Efficiency of Installation of an Additional Gas-Air Heat Exchanger When Operating a Steam Boiler on Gas and Liquid Fuel

F Bakirov¹ and E Ibragimov¹

¹Ufa state Aviation Technical University,
450008, Karl Marx street 12, city Ufa, Republic of Bashkortostan, Russia

E-mail: Ibragimoves5757@mail.ru

Abstract. The article presents the results of calculating the efficiency of reconstruction of the gas and air paths of a steam boiler when working on gas and liquid fuel due to the installation of additional gas-air heat exchangers. Due to the utilization of the thermal energy of the flue gases in the newly installed heat exchangers, the air is heated in front of the boiler air heaters and the fuel efficiency is increased by increasing the boiler efficiency. The increase in the efficiency of the “gross” boiler during the operation of the considered TGM-84 boiler on fuel oil with an average annual operating mode was 2.81 %. The flue gas temperature after the boiler air heaters was 178 °C, and the air temperature at the inlet to the air heaters was 99 °C at the average annual load of the boiler, which ensures an almost corrosion-free operation of the air heater packing. It is revealed that when the liquid fuel boilers, installation of new heat exchangers and their strapping on the side of the air and flue gas has a shorter payback period than the boiler gas fired. The simple payback period of the considered technical solution was 6.82 years when working on gas fuel and 1.35 years when working on liquid fuel.

1. Introduction

The main component of the energy loss of the burned fuel on boilers is the heat loss with the outgoing flue gases. Losses with outgoing flue gases mainly depend on the temperature of the outgoing flue gases and air suckers into the flue gas path of the boiler, which is usually determined by the design and technical condition of the boiler air heaters. The technical condition of the boiler air heaters significantly depends on the type of fuel burned. When working on liquid fuels containing sulfur compounds (high-sulfur fuel oil), the air heater packing is subjected to intense corrosion. To reduce the rate of corrosion processes when working on liquid fuel, the air entering the boiler is preheated in steam heaters, which increases the temperature of the outgoing flue gases and, accordingly, reduces the efficiency of the boiler. When working on gas fuel, the air entering the air heater is not heated at any value of its temperature. Various technical solutions dedicated to the utilization of flue gas heat are known. In [1, 2, 3], options for improving the design of regenerative air heaters (RVP) are considered. In [4, 5, 6], technical solutions based on deep cooling of flue gases due to the installation of an additional heat exchanger in the flue to the chimney, at which their temperature becomes lower than the temperature of condensation of water vapor, are considered. Despite the fact that the use of such a technical solution can significantly increase the efficiency of the boiler, it has not found application on boilers of electric power stations. The main reasons were the inability to operate boilers...
on liquid fuel, reducing the temperature of the outgoing flue gases below the permissible level to ensure reliable and safe operation of the chimneys. Also, the well-known technical solutions for the utilization of the thermal energy of flue gases do not provide a reduction in corrosion damage to the air heaters of boilers. As shown in [7] at low air temperatures, the lack of heating leads to corrosion damage to the air heater packing during operation and on gas fuel. In [8], a computational study of the choice of the optimal design of a new gas-air heat exchanger was carried out and the payback period for its installation on the boiler was calculated. But the calculations are carried out only when the boiler is during operation on gas fuel. The aim of the study was to determine the optimal design of the newly mounted heat exchangers in the flues of the boiler TGM-84, to ensure the practical absence of corrosion damage packing regenerative air heaters of the boiler and the minimum payback period, the costs of implementing this project with the boiler on high-sulfur fuel oil.

2. Methods

The newly installed gas-air heat exchangers and their strapping should ensure that the boiler runs on high-sulfur fuel oil:
- cooling of flue gases to the lowest possible temperature that ensures long-term safe operation of the power plant chimneys, which is 100 °C [9];
- increasing the air temperature before the RVP to a temperature that ensures the temperature of the RVP packing above the temperature of condensation of sulfuric acid vapors in the flue gases over the entire range of boiler loads;
- aerodynamic resistances of the newly installed heat exchanger and air ducts, eliminating the need to replace the existing the smoke fans of the boiler and blower fans boiler (TDU);
- the minimum possible payback period of the developed heat exchanger design.

Design studies were carried out for the TGM-84 power boiler in operation at the power plant (nominal steam capacity of 420 tons/hour, nominal steam parameters of 140 atmospheres and 560 °C). New gas-air heat exchangers (hereinafter referred to as TO) are installed in the existing boiler flues after the existing smoke fans. The boiler is equipped with two smoke fans and two flues after them, through which the flue gases are discharged into the chimney. One heat exchanger is installed in each flue, in total two heat exchangers are installed on the boiler (Fig. 1). The cooling medium in the heat exchangers is the air directed to the heat exchangers from the existing blow fans. The air passes through the heat exchanger pipes, the flue gases wash the pipe bundle from the outside in the direction transverse to the pipe axis. The boiler is equipped with two fans, each heat exchanger is connected to one of the fans through newly installed air ducts. After the heat exchanger, the air is sent through the newly installed air ducts to the existing boiler air ducts in front of the existing air heaters.

![Figure 1. One of the boiler flue gas tracks. A simplified diagram shows the axis (highlighted in red) of one of the newly installed air ducts from one of the boiler's blast fans to the planned installation site of the new heat exchanger. The air duct after the heat exchanger is not shown, so as not to clutter the drawing.](image)

Due to the heat removal from the flue gases, their temperature and heat losses are reduced. Due to the heating of the air in the heat exchanger increases its temperature, which allows to increase the
efficiency of the boiler and increase the temperature packing heaters to a temperature greater than the temperature of the condensation of sulfuric acid vapor in the flue gas of the boiler. When burning high-sulfur fuel oils, the sulfur contained in them leads to the formation of sulfuric acid, which causes corrosion processes in the steel packing of air heaters if the packing temperature is less than the condensation temperature of acid vapor (Fig. 2).

![Figure 2. Corrosion damage of the RVP packing.](image)

The aerodynamic resistance of the new heat exchangers and their strapping with new air ducts should not exceed the existing reserves for the draft and blast of the smoke fans and boiler fans. This requirement leads to significant limitations on the possible design of heat exchangers. The variant of reconstruction of the gas-air path considered in the article is made for a boiler that burns both gas fuel and high-sulfur fuel oil in different periods of time. In the article [8], the dimensions of the heat exchangers were determined to ensure the minimum payback period for the operation of the considered gas-fired boiler. Various options for the arrangement of tube bundles and their fins were considered. It is revealed that the criterion of the minimum payback period for cooling the flue gases to a temperature of 102 °C (under conditions of limiting the maximum permissible aerodynamic resistances of the heat exchanger along the air path and along the flue gas path for the considered boiler with values of 81.8 and 141.7 mm of the water column (mm. w. c.)) corresponds to two possible designs of heat exchangers, the characteristics of which are given in Table. I [8].

| №  | Parameter | Outer diameter pipes \( d=30 \text{ mm} \) | Outer diameter pipes \( d=45 \text{ mm} \) |
|----|-----------|---------------------------------|---------------------------------|
| 1  | \( \sigma_1 \) / \( \sigma_2 \) | 1,613/1,077 | 1,53/1,11 |
| 2  | \( n_v / n_g \) | 102/64 | 68/43 |
| 3  | \( B/H/\text{L} \) / \( \text{mm} \) | 2097/4925/291 | 2195/4671/5 |
| 4  | \( M \), tons | 6,414 | 7,901 |

Symbols used in the table: \( \sigma_1 = S_1/d; \sigma_2 = S_2/d; S_1, S_2 \) - the distance between the axes of the pipes in the transverse and longitudinal direction relative to the flue gas flow; \( n_v \) - the number of rows of pipes in the transverse direction relative to the flue gas flow; \( n_g \) - the number of rows of pipes in the longitudinal direction relative to the flue gas flow; \( B \) - the width of the heat exchanger along the pipe boards (in the direction of the flue gas movement); \( H \) - height of the heat exchanger along the pipe boards (across the flue gas flow); \( L \) - pipe length; \( M \) - the mass of the heat exchanger (including the tube bundle, tube boards and the heat exchanger casing). The layout of the beam is corridor-like. In
order to reduce the weight, manufacturing cost and ensure corrosion resistance, the heat exchangers are made of aluminum alloys.

The results of the calculation of flue gas and air temperatures after the installation of new heat exchangers (TO) in the boiler flues are shown in Table II [8].

| №  | Parameter                                                                 | Rate d load | Average load for the year | Minimum load |
|----|--------------------------------------------------------------------------|-------------|---------------------------|--------------|
| 1  | The temperature of the air in front of TO, °C                              | 27          | 27                        | 27           |
|    | The temperature of the air after TO before the RVP, °C                    | 102, 0      | 98                        | 97           |
| 2  | Flue gas temperature after the RVP before the newly installed TO, °C     | 184, 0      | 166,5                     | 158,5        |
| 3  | The temperature of the outgoing flue gases                            | 119         | 102                       | 97           |
| 4  | leaving the chimney after the newly installed TO, °C                     |             |                           |              |

When switching the boiler to burning high-sulfur fuel oil, the flue gases will contain chemical and mechanical under burning products, which will lead to gradual contamination of the boiler heating surfaces. When manufacturing a heat exchanger according to the layout that provides the minimum overall and mass characteristics (pipe diameter 30 mm), the distance between the outer surface of the pipes in the direction of movement of the flue gases will be 2,3 mm. Such a small gap between the pipes contributes to the intensive drift of the pipe bundle deposits and makes it difficult to clean it. When making a heat exchanger according to the layout corresponding to the pipe diameter of 45 mm, the distance between the outer surface of the pipes in the direction of movement of the flue gases will be 5 mm. Such a gap value, taking into account the fact that the distance between the outer surface of the pipes for the passage of flue gases is 24 mm, and the flue gas velocity at the average annual mode is 7.62 m/s, provides conditions for a low rate of contamination of the pipe bundle. Therefore, for further research, a heat exchanger with an arrangement corresponding to the pipe diameter of 45 mm was chosen.

The positive effect of reconstruction of the boiler when the boiler fuel oil as the temperature of the exhaust flue gases and the increase in air temperature in front of the heaters is to reduce fuel consumption for the boiler due to the increase in its coefficient of performance (CPD) and the reduction of costs of repair and replacement gaskets heaters. A negative factor is the increase in the cost of electricity for its own needs due to the increase in the aerodynamic resistances of the air and gas path of the boiler. The calculation of the economic effect is made for the average annual operating mode of the boiler. The calculation of fuel economy due to an increase in the efficiency of the boiler
by reducing losses with outgoing gases is performed in accordance with [10]. The heat transfer processes in the heat exchanger are calculated in accordance with [11]. The calculation of the aerodynamic resistances is performed in accordance with [12]. The calculation of the boiler performance indicators after the reconstruction was carried out in accordance with the regulatory characteristics of the boiler and the documentation in force in the Russian energy industry [10].

3. Results and discussion

Temperature characteristic points of paths of flue gases and air of the studied boiler at full load of 420 tons/hour, the actual average annual load of 281 tons/hour and minimum load of 210 tons/h to the reconstruction of the air-gas path when working on fuel oil are given in table III.

| №   | Parameter                                                                 | Rated load | Average load for the year | Minimum load |
|-----|---------------------------------------------------------------------------|------------|----------------------------|--------------|
| 1   | Air temperature in front of the steam heaters of the RVP boiler, °C        | 27         | 27                         | 27           |
| 2   | Air temperature after the steam heaters of the RVP boiler, °C              | 70         | 70                         | 70           |
| 3   | The temperature of the flue gases leaving the chimney after the RVP boiler, °C | 177        | 163                        | 158          |

After the reconstruction of the gas-air path of the boiler, the steam heaters are switched off. By utilizing the thermal energy of flue gases in the newly installed heat exchanger, heating the air, which increases the temperature of the air after the heat exchanger, respectively, before established for exchangers heaters boiler. An increase in the air temperature before the boiler air heaters leads to an increase in the air temperature after the air heaters. The heated air is directed to the burner devices of the boiler, which leads to a change in the thermal mode of the boiler and an increase in the temperature of the flue gases leaving the boiler, directed to the air heater. Thus, the installation of new heat exchangers leads to a change in the thermal mode of the boiler, as a result of which the temperature of the flue gases before and after the existing air heaters becomes higher than it was before the reconstruction. The results of the performed thermal calculation of the boiler in terms of flue gas and air temperatures are shown in Table IV.
Table 4

| №  | Parameter                                                                 | Rate d load | Average load for the year | Minimum load |
|----|---------------------------------------------------------------------------|-------------|---------------------------|--------------|
| 1  | The temperature of the air in front of TO, °C                              | 27          | 27                        | 27           |
| 2  | The temperature of the air after TO before the RVP, °C                    | 111         | 99                        | 96           |
|    | flue gas temperature after the RVP before the newly installed TO, °C      | 197         | 178                       | 171          |
| 3  | The temperature of the flue gases leaving the chimney after the newly    | 120         | 111                       | 107          |
|    | installed TO, °C                                                          |             |                           |              |

Installed, that the above sizes of heat exchangers and tube bundles their layout when working on fuel oil, the temperature of exhaust flue gas was higher than when the boiler on gas. For example, in the average annual operating mode on high-sulfur fuel oil, the temperature of the outgoing flue gases is 111 °C, whereas when working on gas, it was 102 °C. This is due to the fact that the required amount of heat output of the newly installed heat exchangers when working on fuel oil, should be greater than when working on gas, to ensure the cooling of the flue gases to the lowest permissible temperature. Therefore, when burning both gas fuel and high-sulfur fuel oil on the boiler, a compromise solution is needed to ensure the most effective solution. To make such a decision, it is necessary to identify the predominant fuel in the fuel balance of the boiler. If heat exchangers are installed the heat exchanger with a thermal capacity, providing cooling of the flue gases at the boiler fuel oil to the lowest temperature for safe operation conditions chimneys of the power plant, during transfer of the boiler burning natural gas, the temperature of exhaust flue gases will be less than the maximum permissible value. Therefore, if gas is the predominant type of fuel for the boiler, then it seems the best option to install heat exchangers with a heat output that provides an extremely low temperature when the boiler is running on gas. In this case, when the boiler is switched to burning fuel oil, the temperature of the outgoing flue gases will be higher than the extremely low value. This will somewhat reduce the economic effect of installing new heat exchangers, but will ensure the reliability of the gas-air path of the boiler and chimneys. If the predominant type of fuel is high-sulfur fuel oil, then it is advisable to install heat exchangers with thermal power that provides cooling of the flue gases to the lowest possible temperature when working on fuel oil for maximum effect. The heat output of the heat exchangers in this case will be greater than when working on gas. In this case, when
switching the boiler to gas combustion, the temperature of the outgoing flue gases will be less than the maximum permissible value due to the large value of the heat capacity of the heat exchangers. To increase the temperature of the exhaust gases to the minimum permissible level, it will be necessary to turn on the existing steam heaters on the boiler. Due to the fact that the efficiency of the reconstruction of the gas-air path of the boiler considered in this article was determined for a power plant where natural gas is the predominant type of fuel, further calculations were carried out for the installation of a heat exchanger with thermal power that provides the minimum temperature of the outgoing flue gases when working on gas. When switching the boiler to fuel oil operation, the temperature of the outgoing flue gases will be higher than the minimum permissible under the conditions of safe operation of the flue pipes for the reasons described above. But, at the same time, the flue gas temperature after the air heaters was $178^\circ C$, and the air temperature after the air heaters was $99^\circ C$, which, in accordance with the recommendations given in [11], provides almost complete elimination of corrosion during the combustion of fuel oil.

The installation of new heat exchangers in the gas-air path of the boiler will increase their aerodynamic resistance. The results of the calculation of the aerodynamic resistance of the tube bundle of the newly installed heat exchangers are shown in Table V. The considered arrangement of the tube bundle of the heat exchanger slightly increases the resistance of the gas-air path of the boiler when working on any type of fuel.

### Table V

| №  | Parameter                                            | Rate load | Average load for the year | Minimum load |
|----|-----------------------------------------------------|-----------|----------------------------|--------------|
| 1  | Resistance in the path of flue gases when working on liquid fuel | 45,8      | 24                         | 15,1         |
| 2  | Resistance along the flue gas path when working on gas fuel | 55,1      | 24,6                       | 14,8         |
| 3  | Resistance along the air path when working on liquid fuel | 55,7      | 30                         | 20           |
| 4  | Resistance along the air path when working on gas fuel | 59,1      | 29,8                       | 18,9         |

The resistance of the boiler air path will increase significantly due to the need to install new air ducts that provide air supply from the blast fans to the newly installed heat exchangers and return the air heated in the heat exchangers to the boiler air path before the RVP. The cross section of the air
ducts is assumed to be 2300 by 2195 mm. The calculated total aerodynamic resistance of the air path after the installation of the new heat exchangers and their binding with air ducts will be 101 mm. w. c.

Before the reconstruction of the gas-air path, when the boiler was working on fuel oil, the air temperature in front of the air heaters was increased to a temperature of 70 °C by heating the air in the steam heaters. To heat the air, the thermal energy of the steam taken from the flow part of steam turbines of the power plant was used. After the reconstruction of the gas-air path, the steam heaters are switched off. Accordingly, the steam extraction from the steam turbines to the air heaters is stopped. This leads to a reduction in the generation of electricity by turbines in the heating cycle. To maintain the electric power of the power plant at the same level, there will be an increase in electricity generation through the condensation cycle (an increase in the steam consumption in the turbine condensers) by the amount of a decrease in electricity generation through the heating cycle. Since the specific cost of thermal energy for the generation of electric energy by turbines in the condensation cycle is greater than in the heating cycle, there will be an increase in the amount of fuel burned. But the value of the increase in the burned fuel for this reason is 296 tons of conventional fuel (t.u.t). significantly less than the decrease in the burned fuel due to the increase in the efficiency of the boiler 4117 t. u. t. due to the installation of new heat exchangers.

The results of the calculation of the economic effect of the installation of new heat exchangers with an average load for the year of the boiler on gas and high-sulfur fuel oil are shown in Table VI.

| № | Parameter                                                                 | Working on gas | Working on fuel oil |
|---|---------------------------------------------------------------------------|----------------|---------------------|
| 1 | Increase in the efficiency of the boiler "gross", %                       | 1,65           | 2,81                |
|   | Reduction of the amount of fuel burned due to the reduction of heat energy losses with outgoing flue gases, t.u.t. | 2297           | 4117                |
| 2 | An increase in the amount of fuel burned due to an increase in the condensation component of the turbine power, t.u.t. | 0              | 296                 |
| 3 | Total reduction in the amount of fuel burned, t.u.t.                       | 2297           | 3821                |
| 4 | Increasing the power consumption of two blast fans, kW                    | 311,95         | 276,88              |
| 5 | Increase in the power consumption of two boiler smoke fans, kW            | 138,24         | 112                 |
| 6 | Increase in electrical own needs, thousand kWh                            | 2354           | 2033                |
Due to the more significant heat removal from the flue gases when working on fuel oil, the effect of installing new heat exchangers is greater when working on fuel oil than when working on gas. The increase in the efficiency of the "gross" boiler after the reconstruction when working on fuel oil with an average annual operating mode was 2.81 %, and when working on gas 1.65 %.

To determine the payback period of the project under consideration, it is necessary to determine the costs of its implementation. Due to the fact that at this stage of research, the project documentation was not developed, the necessary amount of costs is determined in accordance with the data given in [8]. To ensure minimum manufacturing costs for heat exchangers and air ducts, they are made of aluminum alloys. The estimated total costs for the design and manufacture of new heat exchangers, for the design and construction of air ducts and installation of heat exchangers at the boiler operation site amounted to 40111,08 thousand rubles when the boiler is running on gas and 44122,18 thousand rubles when the boiler is running on fuel oil. The difference in the amount of costs is due to the need to install a system for cleaning the tube bundle of heat exchangers from contaminants formed during the combustion of high-sulfur fuel oil. Since the arrangement of the tube bundle of heat exchangers was adopted as a corridor with a sufficiently large gap between the pipes, it was decided that to ensure effective cleaning, it is sufficient to use a system for washing the tube bundle with water sprayed through the nozzles. The cost of installing a water washing system for the pipe bundle and removing contaminated water to the existing sewage disposal system at the power plant in the sludge collector is estimated at about 10 % of the project cost as a whole.

The magnitude of the effect is largely determined by the cost of fuel and electrical energy at the installation site of the boiler. The calculation of the project efficiency was carried out at the cost of natural gas 3551 rubles/t. u. t., fuel oil 7484 rubles/t.u.t., electric energy for own needs 1 rubles 15 kopecks/kWh.

The estimated performance parameters in terms of value are shown in Table VII.

| №  | Estimated performance parameters of the project in terms of value, thousand rubles |
|----|---------------------------------------------------------------------------------|
|    | Working on gas | Working on fuel oil |
| 1  | Reducing fuel consumption | 8157 | 28596 |
| 2  | Reducing the cost of replacing the packing RVP | 425,5 | 6382 |
| 3  | Increase in the cost of electricity for their own needs | 2707,1 | 2338 |
| 4  | Total effect for the year | 5881,4 | 32640 |
| 5  | The cost of the project | 40111,08 | 44122,18 |
| 6  | Simple payback period, years | 6,82 | 1,35 |

When working on fuel oil payback period of capital investment is significantly less than when working on gas because of the higher values increase the efficiency of the boiler after installation of new heat exchangers and due to the significant difference in the cost of natural gas in the plant.
4. Conclusion

1. Reconstruction of the flue gas and air paths of the boiler by installing additional gas-air heat exchangers for the utilization of the flue gas heat energy in order to increase the air temperature in front of the air heaters provides a significant 2.81% increase in the efficiency of the "gross" boiler and virtually corrosion-free operation of the air heaters.

2. The considered technical solution can be attributed to the quickly recouped measures during the operation of the boiler on fuel oil. The simple payback period for the TGM-84 boiler when operating on high-sulfur fuel oil was 1.35 years.

5. References

[1] Storm S, DeCaprio M 2011 Recent Regenerative Airheater Improvements at HECO Kahe Point, Oahu Electric Power Conference (Rosemont, USA)
[2] Storm S, Guffre J 2010 Experiences with Regenerative Air Heater Performance Evaluations & Optimization POWER-GEN Europe (Amsterdam, Holland)
[3] Bespalov V, Bespalov V 2011 Flue gas heat recovery device and method of its operation the patent of the Russian Federation №2436011 available at: http://www.freepatent.ru/patents/2436011
[4] Aronov I 1990 Contact heating of water by combustion products of natural gas 2nd ed Nedra (M, Russia)
[5] Sosnin Yu and Bukharkin E 1988 High-efficiency gas water heaters contact 4nd ed. Stroyizdat (M, Russia)
[6] Kudinov A 2000 Energy saving in heat generating plants UIGTU (Ulyanovsk, Russia)
[7] Trushin V, Ibragimov E, Bakirov F 2019 Reducing the rate of low-temperature corrosion of regenerative air heaters of steam boilers proceeding 2019 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon) (Vladivostok, Russia)
[8] Bakirov F, Ibragimov E 2021 Development of a heat exchanger design for utilization of thermal energy of flue gases of TGM-84 boiler" Innovation and investment 1
[9] RD 153-34.1-21.523-99 Instructions for use of reinforced concrete and brick chimneys and flues in thermal power plants 2000 ORGRES (M, Russia)
[10] RD 34.08.552-95 Methodical instructions on drawing up the report of power plant and joint-stock company of power and electrification about thermal efficiency of the equipment 1995 ORGRES (M, Russia)
[11] Thermal calculation of boilers (standard method) 3nd ed. 1998 NPO CKTI (SPb, Russia)
[12] Mochan S (Ed.) 1977 Aerodynamic calculation of boiler plants (standard method) 3nd ed. Energy (SPb, Russia)