds number and fin thickness have the most important effect on the average condensation rate on the fin surface. Meanwhile, the study on dew point, at which temperature the sulfuric acid vapor or water vapor begins to condense, has received a lot of interest. Bahadori [8] formulated a predictive tool to estimate the acid dew point, for sulfur in various fuels up to 0.10 volume fraction in gas
(0.10 mass fraction in liquid), excess air fractions up to 0.25, and elemental concentrations of carbon up to 3.

Ash deposition, which is influenced by the outer wall temperature of heat transfer tubes, is a factor that deteriorates the heat transfer performance and leads to higher energy consumption and inefficiency in commonly-used industrial heat exchangers [9]. It is generally accepted that Kern and Seaton [10] devised the first general model to describe the fouling process as a dynamic process which is principally influenced by the relation between deposition and removal forces. In the recent years, a considerable amount of researches have been conducted in this field. Shi et al. [11] carried out an experiment in a 75t/h CFB (circulating fluidized bed) boiler unit, employing fouling factor $e$ and overall heat transfer coefficient ratio $\psi$ to evaluate the influence of ash deposition on heat transfer. Shimogori et al. [12] evaluated the effects of fine ash particles and alkali metals on the decreasing heat flux at the initial stages of ash deposition which has a significant effect on heat transfer characteristics during the whole ash deposition process. Kaiser et al. [13] analyzed the formation of fouling layers on cold heat exchanger surfaces using a specialized experimental facility, which contains a so-called dryer exhaust gas simulator and a cooled probe tube in a measuring section. Kim [14] experimentally investigated the deposition of particles onto a cold circular cylindrical surface in high-temperature particle-laden cross flows, and obtained local particle deposition efficiency for two Reynolds number and three wall/gas temperature ratio parameters by using scanning electron microscopy (SEM) techniques. Vuthaluru and French [15] conducted a mineralogical study in order to understand deposit formation in the air heater sections of the boiler through collecting and analyzing several air heater deposit samples in the selected regions of the air heater along with samples of the feed coal, bottom ash and fly ash for comparison of ash chemistry and mineralogy.

Besides the temperature of outer wall, the tube type and tube bundle arrangement of heat exchangers also influence the heat transfer characteristic and the resistance characteristic, and thus attract researchers’ attention. Yang et al. [16] experimentally investigated frictional and heat transfer characteristics of rectangular finned-tube economizer of watercraft boiler, and obtained correlation formulas to describe the relationship between heat transfer characteristics and Reynolds Number. Wang et al. [17] proposed three novel types of fins to both enhance the heat transfer and reduce the acid condensation based on the H-type finned oval tube. Liu et al. [18] studied the characteristics of heat transfer and flow resistance for H-type finned tubes banks, and presented correlation formulas of flow resistance and Reynolds Number. Bouris et al. [19] studied the potential of two passive techniques, namely elliptic-shaped tubes and asymmetric tube bundle arrangement, for deposition rate reduction in lignite-fired utility boiler heat exchangers numerically through comparison with an in-line tube arrangement with circular tubes. Han et al. [20] developed a numerical model to predict the particle deposition rate on the heat exchanger surface using the adhesive and rebound models of particle, and examined the effects of six parameters on fouling rate, as well as on heat transfer and hydrodynamics performance for the purpose of reducing fouling rate. Vessakosol and Charoen suk [21] studied the fouling effect on heat transfer around a cylinder in cross flow numerically by using conjugate heat transfer approach. Kaptan et al. [22] investigated the effects of fouling on heat transfer and flow structures numerically for cross-flow heat exchanger tube geometry, obtaining the distributions of temperature, heat transfer coefficient and heat flux at the surface of fouling for single and double layer fouling cases.

It should be noted from the above discussions, to the authors’ knowledge, few field experiments have been conducted on the coupling effect of acid-ash or water-ash on ash deposition. Besides, the heat transfer and resistance characteristics of H-type elliptical finned tubes in low temperature environment haven’t been seriously studied. Therefore, the aim of this work is to carry out field experiments in the flue pipe of a coal-fired boiler to investigate heat transfer and resistance characteristics of typical H-type elliptical finned tubes in acid-ash coupling deposition condition and in water-ash coupling deposition condition, separately. Finally, some suggestions on the design of heat exchange tubes used in heat recovery equipment are provided.

II. METHODOLOGY

A. Experimental System

Figure 1 shows the schematic diagram of the experimental system. The system mainly includes experimental section installed in the flue pipe of a fluidized-bed combustion boiler (CFB) and a thermostatic water tank for providing constant temperature water. In the experiment, the flue gas flows through expanding section, rectification section and tube bundles of H-type elliptical finned tubes in in-line arrangement and stagger arrangement. Figure 2 shows
the geometrical sketch of the H-style elliptical finned tube. Figure 3 shows different arrangements of tube bundles.

![Geometrical sketch of the tube](image)

![Different arrangements of tube bundles](image)

The main technique specification of the CFB is shown in Table I. The geometric parameters of finned tube bundles are listed in Table 2.

<table>
<thead>
<tr>
<th>Technique specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specified evaporation rate (t/h)</td>
<td>75</td>
</tr>
<tr>
<td>Nominal steam pressure (MPa)</td>
<td>3.82</td>
</tr>
<tr>
<td>Steam temperature (°C)</td>
<td>450</td>
</tr>
<tr>
<td>Exhaust gas temperature (°C)</td>
<td>150</td>
</tr>
<tr>
<td>Thermal efficiency (%)</td>
<td>85</td>
</tr>
<tr>
<td>Coal fineness (nm)</td>
<td>≤13</td>
</tr>
<tr>
<td>Ash content (%)</td>
<td>21</td>
</tr>
<tr>
<td>Volatile content (%)</td>
<td>26</td>
</tr>
<tr>
<td>Total moisture (%)</td>
<td>18.08</td>
</tr>
<tr>
<td>Air-dried moisture (%)</td>
<td>8.34</td>
</tr>
</tbody>
</table>

In the experiment, constant temperature water (i.e., desalted water) is supplied by a thermostatic water tank to the heat exchange tubes, the water outlet is cooled by a radiator and utilized cyclically, the flow rate of the flue gas is adjusted by a shutter and measured by cross-section method using pitots and Dif-pressure gauge, the temperatures of gas inlet and outlet are measured by resistance thermometers. Meanwhile, the mass flow of constant temperature water and qualitative temperature is kept constant. Measuring instruments and the precision thereof are shown in Table 3.

<table>
<thead>
<tr>
<th>Geometric parameters</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Fin length a (mm)</td>
<td>54</td>
</tr>
<tr>
<td>Fin width b (mm)</td>
<td>76.5</td>
</tr>
<tr>
<td>Slit width c (mm)</td>
<td>10</td>
</tr>
<tr>
<td>Long axis diameter d1 (mm)</td>
<td>52.46</td>
</tr>
<tr>
<td>Short axis diameter d2 (mm)</td>
<td>30</td>
</tr>
<tr>
<td>Fin thickness δ (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Fin pitch S (mm)</td>
<td>13.5</td>
</tr>
<tr>
<td>Traversal pitch S1 (mm)</td>
<td>80</td>
</tr>
<tr>
<td>Longitudinal pitch S2 (mm)</td>
<td>100</td>
</tr>
<tr>
<td>Relative traversal distance 1</td>
<td>2.105</td>
</tr>
<tr>
<td>Relative longitudinal distance 2</td>
<td>2.632</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit</th>
<th>Type</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dif-pressure gauge</td>
<td>Pa</td>
<td>Testo512</td>
</tr>
<tr>
<td>Resistance thermometer</td>
<td>°C</td>
<td>PT100</td>
</tr>
<tr>
<td>Pitot</td>
<td>Pa</td>
<td>0.1</td>
</tr>
<tr>
<td>Flowmeter</td>
<td>Pa</td>
<td>LZI-6F</td>
</tr>
<tr>
<td>Data acquisition</td>
<td>HP54970A</td>
<td>2.5</td>
</tr>
<tr>
<td>Flue gas analyzer</td>
<td>NOVA2000</td>
<td></td>
</tr>
</tbody>
</table>

**B. Experiment**

The preparations of the experiment includes: installing the experimental instruments into the flue pipe, closing the shutter to keep the heat exchange surface clean, waiting for the boiler running steadily, heating the water in the tank, and opening the pump and valve to pump the constant temperature water into the heat exchanger continuously.

The experimental procedure is as follows: opening the shutter, controlling the temperature of water inlet using thermostatic water tank so that the wanted temperature of outer wall of heat exchange tubes is obtained, waiting for the ash deposition achieving stable state, recording the parameters to be measured, adjusting the shutter many times to obtain data under different flue gas velocities, lowering the temperature of water inlet to obtain another group of parameters under another temperature of outer wall.

**C. Reynolds Number Calculation**

Reynolds Number Re of flue gas outside tubes can be calculated by Eq. (1).

$$Re = \frac{w \cdot de}{\nu_g} \quad (1)$$

Where \( w \) refers to velocity of flue gas, m·s⁻¹; \( de \) refers to hydraulic diameter of elliptical tubes, m; \( \nu_g \) refers to kinematic viscosity of flue gas, m²·s⁻¹.

**D. Nusselt Number Calculation**

In the experiment, finned tubes are well ribbed with compact heat exchange surface, and the temperature
difference between water inlet and outlet is limited within 5°C by controlling the flow rate of constant temperature water. Hence, the temperature distribution on the surface of outer wall is uniform. In order to avoid disturbing the temperature distribution around the surface of outer wall due to the arrangement of too many resistance thermometers, the heat transfer coefficient \( h \) is calculated using variable separation approach without measuring the temperature of outer wall directly. To be specific, the outer wall heat transfer coefficient \( h_w \) is calculated firstly by the measured parameters and then handled dimensionlessly to obtain the fitting formula of \( Nu \).

According to heat transfer theory, it holds that

\[
\frac{1}{K} = \frac{1}{h_0} \beta \left( \frac{1}{h_i} + r_w + r_f \right) \quad (2)
\]

Where \( K \) refers to overall heat transfer coefficient, \( W \cdot m^{-2} K^{-1} \); \( h_0 \) refers to outer wall heat transfer coefficient, \( W \cdot m^{-2} K^{-1} \); \( \beta \) refers to finned coefficient; \( h_i \) refers to inner wall heat transfer coefficient, \( W \cdot m^{-2} K^{-1} \); \( r_w \) refers to thermal resistance of tube wall, \( m^2 K \cdot W^{-1} \); \( r_f \) refers to thermal resistance of fouling on inner wall, \( m^2 K \cdot W^{-1} \).

In the experiment, \( h_0 \) is much smaller than \( h_i \), so \( \beta \left( \frac{1}{h_i} + r_w + r_f \right) \) keeps invariant, which can be defined as \( R \).

Then the outer wall heat transfer coefficient \( h_0 \) can be written as:

\[
h_0 = \frac{1}{K - R} \quad (3)
\]

Dimensionless criterion number \( Nu \), which describes the heat transfer characteristics of the outer wall of the heat exchanger, can be obtained by Eq. (4).

\[
Nu = h_0 \times \frac{de}{\lambda_e} \quad (4)
\]

Where \( d_e = \frac{4A}{P} \), \( d_e \) refers to hydraulic radius of elliptical tube, \( m \); \( A \) refers to sectional area of elliptical tube, \( m^2 \); \( P \) refers to wetted perimeter, \( m \); \( \lambda_e \) refers to thermal conductivity of flue gas, \( W \cdot (m \cdot k)^{-1} \).

E. Euler Number calculation

Dimensionless criterion number \( Eu \) is used to represent the resistance characteristics of the tubes and can be obtained by Eq. (5)

\[
Eu = \frac{2\Delta p}{W \cdot \rho \cdot z} \quad (5)
\]

Where \( \Delta p \) refers to pressure difference between the flue gas inlet and outlet, \( Pa \); \( z \) refers to the number of rows.

III. RESULTS AND DISCUSSION

A. Ash Deposition Condition

In this experiment, \( Nu \) is calculated to indicate heat transfer characteristic of tubes. As can be seen from Figure 4, \( Nu \) of tubes in different flow field with different \( Re \) of flow gas with different arrangement show same change regulation according to the change of temperature of outer wall.

At the beginning stage, the heat exchanger works at a mere ash deposition condition and the ash deposition reaches a state of equilibrium, and the deposition rate is equal to the denudation rate. When the temperature of outer wall reduces to 70°C, the equilibrium is destroyed and \( Nu \) reduces rapidly. This is because acid vapor starts to condense on the outer wall and the deposition rate is greater than the denudation rate. After hours of acid-ash coupling deposition process, a new equilibrium is established and the heat exchanger works in a steady state again. The new balance can’t be stuck by lowering the temperature of outer wall unless the temperature reaches 50°C. Under this temperature, the water vapor starts to condense on the outer wall, which aggravates ash deposition and causes a rapid decrease of \( Nu \). Finally, a new balance establishes and the heat exchanger works in steady water-ash coupling deposition condition.

Ash samples collected from surfaces of tubes in different ash deposition conditions are studied by energy spectrum analysis method using SU-70 thermal field SEM, and the content of each element is shown in Figure 5. As can be seen, no acid condenses on the outer wall when temperature of the wall is 80°C; when the temperature of outer wall is 65°C, a little element S appears in deposited ash, illustrating that the acid vapor begins to condense on the surface of the exchanger; when the temperature of outer wall comes down to 45°C, which is below water dew point, large amount of acid vapor and water vapor begin to condense on the surface of the exchanger and corrode the surface severely with the oxygen in fuel gas.

Figure 4. Effect of the temperature of outer wall on heat-transfer characteristic

Figure 5. Energy spectrum analysis of ash samples.
Based on the above observation and analysis, the ash deposition can be divided into three stages: mere ash deposition condition above the engineering acid dew temperature, acid-ash coupling deposition condition between the engineering acid dew temperature and the water dew temperature, and water-ash coupling deposition condition below the water dew temperature. In each stage, the ash deposit will reach a stable thickness, respectively. Meanwhile, in each stage, the stable thickness is independent on the temperature of outer wall. The turning points of the three stages in this experiment are 70°C and 50°C, respectively.

B. Heat Transfer Characteristic of H-type Elliptical Finned Tubes

The experimental correlation formula of heat transfer characteristic of H-type elliptical finned tubes in acid-ash coupling deposition condition is obtained by least squares fitting according to the results of field experiment.

Stagger arrangement:
\[ \frac{u}{N} = 0.02767 \cdot Re^{0.80053} \]
\[ R^2 = 0.99184; \ Re=2000\sim20000 \]

In-line arrangement:
\[ \frac{u}{N} = 0.00641 \cdot Re^{0.94963} \]
\[ R^2 = 0.99031; \ Re=2000\sim20000 \]

The experimental correlation formula of heat transfer characteristic of H-type elliptical finned tubes in water-ash coupling deposition condition is obtained by least squares fitting according to the results of field experiment.

Stagger arrangement:
\[ \frac{u}{N} = 0.01517 \cdot Re^{0.83314} \]
\[ R^2 = 0.9881; \ Re=2000\sim20000 \]

In-line arrangement:
\[ \frac{u}{N} = 0.02838 \cdot Re^{0.77026} \]
\[ R^2 = 0.99032; \ Re=2000\sim20000 \]

The heat transfer characteristics of H-type elliptical finned tubes arranged in different mode are compared in Figure 6. As shown in the figure, the heat transfer coefficient increases in the entire experiment field with the increase of Re. It also can been seen that in acid-ash deposition condition, Nu of tubes in stagger arrangement is larger than that in in-line arrangement, while in water-ash deposition condition, Nu of tubes in stagger arrangement is smaller than that in in-line arrangement. The reason is that in acid-ash coupling deposition condition, the ash deposition is not such serious and flow field established in stagger arrangement is beneficial to the heat exchange. Correspondingly, in water-ash coupling deposition condition, large amount of ash adheres to the surface of tubes under the action of water, leading to quick increase of ash deposition and deterioration of heat transfer in stagger arrangement, while in in-line arrangement, the tubes are not contacted with fly ash such sufficiently as in stagger arrangement.

C. Resistance Characteristics of H-type Elliptical Finned Tubes

The experimental correlation formula of resistance characteristic of H-type elliptical finned tubes in acid-ash coupling deposition is obtained by least squares fitting according to the results of field experiment.

Stagger arrangement:
\[ Eu = 16.74288 \cdot Re^{-0.45544} \]
\[ R^2 = 0.99295; \ Re=2000\sim20000 \]

In-line arrangement:
\[ Eu = 3.43151 \cdot Re^{-0.3121} \]
The experimental correlation formula of resistance characteristic of H-type elliptical finned tubes in water-ash coupling deposition condition is obtained by least squares fitting.

**Stagger arrangement:**
\[ Eu = 24.31496 \times Re^{-0.48179} \]  
**In-line arrangement:**
\[ Eu = 7.90988 \times Re^{-0.39299} \]

Figure 7 compares the resistance characteristics of H-type elliptical finned tubes arranged in different modes. As shown in the figure, in all the experiment fields, the resistance characteristics of H-type elliptical finned tubes of in-line arrangement are better than that of stagger arrangement. This may due to the good dust cleaning ability of H-type elliptical finned tubes. It can also be found that as Re increases, the differences of Eu between in-line arrangement and stagger arrangement become small. This is because detour flow formed between tubes decreases with the increase of Re. In addition, with the decrease of the temperature of outer wall, the viscosity of ash increases, which results in the decrease of the dust cleaning ability of H-type elliptical finned tubes and the deterioration of the resistance characteristics.

Based on comprehensive consideration of heat transfer characteristic and resistance characteristic of H-type elliptical finned tubes, the following suggestions can be drawn. When the heat exchanger works in acid-ash coupling deposition condition, in-line arrangement is recommended, and anti-corrosion material should be used. For the water-ash coupling deposition condition, as the heat transfer surface is polluted rapidly by large amount of adhesive ash, causing the heat transfer characteristic and resistance characteristic to deteriorate obviously, it should be avoided unless in particular situation.

**IV. CONCLUSION**

In this paper, a field experiment was carried out with typical H-type elliptical finned tubes in the flue pipe of a 250MW fluidized-bed combustion boiler, and the heat transfer and resistance characteristics of such H-type elliptical finned tubes in acid-ash coupling deposition condition and water-ash coupling deposition condition are studied. The following conclusions can be demonstrated:

1. In the field experiment, when the temperature of outer wall of the heat exchanger is between the engineering acid dew temperature and the water dew temperature, the heat exchanger works in acid-ash coupling deposition condition; when the temperature is below water dew temperature, the heat exchanger works in water-ash coupling deposition condition.

2. In the stable stage of acid-ash coupling deposition condition or water-ash coupling deposition condition, the heat transfer coefficient of heat transfer tubes does not change with the temperature of outer wall.

3. The influence of tube bundle arrangement on heat transfer and resistance characteristics of typical H-type elliptical finned tubes is illustrated.

4. Typical H-type elliptical finned tubes should be in-line arranged when used in low pressure economizer under acid-ash coupling deposition condition.

**REFERENCES**


**Figure 7. Resistance characteristics of H-type elliptical finned tubes**


