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PROBLEMS OF OPERATING HEATING BOILERS OF INCREASED ENVIRONMENTAL EFFICIENCY

Purpose. Ensuring reliable operation of heating heat-generating devices with recirculation and exhaust gas heat recovery.

Methodology. The normative methods of thermal calculation for surface heat exchange devices and the software according to the requirements of regulatory methods for this type of equipment for processing the results of our own experimental studies on heat exchange during deep cooling of combustion products of gas-consuming boilers were used.

Findings. Calculation studies on the thermal operation modes during the heating period under the conditions of recirculation and heat recovery of flue gases of gas-fired water-heating boiler plants not equipped with air heaters were carried out. The main characteristics were determined of the thermal and humidity operation state for the air-supply ducts of these installations under the conditions of recirculation of flue gases' part into the blown air. Regularities of temperature and dew point changes in the mixture of admixed gases and air under the conditions of using traditional heat recovery technologies and without them in different boiler modes and with different parts of recirculated gases were established. Problems of ensuring the operability and reliability of such boiler plants are highlighted. It is shown that these problems are related to condensate formation on the internal surfaces of air ducts and their freezing in some operating modes during in the cold period of the heating season. It is also shown that an effective solution to existing problems can be the use of air heaters in heat recovery systems to preheat the blown air before its mixing with recirculation gases.

Originality. For the first time, the thermal and humidity operation modes of the air-supply ducts of heating boiler plants with increased environmental efficiency, which is ensured by boiler exhaust gases recirculation into the blown air, have been investigated.

Practical value. The obtained research results will be used in the design of systems of recirculation and heat recovery of heat-generating devices' exhaust gases to improve their environmental and thermal efficiency.

Keywords: *nitrogen oxides, exhaust gas recirculation, heat recovery, air-supply channels, thermal and humidity conditions*

Introduction. Modern trends in the use of fuel-consuming thermal power plants for various purposes are largely related to the requirements for improving their environmental and economic performance [1, 2]. The main directions of meeting these requirements in the design and operation of municipal heat and power facilities are the reduction of toxic substances in the environment with gas emissions from boiler plants [3, 4] and fuel savings in them through the use of efficient waste heat recovery technologies [5, 6].

Literature review. The latest heat recovery technologies in the municipal heat and power industry are based on deep cooling of gas emissions from boiler houses through the combined use of recovered heat to heating different heat transfer agents characterized by different temperature potentials [7]. Deep cooling is realized when the exhaust gas temperature drops below the dew point of the water vapor contained in the gases. These technologies provide an increase in the coefficient of the use heat of fuel (CUHF) of heat-generating installations by 5–10 %. In addition to fuel savings as a result of the use of heat recovery technologies, an environmental effect corresponding to a decrease in fuel consumption is also achieved. And if deep flue gas cooling is achieved, there is also an additional environmental benefit due to the dissolution of carbon and nitrogen oxides in the condensate formed during deep cooling.

As for the further improvement of the environmental performance of the considered heat-generating facilities, the corresponding trends are associated with a decrease in the formation of nitrogen oxides in the boiler furnace space, which, according to the research, mainly determine the toxicity of combustion products of heat-generating devices operating on natural gas [3].

Reducing the amount of "thermal" NOx formation can be achieved by influencing mainly the maximum combustion temperature, which is ensured by introducing ballast gases, water and steam into the combustion zone or into the combustion air, as well as by two- and three-stage combustion of fuel, which reduces the temperature level and oxygen content in the maximum temperatures zone.

Among the ways to reduce nitrogen oxide emissions in gas-fired boilers, the most common is the use of the method for recirculating the waste combustion products into the boiler furnace space [3, 6]. Many publications, for example [2, 3], are devoted to the research results on application of this method for ecologization of heat-generating objects, which testify to the effectiveness of its use. In particular, a sufficiently proven way to implement said recirculation is to introduce flue gases into the boiler furnace mixed with blown air. This results

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in a decrease in the combustion temperature in the furnace due to the fuel consumption for heating the introduced ballast (flue gases with a relatively low thermal potential). Reducing this temperature helps to suppress the nitrogen oxides formation in the furnace space, which reduces their emissions by up to 60 % [3, 6], and according to some data, up to 90 % [8].

The use of this method of ecologization of heat and power facilities is quite common in boilers with high heating capacity. In most situations of implementation of this method, exhaust gases are taken for mixing into the blown air before the air heater of such a thermal power plant. The temperature of the selected gases is usually 300–400 °C [4]. The use of the considered method of ecologization for heating boiler installations of small heating capacity, which are usually not equipped with air heaters, is associated with certain problems. So, when a part of the boiler exhaust gases with a temperature significantly lower than 300 °C is added to the cold blown air, condensate formation occurs on the internal surfaces of the air ducts and in the blowing fan [9]. In some operating modes, namely at negative ambient temperatures, icing of specified elements of the considered heat and power plants is observed. These problems are exacerbated in the case by the use of heat recovery systems, as these systems are characterized by a significant decrease in the temperature of the exhaust gases. By mixing cooled gases into the blown air, increased condensate formation on the surfaces of the air ducts is realized. The relevance of this work is to study and analyze the thermal and humidity operation condition of the air-supply ducts of a water-heating boiler plant with and without a heat recovery system in the case of applying a method of ecologization of this installation by recirculating flue gases mixed with blown air into the furnace space.

Purpose. The purpose is to carry out research aimed at ensuring reliable operation of heating heat-generating facilities with recycling and heat recovery of flue gases.

According to the goal, the following main tasks were to be solved:

- execution of a thermal calculation of a boiler with flue gas recirculation into its furnace space mixed with blowing air for the selected heat-network schedule of the boiler house;
- determination of the thermal and humidity characteristics of the formed air-gas mixture at different volumes of gas recirculation (admixing);
- development of directions for ensuring the operation reliability of the considered heat-generating installation during the heating period.

Methods. Calculation studies were performed for a gas-tube heating boiler BSHW-2.0G (steel heater-water gas boiler with a capacity of 2 MW) with a nominal heat capacity of 2 MW, operating on natural gas. The flue gas recirculation technology was implemented by introducing a part of the exhaust gases mixed with the blown air into the gas burner device.

To perform thermal calculations of the boiler, the appropriate software was created in accordance with the requirements of regulatory methods for this type of equipment. Calculations were made for different operating modes of the boiler during the heating period in accordance with the thermal schedule of the boiler room. The share of ballasted gases added to the blown air was 10–20 %, which corresponds to the practical values of this indicator when implementing the considered method of environmentalization. The studies were carried out when the boiler unit was connected to a heating system with an estimated ambient temperature of –20 °C and a temperature difference of the heat-transfer-agent Δt_h = 25 °C. The boiler efficiency was calculated based on the higher heating value of the fuel. The technical characteristics of the boiler in the nominal mode are indicated in Table 1.

During the studies, the boiler relative heating capacity γ varied from 30 to 100 % during the heating period in accordance with the increase in atmospheric air temperature from –20 to +10 °C. To determine the moisture indicators of the combustion products and the air-gas mixture, data on the moisture content of the air in accordance with the specified ambient temperatures were used.

Table 1

The boiler characteristics BSHW-2.0G

Parameter name	Value
Fuel type	natural gas
Boiler load, %	100
Boiler heating capacity, MW	2.0
Higher heating value of the fuel, kcal/m^3	9410
Excess air coefficient	1.1
Heat losses from chemical underburning, %	0.5
Heat loss to the environment, %	1.0
Inlet water temperature, °C	70
Outlet water temperature, °C	95
Efficiency, %	82.0
Fuel consumption, m^3/hour	219
Exhaust gas temperature, °C	160

The operation situations of the considered heat-generating installation with and without a gas emissions heat recovery system were considered under the conditions of using two options for implementing of ballast mixing method into the blowing air (Fig. 1).

At the boiler plant in question, a traditional heat recovery system with a single heat recovery exchanger was used. The heat recovery unit is designed to preheat the return heat network water before it enters the boiler. The temperature indicators of this water corresponded to the parameters of the heating network schedule of the selected heating system and varied from 70 to 35 °C. A wa-

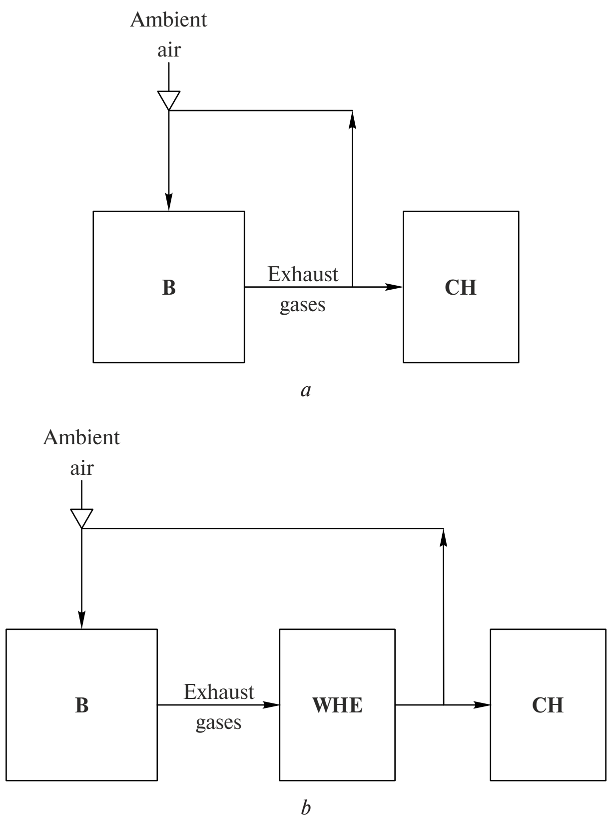


Fig. 1. Implementation options of the method of flue gas mixing into the blown air: with their selection after the boiler (a) and after the heat recovery exchanger (b):

B – boiler; WHE – water-heating heat exchanger; CH – chimney ter-heating heat exchanger with bundles of transverse-finned pipes served as a heat exchanger. Bimetallic pipes with a steel base and aluminum fins were used in the pipe bundle. The movement of heat carriers is countercurrent with the passage of water in the pipes and exhaust gases in the inter-pipe space.

The calculation of the heat recovery unit used was performed using well-known modern regulatory methods and the results of our own experimental studies in the implementation of deep exhaust gas cooling. Namely, the determination of heat transfer coefficients during cooling of gases below the dew point of water vapor contained in combustion products was carried out according to the methodology developed at the Institute of Engineering Thermophysics of NAS of Ukraine using the results of the experiments [10].

Results. When performing the boiler thermal calculation, its main characteristics were determined, in particular, the adiabatic combustion temperature and the temperature and moisture content of the boiler flue gases, depending on its relative heat load. The research data on the adiabatic temperature in the case of using the recirculation scheme according to Fig. 1, *a* are given in Table 2. The data obtained were calculated under the conditions of maintaining the natural gas consumption per boiler, which corresponds in each studied mode to the value of this consumption without flue gas admixture.

The research results show that the addition of ballast to the boiler combustion space under these conditions causes a decrease in the adiabatic combustion temperature tad by 137–263 °C due to the need for fuel heat consumption to heat the introduced ballast to this temperature. And the greater the recirculation share χ, the greater the level of reduction of the specified temperature in the furnace space.

As shown by the calculation studies, if the gas consumption to the boiler is maintained at the level of its value without the use of recirculation, it leads to a decrease in the water heated temperature in the boiler compared of the boiler plant needs according to the heating network schedule. This circumstance is due to a decrease in the adiabatic combustion temperature. For example, in the nominal mode, if the recirculation share χ increases within 10–20 %, the water heated in the boiler temperature decreases by 0.9–1.4 °C, respectively. As a result, when a part of the ballasted gases enters the furnace space, its design heat capacity is not achieved. And the higher the recirculation share χ, the more noticeable the decrease in this heat capacity. The maximum heat capacity of the boiler decreases by 3.6–5.6 % as the χ share increases from 10 to 20 %.

Flue gas recirculation under the considered conditions also causes small changes in the boiler exhaust gases temperature t_{ehg} (Table 3). As can be seen from the table, under the conditions of using the recirculation method, the temperature t_{ehg} decreases slightly (by 1.6–2.5 °C) in the nominal mode (at minimum ambient temperatures, $t_{amb} = -20$ °C) and increases with an increase in these indicators. In particular, temperature t_{ehg} changes by 2.7–4.4 °C at a minimum boiler load of nearly 30 % and $t_{amb} = +10$ °C.

Table 4 shows the calculated data on the values of the boiler exhaust gases absolute moisture content in different its operation modes under the considered conditions of implementing the recirculation combustion products method.

As can be seen from the table, the moisture content value varies slightly only depending on the operational performance of the boiler plant due to changes in the combustion air moisture content during the heating season. In other words, the moisture content X_{ehg} of the waste gases under conditions of their partial recirculation corresponds to the moisture content of admixed ballast, regardless of the proportion of this mixture χ.

Using the obtained data on the temperature and moisture content of the boiler exhaust gases with a recirculation system, calculations were performed of the thermal and humidity parameters of the air-gas mixture that will enter the boiler furnace in its different operation modes. To determine these indicators, as noted, data on air moisture content in accordance with ambient temperatures during the heating period were used. The obtained results for the situation of adding combustion products to the blown air after the boiler (Fig. 1, *a*) are shown in Fig. 2. The given data indicate that, depending on the operating mode and the admixed gases part, the air-gas mixture temperature varies from $t_{mix} = -4$ to $t_{mix} = +21$ °C, and the dew point of this mixture – from $t^{dp}_{mix} = +20$ to $t^{dp}_{mix} = +34$ °C. As can be seen from the above graphs, the temperatures t_{mix} and t^{dp}_{mix} increase when applying the considered method of ecologization of the boiler plant, and the more so, the greater the proportion of admixture χ. The results of the studies also showed that in all the investigated heat-generating installation modes during the heating period, a decrease in the temperature of the mixture *t*mix below the dew point *t*dpmix point is observed. That is, the use of recirculation under consideration in all modes leads to condensation on the internal surfaces of the air-supply ducts and in the fan. In some modes, the temperature of the mixture *t*mix takes on negative values. In particular, the reduction of *t*mix below 0 °C at χ = 10 % is realized at a relative heat load of the boiler γ > of 85 %. According to the accepted heat network schedule, this load corresponds to the ambient temperature $t_{amb} = -15$ °C. As can be seen from the graphs shown in Fig. 2, at χ = 15 and χ = 20 %, negative values of *t*mix are not observed.

It should be noted that the air-gas mixture temperature t_{mix} is usually higher than the temperature t_s of the air-supply networks' inner surface of the boiler plant during their operation in open areas. This is due to heat loss to the environment from the outer surface of these air ducts. The difference between the temperatures t_{mix} and t_s significantly depends on the boiler mode, the design features of the air ducts and their thermal insulation. At ambient temperatures below 0 °C, when t_s takes

Table 2

Adiabatic combustion temperature t_{ad} in different boiler modes during the heating period and at different shares χ of recirculated gases

Share of recirculation χ, %	Adiabatic combustion temperature t_{ad}, °C at different ambient temperatures t_{amb}, °C			
	–20	–10	0	10
0	1848	1856	1866	1878
10	1711	1716	1724	1733
15	1653	1657	1663	1671
20	1600	1604	1609	1615

Table 3

Exhaust gases temperature t_{ehg} in different boiler modes during the heating period and at different shares χ of recirculated gases

Share of recirculation χ, %	Exhaust gases temperature t_{ehg}, °C at different ambient temperatures t_{amb}, °C			
	–20	–10	0	10
0	160.0	133.7	106.2	71.0
10	157.5	135.5	108.2	73.7
15	158.0	136.1	109.0	74.6
20	158.4	136.6	109.6	75.4

Table 4

Exhaust gases moisture content of X_{ehg} in different boiler modes during the heating period

Share of recirculation χ, %	Exhaust gases moisture content X_{ehg}, g/kg d.g. at different ambient temperatures t_{amb}, °C			
	–20	–10	0	10
0–20	139.7	139.8	140.0	140.4

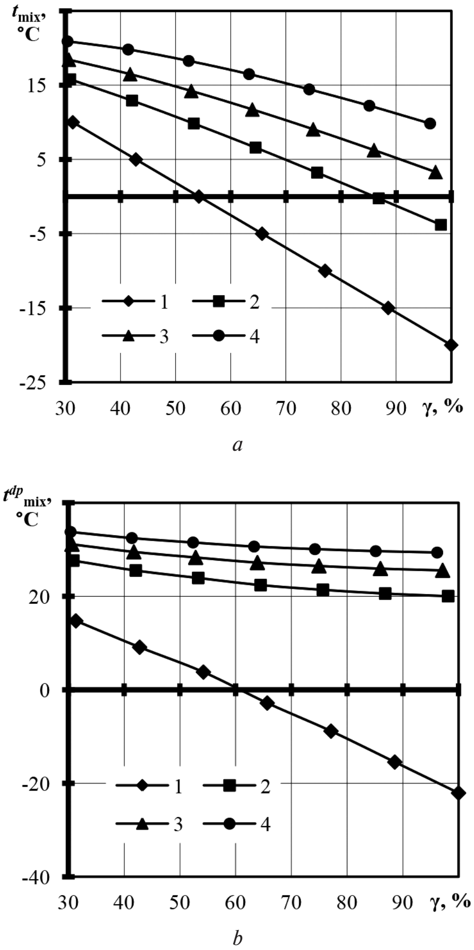


Fig. 2. Dependence of the air-gas mixture temperature t_{mix} (a) and its dew point t^{dp}_{mix} (b) on the boiler's relative load γ at different shares χ of recirculated gases at their selection after the boiler:
1 – χ = 0 %; 2 – 10 %; 3 – 15 %; 4 – 20 %

on negative values, icing of some sections of the air ducts and blower fan is likely. At the same time, icing of these sections will occur at temperatures t_{mix} lightly higher than 0 °C. That is, unfavorable operation mode of the air-supply ducts in terms of their icing will occur at lower boiler loads γ and higher gas recirculation shares, in particular, at χ = 15 and χ = 20 %.

Studies have also been carried out on the thermal and humidity indicators considered in this paper for a boiler plant with flue gas recirculation under the conditions of using a traditional heat recovery system with a water-heating heat recovery exchanger. In this case, the recirculated gases are selected after the heat recovery exchanger, as shown in Fig. 1, *b*.

The results of the performed thermal calculations showed that when applying the heat recovery system under consideration, provided that the gas consumption to the boiler remains at the level without using gas recirculation, the water heated in the boiler temperature may be higher than required by the heat network schedule. This is explained by the fact the boiler is already coming with water heated in a heat recovery exchanger. In this case, the heat capacity of the specified installation (boiler with heat recovery exchanger) in some modes may be higher than planned according to the specified schedule. That is, the nominal heat capacity of this installation may be exceeded (γ ≥100 %).

During the studies on the considered heat generating units, the temperature t^{hr}_{ehg}, moisture content X^{hr}_{ehg} of the exhaust gases (after the heat recovery exchanger), the temperature of the mixture of blown air and these gases t^{hr}_{mix} and its dew point t^{dphr}_{mix} were also determined. The relevant calculated data are given in Tables 5, 6 and Fig. 3.

Table 5

Exhaust gases temperature t^{hr}_{ehg} in different boiler modes during the heating period and at different shares χ of recirculated gases

Share of recirculation χ, %	Exhaust gases temperature t^{hr}_{ehg}, °C at different ambient temperatures t_{amb}, °C						
	–20	–15	–10	–5	0	5	10
0	83.6	76.0	67.2	58.6	56.0	52.2	46.1
10	84.7	77.2	68.2	59.3	56.3	52.7	46.7
15	85.4	77.7	68.7	59.7	56.4	52.9	47.1
20	85.9	78.2	69.2	60.1	56.6	53.1	47.4

Table 6

Exhaust gases moisture content of X^{hr}_{ehg} in different boiler modes during the heating period and at different shares χ of recirculated gases

Share of recirculation χ, %	Exhaust gases moisture content X^{hr}_{ehg}, g/kg d.g. at different ambient temperatures t_{amb}, °C						
	–20	–15	–10	–5	0	5	10
0	139.7	139.7	139.7	139.7	120.1	96.7	67.6
10	139.7	139.7	139.8	139.9	122.2	99.3	70.2
15	139.7	139.7	139.8	139.9	123.2	100.5	71.6
20	139.7	139.7	139.8	139.9	124.1	101.7	72.9

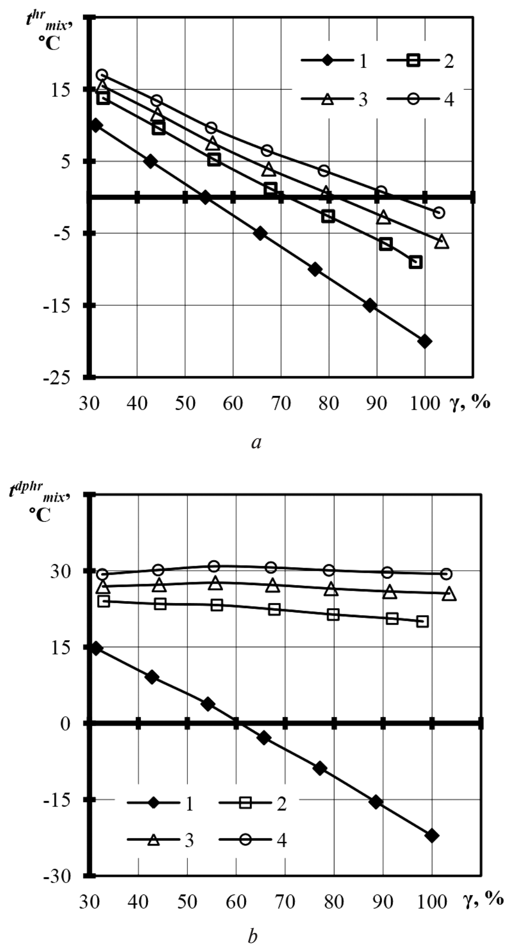


Fig. 3. Dependence of the air-gas mixture temperature t^{hr}_{mix} (a) and its dew point t^{dphr}_{mix} (b) on the boiler's relative load γ at different shares χ of recirculated gases at their selection after the heat recovery exchanger:
1 – χ = 0 %; 2 – 10 %; 3 – 15 %; 4 – 20 %

According to the obtained results, both in the case of gas selection for addition to the blown air after the heat recovery unit and in the case of selection of these gases after the boiler, for all its operation modes, the dew point values exceeds the temperature of the air-gas mixture. And the higher the value of the share χ in this mixture, the more noticeable the decrease in t_{mix}^{hr} and the increase in the dew point t_{mix}^{dphr}. At some boiler loads, negative values of t_{mix}^{hr} are also observed. The research results indicate that the air-gas mixture temperature t_{mix}^{hr} and its dew point t_{mix}^{dphr} when combustion products are selected after heat recovery are somewhat lower than when they are selected after the boiler. For example, in the case of the recirculated gases selection after the heat recovery unit, under the condition of reducing the relative boiler heat load from the maximum to the minimum, the temperature value t_{mix}^{hr} varies from –11 to +16 °C, and the dew point t_{mix}^{dphr} of this mixture is from +20 to +31 °C, respectively, depending on the admixed gases' part. Under the conditions of selecting gases from the boiler, the corresponding indicators varied from t_{mix} = –4 to t_{mix} = +21 °C and from $t_{mix}^{dp} = +20$ to $t_{mix}^{dp} = +34$ °C.

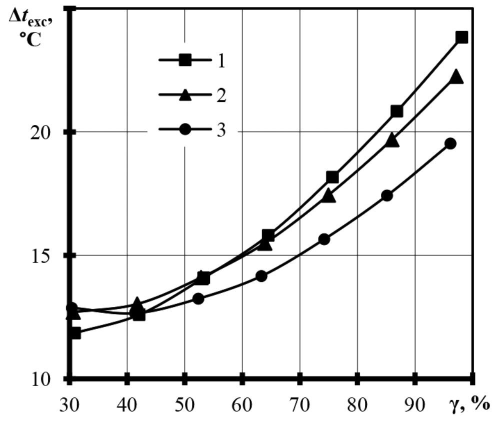
The data obtained also testified that under the conditions of mixing gases into the blown air after the heat recovery exchanger, the mixture temperature t_{mix}^{hr} decreases below 0 °C at lower boiler loads and, accordingly, higher ambient temperatures compared to the situation of recycled gases selection after the boiler.

According to the results of the performed studies, the implementation of negative values the air-gas mixture temperature t_{mix}^{hr} when adding exhaust gases with a share of χ = 10 % to cold air is observed at lower values of the boiler load (γ > 70 %) compared to the situation with the selection of recirculation gases after the boiler, where this indicated decrease occurs only at γ > 85 %. When heat recovery is used in accordance with the selected boiler house heat schedule, the indicated relative heat load γ = 70 % corresponds to the ambient temperature $t_{amb} \approx -6$ °C. Under the condition of mixing gases into the air after the heat exchanger, negative values of t_{mix}^{hr} when adding these gases with a share of χ > 10 % are also observed. Thus, at χ = 15 %, the temperature t_{mix}^{hr} takes negative values approximately at γ > 80 % and under the condition χ = 20 %, $t_{mix}^{hr} < 0$ °C at γ > 90 %. In the case of a relative load γ = 80 %, the ambient temperature corresponds to the value of $t_{amb} \approx$ ≈ -10 °C and at γ = 90 %, the value of $t_{amb} < -15$ °C.

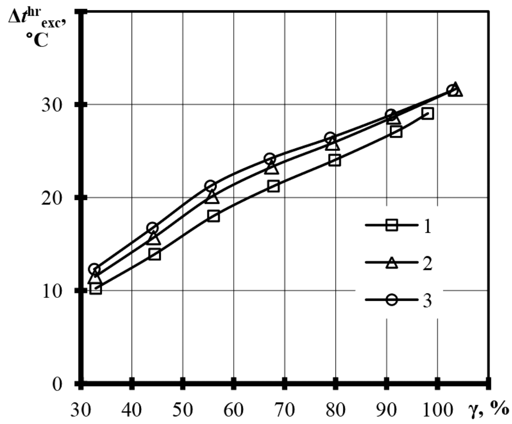
The excess value of the air-gas mixture dew point over this mixture temperature ($\Delta t_{exc} = t_{mix}^{dp} - t_{mix}$, $\Delta t_{exc}^{hr} = t_{mix}^{dphr} - t_{mix}^{hr}$) in different operation modes of the boiler plant during the heating period for both investigated variants of this installation with the considered its ecologization method (Fig. 1) was also evaluated. Fig. 4 shows the relevant data.

The data shown in Fig. 4 shows that the higher the heat load γ (correspondingly, the lower the ambient temperature t_{amb}), the greater values of Δt_{exc} and Δt_{exc}^{hr}. That is, during the heating season in a cold period, the level of gas-air mixture temperature increase required to prevent condensation in the air ducts is higher. This fact is obvious, given the low temperature indicators for the air supplied for combustion during this period.

The obtained research results also show that under the condition of the selection of recirculated gases from the boiler to prevent condensation and icing of its air ducts in the nominal operating mode and, accordingly, during the coldest period of the heating season, the mixture temperature should be higher by at least Δt_{mix} = 25 °C (excluding heat losses from the air ducts surface). During the warmest period of this season (t_{amb} = 10 °C) and, accordingly, at the minimum boiler load ($\gamma \approx 30$ %), the necessary range of Δ*t*mix increase is the smallest and corresponds to Δt_{mix} > 13 °C.



a



b

Fig. 4. Dependence of the excess value Δt_{exc} and Δt_{exc}^{hr} of the air-gas mixture dew point over the this mixture temperature on the boiler's relative load γ at different shares χ of recirculated gases during their selection after the boiler (a) and the heat recovery exchanger (b):

1 – χ = 10 %; *2* – 15 %; *3* – 20 %

According to the results of the studies, under the conditions of adding flue gases to the furnace space after heat recovery, it is necessary to increase the gas-air mixture temperature *t*mix by $\Delta t_{exc}^{hr} = 10\text{–}33$ °C to prevent condensation and icing of the air-supply ducts surfaces, depending on the heat generating unit operating parameters and the shares of admixed combustion products.

As for the comparison of data Δt_{exc} and Δt_{exc}^{hr} for the two variants of the boiler environmentalization method considered in this work, as can be seen, that gas extraction after the heat recovery unit requires a higher level of air-gas mixture thermal potential increase to prevent condensate formation. Thus, at the maximum boiler load and a share χ = 20 % of recirculated combustion products, the value of Δt_{exc} is 20 °C for the variant in Fig. 1, *a* and $\Delta t_{exc}^{hr} = 32$ °C – for the variant in Fig. 1, *b*. That is, the difference between indicated options regarding the excess of the dew point over the air-gas mixture temperature ($\Delta t_{exc}^{hr} - \Delta t_{exc}$) in this case is equal to 12 °C. During the warm period of the heating season, the difference between the respective values becomes noticeably smaller and does not exceed 3 °C.

As already noted, the study results shown in Figs. 2–4 were obtained without taking into account heat losses from the air-supply channels surface. These losses are mainly determined by the design features of these channels and the conditions of their heat exchange with the environment. The actual levels of excess of the dew point temperature over the temperature of the air-gas mixture will be higher and will be calculated for the specific conditions of the considered ecologization boiler plants method application.

It should also be emphasized that the calculation results obtained in this paper relate to the implementation of the described recycling method provided that the natural gas consumption of the heat generating unit remains at the same level as the value of this consumption without recycling, i.e., at $\chi = 0$ %. Calculation studies were also carried out, provided that the needs of the boiler house heat schedule with respect to the direct water heated in the boiler for the two investigated variants of boiler plants (Fig. 1). The research results showed that when using flue gas recirculation without heat recovery (Fig. 1, *a*), gas consumption per boiler slightly increases. For the variant in Fig. 1, *b*, the fuel consumption is somewhat reduced due to the partial heating of the heating system return heat-network water in the heat recovery exchanger. The research results also showed that the obtained changes in gas consumption do not cause significant changes in the thermal and humidity parameters of flue gases and air-gas mixture in both considered variants of flue gas selection for mixing into the blown air.

Therefore, based on the results of the research performed, it can be concluded that the operation of the considered heating installations with the addition of combustion products to the cold blown air causes conditions favorable for condensate formation in the air-supply communications of these heat-generating facilities. Throughout the entire period of operation during the heating season, this condensate formation will occur, and during operation at negative ambient temperatures, icing of these communications will also occur. Ensuring the operability of the considered heat generating units of increased environmental efficiency requires the development of special measures to ensure that the mixture of recirculated gases and air temperature exceeds the dew point. One such measure could be the use of heat exchangers to preheat the air before it is mixed with recirculated combustion products. These heat exchangers can be air heaters-heat exchangers, which are part of heat recovery systems with the combined use of recovered heat for heating the return heat-network water and combustion air. In these air heaters, this air will be heated by cooling in the process of heat recovery of the boiler's gas emissions. The level of air heating and the level of these emissions cooling must ensure the absence of condensate formation in the air ducts and fan of boiler plants when using flue gas recirculation systems into blown air. In this case, to prevent condensation in the gas exhaust ducts of these installations with deep cooling of gas emissions, appropriate thermal methods of protection these ducts should be applied [7].

The second measure to improve the reliability of the heat generating unit with the ecologization considered method can be the organization of hot combustion products extraction from the convective part of the boiler. The use of this measure is very problematic, usually, due to the developers' prohibition of boilers to interfere in its design, since this leads to disruption of the heat transfer processes in this heat unit itself.

The next measure, which can ensure that the mixture of recirculated gases and air temperature exceeds the dew point temperature for environmentally efficient boilers, is to add a part of this agent, already preheated outside the heat recovery systems, into the cold blown air. The use of this measure, for example, is possible if there is another boiler equipped with an air-heater in the boiler plant and if it is possible to organize this measure, given a number of conditions for its successful implementation. In particular, the need for boilers' simultaneous operation, the technical feasibility and economic viability of supplying the heated agent, etc.

The analysis of the above measures indicates that the most acceptable for the considered boiler plants is the use of heat recovery systems equipped with air heaters-heat recovery. The use of these heat recovery exchangers will ensure not only reliable operation of heat generating units with increased environmental efficiency, but also fuel savings in them, as well as an additional environmental effect by reducing the gas emissions temperature potential.

Conclusions. For heating gas-consuming boilers using flue gas recirculation into the blown air method, a set of studies was carried out on the patterns of changes in the main thermal characteristics and thermal and humidity parameters of the exhaust gases and air-gas mixture of the boiler in its various modes using traditional heat recovery technologies and without them. In particular:

1. The adiabatic combustion temperature in the boiler furnace is determined. It is shown that the addition of recirculation gases to the furnace space under the considered conditions causes a decrease in this temperature by 137–263 °C due to the need to consume fuel heat for heating ballast gases. And the greater the proportion of recirculation χ, the greater the decrease in the specified temperature in the boiler furnace.

2. The regularities of changes in the mixture of air and recirculated gases thermal and humidity characteristics (temperature and dew point) during the heating period at different shares of the recirculation gases selection after the boiler were established. It is established that:

- the use of recirculation leads to a decrease in the air-gas mixture temperature below its dew point in all studied modes during the heating period;
- in some operating modes, there is a decrease in the mixture temperature below 0 °C, which can cause icing of the air-supply ducts surfaces operated in open areas.

3. The thermal and humidity indicators of the air-gas mixture under the conditions of using the considered heat recovery system for a boiler plant and when selecting exhaust gases cooled in the heat recovery process for mixing into the blown air were determined. Comparison of the obtained indicators with the corresponding indicators without the use of heat recovery systems is carried out. It is shown that negative values of the air-gas mixture temperature during the selection for cooled gases recirculation after the heat recovery exchanger are observed at lower values of the boiler relative heat load ($\gamma > 70$ %) compared to the situation of the selection of recirculation gases after the boiler, where negative values of the mixture temperature are achieved only at $\gamma > 85$ %.

4. The problems of ensuring the operability and reliability of the considered heating boiler installations of relatively low heating capacity when using the specified flue gas recirculation method are highlighted. It is shown that an effective way to solve the existing problems can be the use of heat recovery exchangers in heat recovery systems designed to preheat atmospheric air before it enters for mixing with recirculation gases.

5. The minimum levels of preheating of the blown air, which should ensure the absence of condensate formation in the air-supply ducts of the boiler plant, are determined. These levels during the gases recirculation after the boiler are 13–25 °C, and when the cooled gases recirculation after heat recovery they correspond to the value of 10–33 °C.

The obtained research results will be used in the design of new boiler plants using the considered method of their ecologization, in the creation of new efficient heat recovery systems with the complex use of recovered heat for heating water and blown air, as well as in the reconstruction of existing boiler plants to improve their environmental and energy performance.

The research data can also be used in educational process in the training of specialists in heat-power engineering disciplines and environmental protection.

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Проблеми експлуатації опалювальних котельних установок підвищеної екологічної ефективності

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Мета. Забезпечення надійної експлуатації опалювальних теплогенеруючих апаратів із рециркуляцією та теплоутилізацією відхідних газів.

Методика. Використовувались нормативні методики теплового розрахунку поверхневих теплообмінних апаратів та програмне забезпечення згідно з вимогами нормативних методик для даного виду техніки для обробки результатів власних експериментальних досліджень щодо теплообміну при глибокому охолодженні продуктів згоряння газоспоживальних котлів.

Результати. Виконані розрахункові дослідження щодо теплових режимів роботи протягом опалювального періоду за умов рециркуляції й теплоутилізації димових газів газоспоживальних водогрійних котельних установок, що не оснащені повітронагрівачами. Визначені основні характеристики тепловологісного стану експлуатації повітропідвідних каналів цих установок у разі рециркуляції частини димових газів у дуттьове повітря. Встановлені закономірності зміни температури й точки роси суміші підмішуваних газів і повітря за умов застосування традиційних теплоутилізаційних технологій і без них у різних режимах котла й за різних часток рециркульованих газів. Висвітлені проблеми забезпечення працездатності й надійності таких котельних установок. Показано, що дані проблеми пов'язані з випаденням конденсату на внутрішніх поверхнях повітроводів і їх обмерзанням у деяких режимах роботи в холодний період опалювального сезону. Показано також, що ефективним напрямом вирішення наявних проблем може бути використання в системах теплоутилізації повітронагрівачів для попереднього підігрівання дуттьового повітря перед його змішуванням з газами рециркуляції.

Наукова новизна. Уперше досліджені тепловологісні режими експлуатації повітропідвідних каналів опалювальних котельних установок підвищеної екологічної ефективності, що забезпечуються завдяки рециркуляції відхідних газів котлів у дуттьове повітря.

Практична значимість. Отримані результати досліджень будуть використанні при проектуванні систем рециркуляції та утилізації теплоти відхідних газів теплогенеруючих апаратів для підвищення їхньої екологічної та теплової ефективності.

Ключові слова: *оксиди азоту, рециркуляція димових газів, теплоутилізація, повітропідвідні канали, тепловологісний режим*

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