Investigation of Methods for Increasing of Energy Efficiency of Hot Water Boilers of Small and Average Capacity at the Expense of Reduction of Heat Losses with Exit Gases

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Abstract. Boiler units, being a considerable time in use, lose their effectiveness and even the high-quality performed commissioning works, are not always able to increase the efficiency (coefficient of efficiency) of such unit up to the declared values of parameter chart. Both domestic and foreign boiler equipment have this problem. This issues is reflected in increase of exit gases temperature and, consequently, increase of value of heat losses with exit gases and decrease in efficiency of boiler unit. The purpose of the investigation is to select the most effective way to solve this problem and at the same time the least expensive in terms of investment and modernization of the used equipment. Analytical and experimental studies of heat losses with exit gases, domestic and foreign boiler units of small and average capacity were carried out. The obtained results allow us to formulate recommendations for improving the energy efficiency of boiler equipment for operating organizations and for organizations on the balance of which such equipment is located.

1. Introduction

The biggest impact on the efficiency (coefficient of efficiency) of operation of the boiler equipment for gaseous fuels is the value of the boiler unit heat losses with the exit gases, $q_2$. This is most clearly seen from the below formula to determine the efficiency of the boiler unit by the reverse balance method, %:

$$\eta = 100 - q_2 - q_5,$$

where $q_2$ – heat losses with exit gases, %; $q_5$ – heat losses from the external cooling of the surface, % [1-20].

During operation, the inner surface of the gas ducting (fire tubes) is covered with various deposits, soot, carbon deposits, which reduces the intensity of heat exchange between the fire gases having a high temperature, and the gas ducting walls and, consequently, the heat transfer of the water heated in the boiler unit reduces [1, 2, 11].

To date, various methods of heat transfer intensification have been developed, which can be divided into two main groups [13]:

– passive, do not require additional energy supply, due to surface finning and other devices on the surface of the heat conductor with a low heat transfer coefficient, the use of various turbulizing inserts, swirlers or rough surfaces of heat exchange;
– active, requiring additional supply of energy.

Increasing of the heat exchange intensity in the tubes is possible due to [8]: changes in thermal resistance; changes in the flow rate; finning of the heat exchange surface; artificial turbulence of the flow.

The easiest in technical terms and the least capital – intensive, but at the same time effective way is to install metal inserts-turbulators having form of metal spirals in gas ducting or fire tubes of the boiler unit. The turbulators use allows you to unite almost all methods of increasing the intensity of heat transfer. Turbulators slow down the speed of the exit gases flow, thereby increase the time of heat exchange, cause turbulence of the flow, change the direction of the gas flow, pressing it to the walls of the tubes.

2. Method of analytical determination of heat losses with exit gases from boiler unit

$q_2$, heat losses with exit gases, %, according to the literature data [1, 17, 18], are determined by:

$$q_2 = \frac{(t'_{\text{e,g}} - \alpha_{\text{e,g}} \cdot t_a) \cdot (100 - q_4)}{Q_a},$$

where $t'_{\text{e,g}}$ – the enthalpy of exit gases behind the boiler, kJ/m³; $t_a$ – the enthalpy of cold air supplied to the air heater, entering the boiler circuit, working on the heat of the exit gases of the boiler, kJ/m³; $\alpha_{\text{e,g}}$ – excess air ratio in the exit gases; $q_4$ – heat losses from mechanical incompleteness of fuel combustion, %. For boilers operating on natural gas, the value of $q_4 = 0$%; $Q_a$ – the available heat introduced into the furnace with fuel and air, kJ/m³.

Or by a simplified method [17] heat losses with exit gases, %:

$$q_2 = 0.01 \cdot Z \cdot (t'_{\text{e,g}} - t_a),$$

where $Z$ – is an empirical reference factor for determining heat losses with exit gases [2], depending on the CO₂ content in combustion products and their temperature; $t_{\text{e,g}}$ – the exit gases temperature, °C; $t_a$ – the air temperature before the burners, °C.

All the studied literature data give approximate results of calculation of heat losses with exit gases, besides, the exit gases temperature is taken from the table reference data [1, 2, 6, 9, 17] only by fuel type without taking into account any features of its combustion process and, therefore, require experimental confirmation of the calculation results.

3. Experimental investigation of the value of heat losses with exit gases

The value of heat losses with exit gases is determined by the instrument method using modern devices – gas analyzers [10, 11, 14, 15], for example, the brand Testo, in automatic mode, performing calculations according to the methods used in our country [17]. Experimental investigation were carried out on hot water boilers Turboterm TT of series production by GC «Remex» and «Vitomax 200» of company Viessmann, in operation for more than 10 years.

4. Analysis of results of the performed investigations

Efficiency indicators of the boiler equipment are determined by the results of the experimental investigations of the value of the heat losses with exit gases $q_2$.

The results of the study [1, 2, 6, 9, 17], carried out for a hot water boiler Turboterm TT of series produced by GC «Remex» (Russia) can be given in tabular (table 1) and graphical form (figure 1).
Table 1. The average exit gases temperature depending on the load of the boiler Turboterm TT of series produced by GC «Remex» obtained from the calculation results.

| The heat load of the boiler N, % | t_{e,g}, °C | Heat losses with exit gases q_2, % |
|-------------------------------|------------|---------------------------------|
| 31                            | 180        | 6,2                             |
| 66                            | 210        | 7,43                            |
| 90                            | 245        | 8,94                            |

Figure 1. The exit gases temperature depending on the mode of operation of the hot water boiler (of thermal power N, %).

Figure 2. The heat losses with exit gases obtained from the results of analytical research of literature data.

In order to confirm the reliability of the obtained data [1, 2, 6, 9, 17, 22] a mathematical model of the gas ducting tube with a turbulator was developed using ANSYS software, which is one of the most effective for solving heat transfer problems. In the Fluent module, according to the results of the boundary conditions, the parameters of modeling and solving the heat transfer problem are selected.

As a result of the modeling, temperature contours on the turbulator surface were obtained (figure 3), which show a high degree of convergence of the results (95,4%) with the values given in table 1.
Figure 3. The temperature distribution across the wall of the turbulator.

The results on the boilers experimental studies of the exit gases temperature and heat losses with the exit gases using turbulators and without them are shown in tables 2 and 3, as well as in graphical form (figure 4, 5).

Table 2. The average exit gases temperature depending on the load of the boiler Turboterm TT of series produced by GC «Remex» on the results of experimental studies.

| The investigated parameters of the boiler | Modes of operation of the boiler without a turbulator | Modes of operation of the boiler turbulator |
|------------------------------------------|-----------------------------------------------------|--------------------------------------------|
| The heat load of the boiler $N$, %       | 31 66 90                                           | 31 66 90                                   |
| $t_{e,g}$, °C                           | 183 220 255                                        | 137 171 193                               |
| The heat losses with exit gases $q_2$, % | 6,32 7,85 9,36                                     | 4,4 5,8 7,3                               |

Table 3. The average exit gases temperature depending on the load of the boiler «Vitomax 200» of company Viessmann on the results of experimental investigation.

| The investigated parameters of the boiler | Modes of operation of the boiler without a turbulator | Modes of operation of the boiler turbulator |
|------------------------------------------|-----------------------------------------------------|--------------------------------------------|
| The heat load of the boiler $N$, %       | 31 66 90                                           | 31 66 90                                   |
| $t_{e,g}$, °C                           | 188,0 225,4 245,1                                  | 145 180 205                               |
| The heat losses with exit gases $q_2$, % | 6,5 8,1 9,0                                       | 4,75 6,195 7,23                          |
Figure 4. Results of experimental studies of the exit gases temperature.

Figure 5. Results of experimental studies of heat losses.

Experimental investigation have shown a decrease in the value of the exit gases temperature and heat losses with the exit gases when using turbulators by 20–30%, which is not taken into account when performing calculations by standard methods. Therefore, the carried out researches are actual and their results can be demanded by the experts and the organizations which are engaged in operation of the boiler equipment. The obtained results also show the coincidence of experimental values for boiler units, regardless of the equipment brand.

5. Conclusion
For hot water boiler units that have been in operation for 10 years and a more effective way to reduce the exit gases temperature is the turbulators use. The obtained calculated and experimental data make it possible to take into account, when performing thermal calculations and considering measures for energy saving, reducing the amount of heat losses with exit gases and increasing the energy efficiency of the boiler unit in similar conditions.
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