Postprint: Calculation and Analysis of Heat Absorption Deviation of a Novel Diamond-Shaped Heating Surface

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Abstract

Based on a cement waste heat integrated utilization technology platform, the heat absorption deviation of a novel diamond-arranged heating surface serving as a waste heat boiler superheater is calculated and analyzed. Non-uniform thermal load on the heating surface constitutes the primary factor causing thermal deviation. This paper proposes the concept of an equivalent heat absorption non-uniformity coefficient, presents a mathematical method for calculating this coefficient when the heating surface arrangement forms a certain angle with the flue gas flow direction, and verifies its reliability through experimental results. The tube bundle arrangement of the diamond-shaped heating surface enables rational and efficient utilization of thermal energy, with heat absorption deviation ranging between 0.82 and 1.07. Compared with in-line arranged heating surfaces, it demonstrates excellent heat absorption uniformity and offers significant structural advantages for reducing thermal deviation.

Full Text

Preamble

Calculation and Analysis of Thermal Deviation in a Novel Diamond-Shaped Heat Transfer Surface

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Abstract

Based on a cement waste heat integrated utilization technology platform, this paper calculates and analyzes the heat absorption deviation of a novel diamond-shaped heat transfer surface when used as a superheater in a waste heat recovery boiler. Uneven thermal load distribution is the primary factor causing thermal deviation. The concept of an equivalent heat absorption non-uniformity coefficient is proposed, and a mathematical method for calculating the heat absorption non-uniformity coefficient is presented for cases where the heating surface arrangement forms an angle with the flue gas flow direction. The reliability of this method is verified through experimental results. The tube arrangement of the diamond-shaped heating surface enables rational and effective utilization of thermal energy, with heat absorption deviation ranging between 0.82 and 1.07. Compared with in-line arranged heating surfaces, this demonstrates excellent heat absorption uniformity and offers significant structural advantages for reducing thermal deviation.

Keywords: waste heat recovery boiler; heat transfer surface; superheater; thermal deviation; thermal load distribution

Introduction

Based on numerical simulation results of heat transfer and flow characteristics, this study performs calculations and analysis of the heat absorption deviation of diamond-shaped heating surfaces for superheater systems in waste heat recovery boilers, providing a reference for future optimal design and safe operation of waste heat boiler systems. The waste heat recovery boiler is the most critical thermal energy conversion equipment in waste heat power generation systems, and its heat exchange capacity and thermal efficiency largely determine power output and overall system efficiency. Therefore, actively developing high-efficiency boilers suitable for low-grade waste heat power generation has become a top priority for future work.

1. Theory of Thermal Deviation in Superheater Systems

Thermal deviation arises from uneven heat absorption among superheater tubes combined with non-uniform steam flow distribution inside the tubes, resulting in different enthalpy increases in each tube. As the heating surface operating in the most severe conditions, the superheater is located in the highest temperature region of the boiler flue. The high-temperature, high-pressure steam flow inside the tubes is complex, and uneven heat absorption and flow distribution among parallel tubes create thermal deviation. The existence of thermal deviation causes local overheating of the superheater. When individual tube wall temperatures become excessively high while steam flow is low, and thermal deviation exceeds allowable limits, tube rupture and leakage accidents can easily occur, leading to reduced operating efficiency and safety hazards.

This study is based on a waste heat integrated utilization technology platform established by Shandong University at a domestic cement plant. Using waste heat boiler performance test data and numerical simulation results as a foundation, the heat absorption deviation of diamond-shaped heating surfaces is calculated and analyzed. The thermal deviation coefficient is typically used to characterize the degree of thermal deviation, defined as the ratio of steam enthalpy increase Δi_i in a particular deviated tube to the average enthalpy increase Δi across the entire tube group:

 = Δi_i / Δi = (q_i/q) × (A_i/A) / (G_i/G) = _q × _A / _G

where q_i and q represent the heat load of a particular deviated tube and the average heat load of the tube group, respectively; A_i and A represent the heating surface area of a particular deviated tube and the average heating surface area per row in the tube group, respectively; and G_i and G represent the steam mass flow rate in the deviated tube and the average steam flow rate in the tube group, respectively. In this equation, _q = q_i/q, _A = A_i/A, and _G = G_i/G are referred to as the heat absorption non-uniformity coefficient, structural non-uniformity coefficient, and flow non-uniformity coefficient, respectively. Thus, superheater thermal deviation is caused by three types of non-uniformity: thermal characteristics, structural characteristics, and hydraulic characteristics.

Flow non-uniformity primarily results from header effects, tube structural differences, and thermally induced flow. For the object of this study, the diamond-shaped heating surface header system has relatively small geometric dimensions and employs a U-type arrangement. The pressure difference across tube circuits changes little, resulting in relatively uniform flow distribution. Previous research has established criteria under which header pressure drop effects on flow distribution can be neglected, and has shown that gravitational head deviation can be disregarded in multi-pass convection superheaters. Under the assumption of identical inlet steam temperature and structure for all tubes in the same panel, without considering header static pressure variation and gravitational pressure drop effects, researchers have derived relationships between flow non-uniformity coefficients and steam specific volume deviation. If the heat load distribution among tube bundles is relatively uniform, specific volume deviation is generally small. Based on calculation methods from relevant literature, the flow non-uniformity coefficient _G for diamond-shaped heating surface tubes is estimated to be 0.98-1.02, indicating small flow deviation among branch tubes with minimal impact on thermal deviation. Since the heating surface has a symmetrical structure with identical tube dimensions, the structural non-uniformity coefficient _A = 1. Therefore, thermal deviation in diamond-shaped heating surfaces is primarily determined by the heat absorption non-uniformity coefficient.

Heat absorption non-uniformity, or uneven thermal load distribution across the heating surface, is the most significant factor causing superheater thermal deviation and also affects steam flow distribution inside tubes, creating thermally induced flow deviation. Cement waste heat boilers use hot air from grate coolers as the heat source without an internal combustion process. Diamond-shaped heating surfaces undergo transverse 冲刷 by hot air, with heat transfer primarily through convection and negligible radiation. Consequently, heat absorption deviation is mainly influenced by non-uniformity along both the width and height directions of the boiler convection flue. Notably, waste heat in the cement industry is significantly affected by rotary kiln operating conditions, characterized by temperature instability and high dust content, all of which exacerbate thermal deviation. This paper focuses on calculating superheater heat absorption deviation under stable rotary kiln operating conditions, with other influencing factors to be studied in future experiments.

2. Calculation of Superheater Heat Absorption Deviation

2.1 Heat Absorption Non-uniformity Coefficient Along Boiler Width

Under normal operating conditions, the thermal load distribution across the width of a single-furnace, symmetrical boiler convection flue is relatively fixed, typically highest in the middle and lower on both sides. Using calculation methods from established literature, an approximate functional expression for the heat absorption non-uniformity coefficient can be derived.

Establish X- _q^a coordinate axes, where the flue width is a and the coordinate origin is at the left side of the flue. The relative coordinate X = x/a represents the dimensionless flue width. Assuming the heat absorption non-uniformity coefficient is a fourth-power function of X:

_q^a(X) = AX^4 + BX^3 + CX^2 + DX + E

Five known conditions are required to determine coefficients A through E:

1. At X = 0, _q^a(0) =
2. At X = 1, _q^a(1) =
3. At X = m, a maximum exists with zero curve slope: d _q^a/dX|_{X=m} = 0
4. At X = 0 and X = 1, the curve slope is zero: d _q^a/dX|*{X=0}* = *d _q^a/dX/*{X=1} = 0
5. The area under the curve equals 1: _0^1 _q^a(X) dX = 1

Based on the constraints of the research object with axisymmetric heat load distribution, m = 1/2. From the structural parameters of the diamond-shaped heating surface and boiler tests, = 0.73 and = 1.26. Substituting these conditions into the equation yields the functional expression:

_q^a(X) = 10X^4 - 20X^3 + 10.38X^2 - 0.38X + 0.73

The distribution of the heat absorption non-uniformity function along the boiler width is shown in [Figure 3: see original paper].

2.2 Heat Absorption Non-uniformity Coefficient Along Boiler Height

Thermal load distribution non-uniformity also exists along the boiler flue height direction. Related test results indicate that the heat absorption non-uniformity coefficient along the height direction has a linear relationship with the relative position of deviated tubes in the flue height. Current theoretical research on this topic is limited; therefore, this study combines experimental and numerical simulation results to fit and calculate the heat absorption non-uniformity function curve along the flue height direction.

Establish Φ- _q^h coordinate axes, where the flue height is h and the coordinate origin is at the top of the flue. The relative coordinate Φ = /h represents the dimensionless flue height. Based on test results, the maximum and minimum heat absorption non-uniformity coefficients at the top and bottom of the flue are = 1.16 and = 0.84, respectively. The fitted function is:

_q^h(Φ) = -0.32Φ + 1.16

However, for diamond-shaped heating surfaces, the tube arrangement characteristics show gradually increasing tube density along the height direction, densest in the middle and sparse at both ends, making the heat absorption non-uniformity coefficient non-linear. Assuming the heat absorption non-uniformity coefficient is a fourth-power function of Φ:

_q^h(Φ) = A' Φ^4 + B' Φ^3 + C' Φ^2 + D' Φ + E'

With the following conditions: 1. At Φ = 0, _q^h(0) = 1.16 2. At Φ = 1, _q^h(1) = 0.84 3. At Φ = 0, a maximum exists: d _q^h/dΦ|*{Φ=0} = 0 4. At Φ = 1, a maximum exists: d _q^h/dΦ/*{Φ=1} = 0 5. The area under the curve equals 1: _0^1 _q^h(Φ) dΦ = 1

The resulting function expression is:

_q^h(Φ) = 0.64Φ^3 - 0.96Φ^2 + 1.16

Compared with the linear function, this expression more accurately represents the heat absorption non-uniformity distribution along the flue height for the research object. The function is illustrated in [Figure 4: see original paper]. Numerical simulations of heat transfer and flow characteristics for diamond-shaped heating surfaces have yielded consistent heat load distribution patterns.

2.3 Heat Absorption Deviation for Heating Surface at an Angle to Flue Gas Flow

Unlike conventional in-line or staggered tube arrangements, diamond-shaped heating surfaces feature gradually increasing tube density along the height direction. Therefore, heat absorption non-uniformity coefficients no longer follow a linear distribution. For vertical superheaters, research indicates that height-direction heat absorption non-uniformity affects all tubes identically, with only width-direction non-uniformity having a distinct impact. This conclusion applies when tube bundles occupy the entire flue height. However, each panel of the diamond-shaped heating surface occupies only a portion of the flue height at different relative positions, making it impossible to equate width-direction heat absorption non-uniformity directly with the heating surface' s overall heat absorption non-uniformity. Both width and height directions must be considered simultaneously. Furthermore, since the heating surface tube arrangement forms a 45° angle with the flue gas flow direction and occupies only a portion of the flue width, values cannot be read directly from heat absorption non-uniformity function curves.

To address this issue, this paper proposes the concept of an equivalent heat absorption non-uniformity coefficient, defined as the average value of heat absorption non-uniformity coefficients over the projection segments of a deviated tube (or tube panel) in both width and height directions. The calculation method divides the area formed by the projection segment and the corresponding heat absorption non-uniformity function curve by the relative length of the projection segment. For a vertical boiler with downward flue gas flow, let the longitudinal length of a deviated tube (or panel) be L, the angle with the flue gas flow direction be , the relative width position of the topmost tube be X, and the relative height position be Φ. The width-direction projection segment length is L sin , occupying relative width from X to X + L sin ; the height-direction projection segment length is L cos , occupying relative height from Φ to Φ + L cos , as shown in [Figure 5: see original paper].

The equivalent heat absorption non-uniformity coefficients are calculated as:

_q^{a*} = (1/(L sin)) _X^{X+L sin } _q^a(X) dX _q^{h*} = (1/(L cos)) _Φ^{Φ+L cos } _q^h(Φ) dΦ

A correction coefficient K is introduced to ensure the area under the heat absorption non-uniformity function curve equals 1. Establishing a - _q^* coordinate axis, assuming the number of tube panels is n, the unit scale of the -axis is 1/(n-1). All calculated heat absorption non-uniformity coefficients for each panel are fitted into a curve within the 0-1 range of the horizontal coordinate, with the function equation _q^*( ). The K value should be the reciprocal of the area under the _q^*( ) function curve.

The actual heat absorption non-uniformity coefficient for a tube segment is:

_q = K _q^*

In reality, the above calculation method also applies when tube bundles occupy the entire flue height. In such cases, the height-direction projection segment equals the flue height, the area formed with the heat absorption non-uniformity function curve is 1, the relative projection length is 1, and the K value is also 1. Therefore, only width-direction heat absorption non-uniformity needs consideration, and values can be read directly. For segmented superheaters where each segment occupies different relative heights, the equivalent heat absorption non-uniformity coefficient calculation method can also be applied to account for varying heat absorption conditions at different positions.

Based on the relative position parameters of 24 tube panels in the diamond-shaped heating surface, the calculated heat absorption non-uniformity coefficients for each panel were obtained using equations (8)-(11). These calculated values are compared with experimental results later in this paper to verify their reliability.

3. Experimental Verification

3.1 Experimental System and Method

The research team designed and installed a U-type vertical once-through waste heat recovery boiler consisting of a diamond-shaped heating surface and seven other in-line arranged heating surfaces. The heat source is medium-low temperature air from a grate cooler, extracted by a fan before the boiler exhaust stack. Before entering the waste heat recovery boiler, the hot air passes through a cyclone dust collector. The hot air is transported via pipelines connected to the grate cooler, entering vertically downward from the upper inlet of the diamond-shaped heating surface. After passing through the bottom ash hopper, the hot air direction changes to vertical upward, then passes through four subsequent heating surfaces before exiting from the upper outlet of the waste heat recovery boiler. The exhaust gas is treated by electrostatic precipitation before being discharged to the atmosphere.

Water is supplied from a cylindrical steam-water separation tank with a volume of 32 m^3. Circulation is provided by a vertical centrifugal pump with a rated flow of 32 m^3/h and a head of 52 m. Water flow rate is controlled through valve opening. After pressurization, water enters the waste heat recovery boiler, undergoes heat exchange with hot air across eight heating surfaces, and exits from the superheater outlet into a baffle-type steam-water separator. Steam and water then return to the tank separately through steam and hot water circuits, with steam discharged from the tank’ s vent and hot water from the completed cycle re-entering the boiler. Under these test conditions, the boiler inlet water temperature gradually increases. After a period, superheated steam is produced at the superheater outlet, and the system reaches equilibrium and stability. The experimental system diagram is shown in [Figure 6: see original paper].

Test sections are installed before and after the superheater flue for mounting air-side temperature measurement points. Steam-side temperature and pressure measurement points are installed at the superheater inlet and outlet pipelines. Several wall temperature measurement points are arranged on the outer walls of diamond-shaped heating surface tubes. In the experimental system, hot air and steam temperatures are measured by Pt100 resistance thermometers, steam pressure by EJA430A pressure transmitters, feedwater flow by LWGY-80 turbine flowmeters, and steam flow by DY digital vortex flowmeters combined with XSJ-39AIK flow digital integrators. All instrument data are displayed and recorded in real time by an XMD5000 data logger. A LaiYing 3016 boiler energy efficiency comprehensive tester is used for auxiliary measurements, and an infrared thermometer gun measures hot air temperature at different positions in the superheater flue through flange ports on the test section housing.

Before each test, the water pump is operated at full load for at least 1 hour to ensure the boiler pipeline is completely filled with water. During formal testing, the hot air pipeline valve at the grate cooler outlet is opened and the fan is started. The hot air temperature for each test is determined by the actual rotary kiln operating conditions, with coarse control achieved by adjusting the damper openings at the kiln head and grate cooler outlet. Using the control variable method, the fan extraction rate is maintained at 30,000 Nm^3/h, feedwater flow is kept constant at 3 t/h, and hot air temperature is varied for waste heat recovery boiler tests under different operating conditions. When all parameters no longer fluctuate significantly, the system enters a stable stage. At this point, the superheater inlet and outlet air and steam temperatures are measured, and relevant flow and pressure values are read and recorded.

3.2 Uncertainty Analysis

Using Moffat's method, uncertainty analysis was performed on directly measured data, with results listed in . The analysis meets experimental requirements.

4. Comparison and Analysis of Experimental and Calculation Results

Ten different inlet air temperature conditions were selected to obtain the distribution pattern of air temperature along the flue width. Using the method from reference [10], the minimum and maximum values of the heat absorption non-uniformity coefficient along the width direction were calculated, as shown in [Figure 7: see original paper]. Within the 250–350°C range, the value remains relatively stable with small fluctuations, while the value shows a gradually decreasing trend, indicating that higher air temperatures result in smaller heat absorption deviation in the middle of the boiler and relatively more uniform thermal load distribution compared to lower air temperatures. Considering that most tests were conducted at air temperatures above 300°C, the average and values in this temperature range were used for heat absorption non-uniformity coefficient calculations.

Based on relevant experimental data, thermal calculations were performed to obtain the experimental solution for heat absorption deviation of the superheater heating surface. Due to limitations of the test apparatus, only the heat absorption non-uniformity coefficients of tube panels numbered 1, 6, 12, 18, and 24 are compared with calculated values, as shown in [Figure 8: see original paper]. Panel 1 is the panel closest to the superheater inlet, panel 2 is below it, and so on.

[Figure 8: see original paper] shows the calculated and experimental heat absorption non-uniformity coefficients for each tube panel. Table 2 provides a comparison of calculated and experimental values along with error analysis. The results indicate that experimental values are essentially consistent with calculated values within the error range acceptable for engineering purposes, effectively proving the reliability of the calculation method.

Due to the 45° angle between the tube arrangement and flue gas flow direction, the heat absorption deviation distribution in diamond-shaped heating surfaces is not a simple axisymmetric function with high middle and low sides, but exhibits a certain offset. The maximum value occurs at panel 9, gradually decreasing toward both sides, but the degree of reduction differs, as reflected in the slope variation of the distribution function. The heat absorption non-uniformity coefficient decreases faster toward the superheater outlet than toward the inlet due to the influence of thermal load distribution non-uniformity along the flue height direction. Panel 1 is located at the highest position of the superheater, closest to the hot air inlet, where the surrounding area has the highest temperature and thermal load. Moving toward the superheater outlet, the temperature gradually decreases and thermal load diminishes. Although panel 24 has approximately equivalent width-direction thermal load distribution to panel 1, it is located at the lowest position and is most affected by height-direction thermal load distribution, resulting in the smallest heat absorption non-uniformity coefficient and making it the panel with the least heat absorption. Numerical simulations of diamond-shaped heating surfaces have demonstrated consistent patterns. From the overall tube arrangement perspective, the diamond-shaped heating surface features dense tubes in the high thermal load middle region and fewer tubes in the low thermal load side regions, enabling rational and effective utilization of thermal energy.

The calculation method reveals that when tube panels form an angle with the flue gas flow direction, the heat absorption non-uniformity coefficient must consider both width and height directions of the boiler convection flue, which to some extent homogenizes heat absorption deviation. For each tube panel, this homogenization reduces the impact of large thermal loads at middle and top positions while increasing the impact of small thermal loads at side and bottom positions, bringing heat absorption deviation closer to the average value. Numerically, the heat absorption non-uniformity coefficient of diamond-shaped heating surfaces ranges from 0.82 to 1.07, with approximately three-quarters of all panels falling within the 0.94-1.06 range. In contrast, heat absorption deviation of conventional in-line heating surfaces is determined solely by width-direction heat absorption non-uniformity. Based on experimental data from the evaporator preceding the diamond-shaped heating surface, its heat absorption non-uniformity coefficient ranges from 0.75 to 1.38. By comparison, diamond-shaped heating surfaces demonstrate excellent heat absorption uniformity and offer significant structural advantages for reducing thermal deviation.

5. Conclusions

Based on a waste heat integrated utilization technology platform established at a domestic cement plant, this paper calculates and analyzes the heat absorption deviation of a novel diamond-shaped heating surface when used as a superheater. The following conclusions are drawn:

1. Due to the angle formed with the flue gas flow direction, the heat absorption deviation of diamond-shaped heating surfaces differs slightly from conventional in-line or staggered arrangements. Non-uniform thermal load

distribution is the primary factor causing thermal deviation, including non-uniformity along both the width and height directions of the boiler convection flue.

2. The concept of an equivalent heat absorption non-uniformity coefficient is proposed. Based on this concept, a mathematical method for calculating heat absorption deviation (heat absorption non-uniformity coefficient) is presented for cases where the heating surface arrangement forms an angle with the flue gas flow direction. Comparison with experimental results verifies its reliability.
3. The tube arrangement density of the heating surface corresponds to the thermal load distribution, enabling rational and effective utilization of thermal energy. The heat absorption non-uniformity coefficient ranges from 0.82 to 1.07, demonstrating excellent heat absorption uniformity. Compared with in-line arranged heating surfaces, diamond-shaped heating surfaces offer significant structural advantages for reducing thermal deviation.

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