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**N. M. Fialko,**
orcid.org/0000-0003-0116-7673,
**R. O. Navrodska*,**
orcid.org/0000-0001-7476-2962,
**S. I. Shevchuk,**
orcid.org/0000-0001-8046-0039,
**G. O. Gnedash,**
orcid.org/0000-0003-0395-9615

Institute of Engineering Thermophysics of National Academy of Sciences of Ukraine, Kyiv, Ukraine
* Corresponding author e-mail: navrodska-ittf@ukr.net

# NEW COMPLEX HEAT-RECOVERY SYSTEMS OF ENVIRONMENTALLY EFFICIENT BOILER INSTALLATIONS

**Purpose.** To establish the effectiveness of the proposed new technical solution of a small-sized and low-metal combined heat-recovery units for gas-consuming environmentally efficient heating boilers.

**Methodology.** Known methods of thermal calculation of boiler plants and experimental research data obtained by the authors were used.

**Findings.** A schematic circuit of a boiler plant with gas recirculation and a new complex heat-recovery system designed for heating such heat-transfer agents as heat network water and combustion air is proposed for the beneficial use of flue gas waste heat. Calculation studies on the main indicators of the thermal efficiency of the specified system and the heat-humidity condition in the air ducts of the boiler plant in different modes of its operation were performed. It is shown that the use of the proposed system ensures an increase in the efficiency of the boiler and the absence of condensation in the specified ducts. The indicators of the relative metal content of the considered heat-recovery exchangers were also obtained. A comparison of the calculated indicators with the corresponding indicators for the known heat-recovery system with heating of the specified heat-transfer agents was performed. The research results show that the new system with a water-heating air heater is characterized by a significantly lower relative metal capacity of this system equipped with a gas-heating air heater. Due to the use of a developed heating surface in it, the proposed water-heating air heater is low in metal consumption and highly compact, which is essential in its design and manufacture, as well as placement in the compressed conditions of boiler houses.

**Originality.** For the first time, the effectiveness of a new complex heat-recovery system for heating boiler installations of increased environmental efficiency was proposed and investigated.

**Practical value.** The obtained research results will be used to improve the environmental and thermal characteristics of boiler plants.

**Keywords:** *heat recovery, heating of water, combustion air, waste gas recirculation*

**Introduction.** For gas-fired boiler plants of municipal heat and power generation, one of the directions for increasing their thermal efficiency is the development and implementation of various heat-recovery technologies. In recent years, special attention has been paid to the implementation of combined use [1, 2] of recovered heat for various needs of boiler houses, in which this heat is used simultaneously to heat two or more heat-transfer agents for different purposes and with different temperature potentials. In particular, such heat-transfer agents are process water (return heat network water or cold water for the chemical water treatment system) and air intended for combustion in a gas burner device. The effectiveness of these technologies is determined by the depth of cooling of the output gases, namely the level of lowering their temperature. The highest efficiency of the heat-recovery system corresponds to a decrease in the temperature of the waste gases at the outlet of the heat-recovery unit below the dew point of water vapor contained in the gases. Under these conditions, condensation of part of the steam and use of the heat of such a phase transition occur [3, 4].

The most famous classic complex heat-recovery system for gas-fired heating boiler plants is a system using the heat of the boiler exhaust gases to heat the heating network water and combustion air [5, 6]. In most cases, in the case of implementing such a scheme, the water heat-recovery exchanger is installed first in the gas flow, and the air heater is installed second. In both heat-recovery systems, the boiler waste gases are the warms heat-transfer agent. However, the use of this scheme due to the use of a gas-air heater in it has certain negative aspects. Thus, the cooling of waste gases below the

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dew point temperature, i. e. with the formation of condensate, occurs in the cold period of the heating season precisely in this heat-recovery exchanger, which requires expensive corrosion-resistant materials for its construction. In addition, gas-air heaters of various types are characterized by a large metal capacity and dimensions. Because of this, their design and placement in boiler houses is very complicated, especially for boilers with high heat output. The relevance of this research is to find and analyze the effectiveness of alternative solutions for complex heat-recovery systems with a reduction in their metal consumption, dimensions and cost.

**Literature review.** A significant number of scientific works are devoted to the study of complex systems for the recovery of waste gases from heating boilers in order to increase their thermal efficiency. In particular, works [7, 8] concern the tasks of increasing the efficiency of waste gas heat-recovery systems of boiler plants by including heat pumps in these systems. This allows reducing the water temperature at the inlet to the heat-recovery unit-water heater [7] below the values of the heating network water and thus achieving deeper cooling of the waste gases. The use of heat pumps makes it possible, due to artificial cooling of these gases below their dew point temperature, to transfer the extracted cooling heat to the return water of the heating network before it enters the boiler. Such recovery schemes are called active. As stated in [9], reducing the temperature of the cooling water by 5 °C in the temperature range of 50–60 °C increases the economic efficiency of the condensing heat-recovery unit by 50 %.

Scientific publications [10, 11] investigate the issues of thermal and exergy efficiency of complex heat-recovery systems of heating boiler plants using recovered heat for heating heat-network water and combustion air. In particular, it is shown that in such systems deep cooling of waste gases is implemented throughout the heating period due to the installation of a heat-recovery exchanger for heating combustion air downstream of the traditional heat-recovery exchanger for heating heat-network water. In this case, deep cooling of waste gases in the coldest period of the heating season occurs in the air heater due to the low temperature of the heated air ($t_a < 0$ °C), and in the warm period of this season ($t_a > 0$ °C), the condensation mode of operation takes place in the heat-recovery exchanger for heating water. In work [5], the thermal characteristics of the specified systems are investigated. The dependences of the boiler unit operating parameters on such characteristics as the heat output of the heat-recovery unit, the boiler efficiency, the volume of condensate formed in the unit, etc. were established. The regularities of the influence of the ratio of the areas $F_w/F_a$ of the surfaces of the water and air heating equipment and climatic conditions on the annual production $W$ of thermal energy in the heat-recovery unit and the amount of fuel savings in the boiler unit were revealed. It was shown that the value of the ratio $F_w/F_a$, which corresponds to the maximum value $W$, significantly depends on the climatic zone. At the same time, for cities of Ukraine with a relatively cold climate [12] under the conditions of the moisture content of waste gases at the entrance to the heat-recovery unit $X_1 = 0.14$ kg/kg d.g. (dry gases), this ratio is ≈ 0.75, and for cities with a relatively warm climate – approximately 1.2. With increasing moisture content ($X_1 \geq$ ≥ 0.16 kg/kg d.g.), regardless of the climate zone, the optimal ratio of the areas of water and air heaters $S_{opt}$ is 1.2. Under the conditions of applying the optimal ratio for climatic conditions with a cold climate, with an initial moisture content of waste gases $X_1 < 0.14$ kg/kg d.g., the increase in boiler plant efficiency is 6.8–8.4 %. In the case of increasing the initial moisture content $X_1$ from 0.14 to 0.2 kg/kg d.g., a noticeable increase in the total heat output of the heat-recovery system and a corresponding increase in the heat output of its elements are ensured. Thus, for the conditions under consideration, the total increase in efficiency Δη reaches 9.5 % at $X_1 = 0.14$ kg/kg d.g., and the maximum value Δη = 11.4 % corresponds to $X_1 = 0.2$ kg/kg d.g.

Studies on improving the environmental and thermal performance of boiler plants with waste gas recirculation are published in [13, 14]. In such plants, a reduction of up to 90 % of $NO_x$ emissions is ensured by recirculating part of the exhaust gases mixed with combustion air into the boiler combustion chamber.

When using waste gas recirculation systems for boiler plants not equipped with air heaters, problems arise with condensation in the air supply ducts and air blowers of these plants, which requires the use of special measures to prevent these negative phenomena [15, 16]. In [17], the use of complex heat-recovery systems with the applying of air heaters is proposed for such environmentally efficient plants.

The schematic circuit of a boiler plant with recirculation and heat-recovery system is shown in Fig. 1. The use of such systems allows compensating for heat consumption for waste gas recirculation and also reducing fuel consumption for the boiler.

The resulting increase in efficiency with the heat-recovery and recirculation system is 1.0–3.8 %. The use of the proposed system also prevents condensation and icing of the boiler supply air ducts, which occurs when recirculation is used without preheating the combustion air before mixing it with the recirculation waste gases.

It should be emphasized that under the conditions of operation of heat-recovery equipment in the condensation mode, in addition to the thermal effect, a significant environmental effect is observed due to the reduction of natural gas consumption and the dissolution of carbon and nitrogen oxides, and sometimes sulfur oxides, in the aqueous condensate. The resulting aqueous condensate is chemically aggressive. Its pH value is within 3–6. Therefore, special attention is paid to the protection against corrosion of the inner surface of the gas discharge channels and the chimney when designing complex heat-recovery systems [18].

The reason for the destruction of the specified exhaust-gas tracts in the case of the use of complex heat-recovery systems is the "shift" of the dew point temperature in the direction of its decrease as a result of deep cooling of waste gases in these systems. This process is characterized by the increased formation of acidic water condensate from waste gases [19, 20], which creates favorable conditions for corrosion of metal parts of exhaust-gas channels and the appearance of defects in the lining [21]. The destruction of the chimney casing occurs gradually; for example, first voids are formed through which condensate can get onto the outer sur-

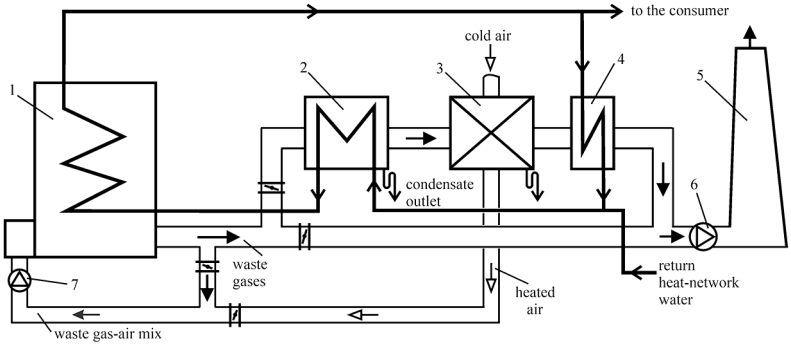


*Fig. 1. Schematic circuit of a boiler plant using gas warms heat-recovery units for heating heat-network water and combustion air:*

*1 – hot water boiler; 2 – gas warm return water heat-recovery exchanger (water heater); 3 – gas warm combustion air heat-recovery exchanger (air heater); 4 – water exhaust-gas heater; 5 – chimney; 6 – exhauster; 7 – air blower*

face of the casing, then under the influence of atmospheric conditions it causes freezing and thawing of its structure and as a result – the formation of through holes, which is unacceptable for the safe use of boiler units. Therefore, under conditions of high level of decrease in temperature of waste gases in heat-recovery systems, it is necessary to apply measures to prevent condensate formation in the exhaust-gas tract including to the mouth of the boiler house chimney. The main and effective methods for protecting the exhaust-gas tract of fuel-fired energy-power plants include the following thermal methods: *1* – passing part of the hot gases from the boiler unit past the heat-recovery system (bypass method); *2* – heating of the waste gases cooled in the heat-recovery equipment in the gas heater (drying method); *3* – mixing relatively dry air, compared to them, preheated in various ways, into the cooled waste gases (air method).

Thus, in work [17], the most common thermal method for protecting the exhaust-gas tract is proposed by equipping the heat-recovery system with a surface water-gas heater, in which the cooled waste gases are heated to the required temperature.

Based on the analysis of recent studies and publications, it is shown that they relate to the assays of the effectiveness of the use of complex schemes of various types and do not consider the issues of the actual design and placement of heat-recovery equipment in boiler houses, given their cost and dimensions.

**Purpose.** The aim of the work is to develop small-sized and material-intensive complex heat and power plants for gas-fired, environmentally-efficient heating boilers and to study their efficiency.

In accordance with the set goal, the following main tasks were to be solved:

- development of a new heat-recovery scheme for the selected boiler using recovered heat to warm the heating network water and combustion air;
- performing thermal calculation of a boiler plant with the proposed heat-recovery system in different operating modes during the heating period and with various fractions of waste gas recirculation (bypassing);
- comparison of the obtained results with the results received using known complex systems of similar purpose.

**Methodology.** To determine the main characteristics of heat-recovery systems, the known methods of thermal calculation of boiler plants and data from experimental studies obtained by the authors were used.

Thus, the calculation of the heat transfer coefficient from waste gases during their deep cooling was carried out using the number $\mathrm{Nu}_g$ in the form of two components

$$\mathrm{Nu}_g = \mathrm{Nu}_g^{dry} + \mathrm{Nu}_g^{con},$$

where $\mathrm{Nu}_g^{dry}$ is the Nusselt number at soi-disant "dry heat transfer", calculated using known methods for heat transfer conditions without condensation; $\mathrm{Nu}_g^{con}$ is an additional component associated with the process of condensation of steam from waste gases under conditions of their cooling below the dew point of this steam.

This component is determined by the experimental dependence

$$\mathrm{Nu}_g^{con} = A \cdot \mathrm{Re}_g^{0.6} \cdot e^{-14\theta},$$

where $A$ is the correction factor depending on the initial moisture content of the waste gases $X_{in}$

$$A = 0.0001 \cdot e^{87 X_{in}} + \frac{0.3}{X_{in}},$$

where θ is dimensionless temperature

$$\theta = \frac{t^w}{t^{dp}},$$

where $t^w$ and $t^{dp}$ are temperatures of water and dew point respectively.

Calculation studies were performed for gas-fired water-heating boiler plants with a heat output of 2.0 MW. The boiler characteristics in nominal mode are:

- fuel type – natural gas;
- boiler thermal output – 2.0 MW;
- higher calorific value of fuel – 9,410 kcal/m$^3$;
- excess air coefficient – 1.1;
- heat loss from chemical underburning – 0.5 %;
- heat loss to the environment – 1.0 %;
- inlet temperature of heating network water – 70 °C;
- outlet temperature of heating network water – 95 °C;
- efficiency by higher heating value of fuel – 82.0 %;
- natural gas consumption – 219 m$^3$/h;
- waste gas temperature – 160 °C.

Thermal calculations of a boiler plant with a heat-recovery system were carried out for a heating system

with a calculated minimum ambient temperature of –20 °C, a coolant temperature difference in the system of 25 °C and in the range of changes in the boiler's heat output within the heating period from 29 to 100 %, which corresponds to a change in the ambient temperature during the heating period from +10 for the autumn-spring season to –20 °C in winter.

The indicators of the thermal and moisture state of the mixture of air and bypass gases $t_{mix}$, their dew point $t^{s}_{dp}$, the temperature of the heated air $t_a$, the resulting increase $\Delta\eta_{res}$ in the efficiency of the boiler with a heat-recovery system and the relative metal content $M/Q$ of the corresponding heat exchangers were determined. The value of $M/Q$ was determined by the ratio of the mass $M$ of the heat exchanger to its heat capacity $Q$.

When performing the calculations, two heat-recovery systems were considered: the known one – using an air heater, where waste gases are as the heat carrier (Fig. 1), and the new scheme – with its completion with a water-heating air heater (Fig. 2).

The water-gas heat exchangers in the considered variants (water heater, air heater and gas heater) were composed of transversely ribbed bimetallic pipes (steel base and aluminum finning with a finning coefficient of approximately *7*), and the heat exchange surface of the gas-heating air heater consisted of 2 mm thick stainless steel plates.

**Findings.** For the beneficial use of exhaust heat of waste gases, a boiler plant scheme (Fig. 2) with waste gas recirculation and a new complex heat-recovery system using the recovered heat to warm the heating network water and combustion air is proposed. In this scheme (Fig. 2), unlike the known one (Fig. 1), an air heater is used, in which the heating heat-transfer agent is the return water of the heating network before it enters for heating in the heat-recovery water heater. In the scheme shown in Fig. 2, waste gases enter sequentially into the water heater *2* and the gas heater *4* and are removed through the exhauster *6* into the chimney *5*.

Cold combustion air from the atmosphere is supplied for heating to the air heater *3*, where the heat-transfer agent is the return heating network water. The heated air enters the recirculation gas duct to mix with waste gases. The return water cooled in the air heater *3* is supplied for heating to the gas water heater *2*, where it is partially heated by cooling the waste gases. The heated water enters the boiler for further heating to the required direct water temperature. Direct water from the boiler is supplied to the consumer through the heating network. Part of the direct water is used in the gas heater *4* to warm the waste gases in order to protect the gas outlet channel and chimney *5* from condensation and its negative effects.

By equipping the boiler plant with a network water heater in the exhaust duct following the movement of waste gases and connecting it to the combustion air heater and the water circulation circuit of the heat supply system via the water path, the return network water is heated and the temperature of the heated air at the boiler inlet is increased. In addition to increasing the efficiency of heat recovery, air heating ensures that, when waste gas recirculation is used, the temperature of the gas-air mixture exceeds its dew point temperature in all operating modes of the plant during the heating period, in particular, it eliminates the possibility of icing of the air supply ducts of the plant during the winter period of its operation. By equipping the plant with a gas heater, the waste gases are heated in front of the exhauster and the corresponding prevention of condensate formation in the exhaust duct and chimney.

In the case of implementing the proposed scheme in the air heater *3*, the temperature of the return water decreases before it enters the water heater *2*, which increases its efficiency. Herewith, the air heater *3* can be manufactured using finned tubes, for example, from bimetallic tubes (steel base and aluminum fins). Such an air heater will be characterized by smaller dimensions and metal capacity than the gas warm air heater *3* according to the scheme in Fig. 1, where the heat exchange surface consists of thin-sheet steel plates, which is usually practiced for gas-gas heat exchangers.

Thermal calculations of the proposed heat-recovery system and calculations of the heat and moisture regime in the air supply ducts of such a plant are performed. The main results of the performed calculations are given in Figs. 3–5 and in Tables 1, 2. Fig. 3, *a* illustrates the patterns of changes in all operating modes of the boiler plant during the heating period in the heat and moisture indicators (temperature $t_{mix}$ and dew point $t^{dp}_{mix}$) of the mixture of air and recirculated waste gases at different

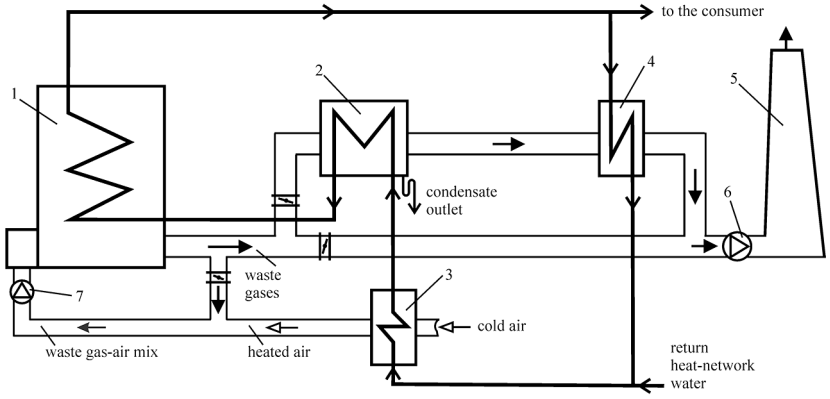


*Fig. 2. Schematic circuit of a gas-fired boiler plant using a heat-recovery exchanger for heating network water and a water heat-recovery exchanger for heating combustion air:*

*1– hot water boiler; 2 – gas warm return water heat-recovery exchanger (water heater); 3 – water air heater; 4 – water exhaust-gas heater; chimney; 6 – exhauster; 7 – air blower*

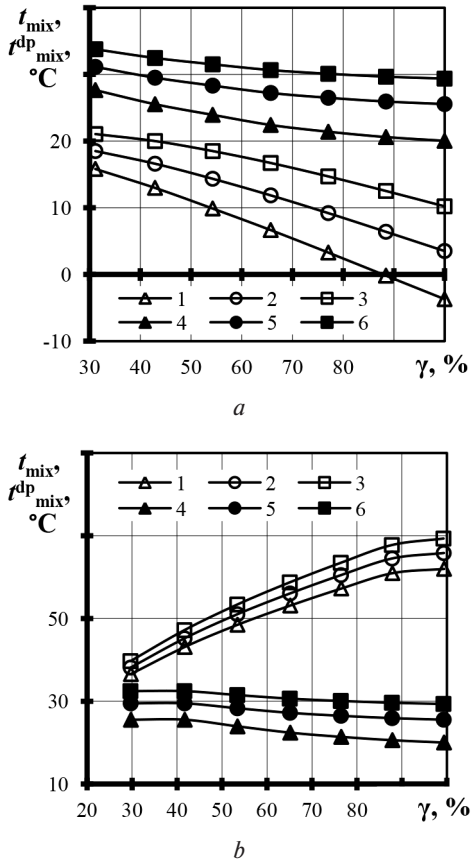


*Fig. 3. Dependence of the relative boiler load γ of the temperature $t_{mix}$ (1–3) and the dew point $t^{dp}_{mix}$ (4–6) of the mixture of combustion air and recirculated waste gases at different gas recirculation fractions σ without using the heat-recovery system (a) and in the presence of the proposed system with a water warm air heater (b):*

*1, 4 – σ = 10 %; 2, 5 – σ = 15 %; 3, 6 – σ = 20 %*

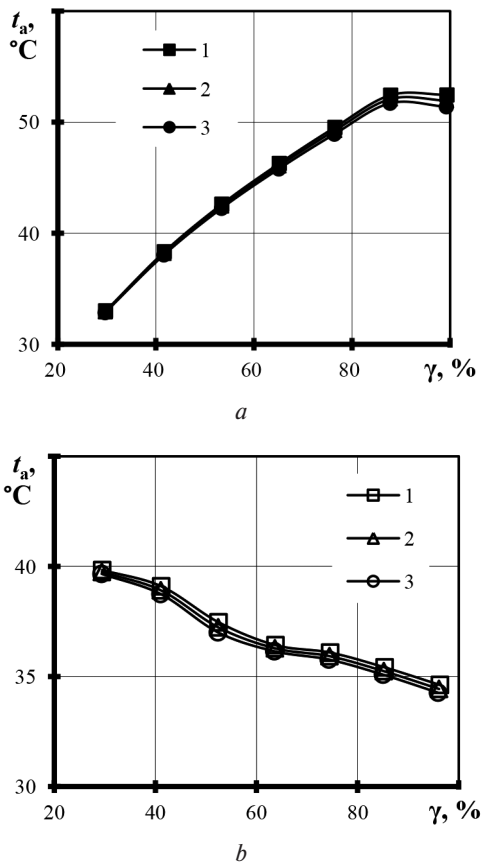


*Fig. 4. Dependence of the temperature $t_a$ of heated air in a water warm air heater (a) and in a gas warm air heater (b) on the relative boiler load γ for different fractions σ of gas recirculation:*

*1 – σ = 10 %; 2 – σ = 15 %; 3 – σ = 20 %*

fractions of their bypassing into the boiler supply duct in the absence of a heat-recovery system with preheating of the air. As the results obtained (Fig. 3, *a*) show, the use of waste gas recirculation without preheating of the air leads to the formation of condensate in the supply air ducts of the boiler plant. In all modes of its operation during the heating period, the temperature of the mixture $t_{mix}$ is lower than the dew point temperature $t^{dp}_{mix}$ by 12–24 °C.

Moreover, lower values of the dew point excess over the mixture temperature correspond to small boiler loads and positive temperatures of the heating period, and higher values are observed at high boiler thermal loads (corresponding to negative ambient temperatures). At ambient temperatures below zero, icing of air ducts and air blowers is possible. That is, increasing the environmental friendliness of the boiler installation in this way reduces its reliability and does not ensure operability in some operating modes.

Fig. 3, *b* shows data on the corresponding thermo-humidity indicators of the air-gas mixture under the conditions of using the proposed heat-recovery system (Fig. 2). The analysis of the obtained data shows that in the studied boiler operating modes, an excess of the mixture temperature $t_{mix}$ over the dew point temperature $t^{dp}_{mix}$ is observed. The specified excess is 7–42 °C. Lower values of the excess occur in the warm period of the heating season, and higher values correspond to low temperatures of this period.

The performed calculation studies also showed (Fig. 4, *a*) that under the conditions of using the proposed heat-recovery system, cold atmospheric air is heated to 53 °C depending on the operating mode and the proportion of bypassed waste gases after the boiler.

This fact indicates the improvement of the characteristics of the air-gas mixture to prevent condensation in the air supply channels of the boiler plant. This applies especially to low ambient temperatures, which are threatening to freeze the air ducts and the air blower without heating the combustion air in the heat-recovery system.

As shown by the performed calculation studies (Fig. 4, *a*), in the cold period of the heating season, which corresponds to high boiler loads, the level of air heating in the water warm air heater according to the scheme in Fig. 2 is higher than the level of heating in the gas warm one (Fig. 1). And this difference is about 20 °C. This indicates that the boiler plant is more reliable in terms of the absence of icing of the surfaces of the air supply channels, which is observed precisely in the cold period with high heat outputs of boiler plants (Fig. 3, *a*). In the warm period of the heating season (with low boiler loads), on the contrary, the temperature of the heated air in the water warm air heater (Fig. 4, *a*) is lower by about 8 °C than in the gas warm one (Fig. 4, *b*). But at

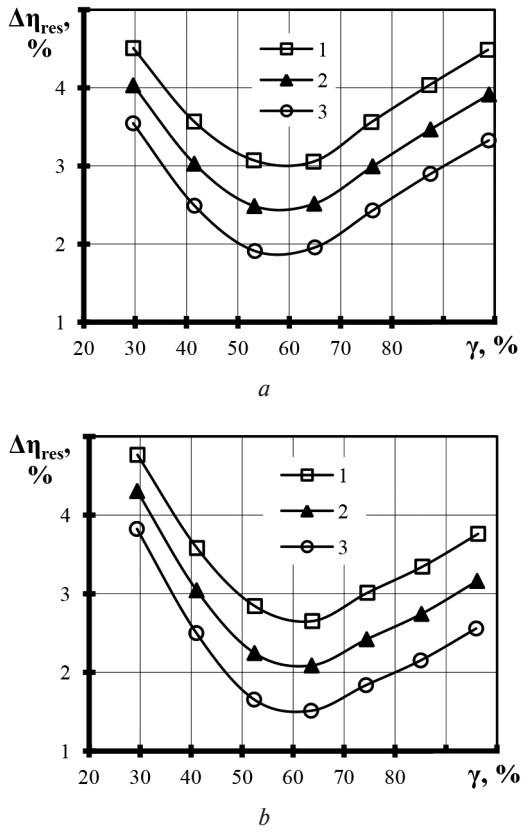


*Fig. 5. Dependence of the resulting boiler efficiency* $\Delta\eta_{res}$ *on its relative heat load* γ *for different fractions* σ *of gas recirculation at using water warm* (*a*) *and gas warm* (*b*) *air heaters:*

*1 –* σ *= 10 %; 2 –* σ *= 15 %; 3 –* σ *= 20 %*

low boiler loads and correspondingly high ambient temperatures during the heating season, there is no danger of icing of the air duct surfaces. Therefore, the use of the proposed heat-recovery system ensures the operability of the boiler plant with increased environmental efficiency in all operating modes during the heating period.

According to the research results, it can also be concluded that changing the recirculation fraction σ has a small effect on the temperature indicators of heated air for the two considered options.

A study was also conducted on the thermal efficiency of the proposed waste gas heat-recovery system equipped with a water warm air heater. Fig. 5, *a* demonstrates the patterns of changes in the efficiency of this installation during the heating season.

The resulting boiler efficiency value was determined taking into account its decrease due to bypassing part of the waste gases into the boiler combustion space with combustion air. This decrease is usually 1–3 % for the adopted fractions of boiler exhaust gases bypassing into this air. According to the results obtained, the level of efficiency increase when using the new scheme is 1.5–4.8 % depending on the boiler load and the fractions of waste gas recirculation. The higher values of the boiler efficiency increase correspond to the extreme values of the considered range of boiler thermal load. Moreover, for the known heat-recovery system, the efficiency increase is somewhat higher at the lowest values of the specified load. The lower level of boiler efficiency increase for both considered systems corresponds to boiler thermal productivity of 55–60 %, which is realized at ambient air temperatures from minus 5 to 0 °C. At such boiler load levels, a small level of deep cooling of waste gases in the gas warm water heater is achieved due to the insufficiently low temperature (> 50 °C) of the return water at the inlet to the heat-recovery system according to the selected temperature schedule of the heating system. The results obtained regarding the levels of efficiency increase at low boiler loads are explained by the fact that the specified temperature decreases and this contributes to an increase in the level of condensation of steam from waste gases in the gas warm water heater *2* and the efficiency of the boiler installation increases. Under conditions of high boiler loads, the increase in its efficiency occurs due to an increase in the efficiency of the water warm air heater due to the low inlet temperature of the heated air, which provides a significant reduction in fuel consumption for the boiler.

To assess the thermal efficiency of the proposed heat-recovery system (Fig. 2), Fig. 5, *b* shows data on the change in the efficiency of a boiler plant with waste gas recirculation under the conditions of using a gas warm air heater (Fig. 1). As shown by the comparison of efficiency values, their level is commensurate with the excess for the proposed heat-recovery system.

The work also carried out a study on the relative metal capacity of the considered heat exchangers (heat-recovery units). The corresponding data are given in Tables 1 and 2. The obtained results are explained by the fact that, as already noted, the heat exchangers in the considered heat-recovery schemes (Figs. 1 and 2) are mainly gas and air-water, the heat exchange surface of which is bundles of finned bimetallic pipes, and the gas warm air heater is of the plate type using stainless steel plates.

*Table 1*

Relative metal capacity *M*/*Q* of a heat-recovery system with a water warm air heater (Fig. 2) at different relative boiler loads γ and at different fractions σ of recycled waste gases

| Recirculation fractions σ, % | Relative metal content *M*/*Q* of the heat-recovery system and its elements, *t*/MW | | | | | | |
|---|---|---|---|---|---|---|---|
| | relative boiler loads γ, % | | | | | | |
| | 30 | 42 | 53 | 65 | 75 | 86 | 97 |
| Gas warm water heater | | | | | | | |
| 10 | 4.8 | 4.5 | 4.5 | 4.1 | 3.2 | 2.6 | 2.1 |
| 15 | 4.6 | 4.4 | 4.3 | 3.8 | 3.0 | 2.4 | 2.0 |
| 20 | 4.5 | 4.2 | 4.2 | 3.6 | 2.8 | 2.3 | 1.9 |
| Water warm air heater | | | | | | | |
| 10 | 22.0 | 10.7 | 6.5 | 4.4 | 3.2 | 2.5 | 2.0 |
| 15 | 21.0 | 10.3 | 6.2 | 4.2 | 3.1 | 2.4 | 1.9 |
| 20 | 20.1 | 9.8 | 6.0 | 4.0 | 3.0 | 2.3 | 1.8 |
| Heat-recovery system in general | | | | | | | |
| 10 | 7.4 | 6.1 | 5.2 | 4.2 | 3.2 | 2.5 | 2.1 |
| 15 | 7.1 | 5.9 | 5.0 | 4.0 | 3.0 | 2.4 | 2.0 |
| 20 | 6.8 | 5.7 | 4.8 | 3.8 | 2.9 | 2.3 | 1.9 |

*Table 2*

Relative metal capacity $M/Q$ of a heat-recovery system with a gas warm air heater (Fig. 1) at different relative boiler loads γ and at different fractions σ of recycled gases

| Recirculation fractions σ, % | Relative metal content $M/Q$ of the heat-recovery system and its elements, $t$/MW | | | | | | |
|---|---|---|---|---|---|---|---|
| | relative boiler loads γ, % | | | | | | |
| | 30 | 42 | 53 | 65 | 75 | 86 | 97 |
| Gas warm water heater | | | | | | | |
| 10 | 4.9 | 4.6 | 4.6 | 4.2 | 3.3 | 2.7 | 2.2 |
| 15 | 4.7 | 4.5 | 4.4 | 4.0 | 3.1 | 2.5 | 2.1 |
| 20 | 4.6 | 4.3 | 4.3 | 3.8 | 2.9 | 2.4 | 2.0 |
| Gas warm air heater | | | | | | | |
| 10 | 35.4 | 22.0 | 15.5 | 11.5 | 8.8 | 7.0 | 5.7 |
| 15 | 33.8 | 21.0 | 14.9 | 11.0 | 8.4 | 6.7 | 5.4 |
| 20 | 32.4 | 20.2 | 14.3 | 10.5 | 8.0 | 6.4 | 5.2 |
| Heat-recovery system in general | | | | | | | |
| 10 | 10.5 | 9.1 | 8.2 | 6.9 | 5.4 | 4.3 | 3.6 |
| 15 | 10.1 | 8.8 | 7.9 | 6.6 | 5.1 | 4.1 | 3.4 |
| 20 | 9.8 | 8.4 | 7.6 | 6.3 | 4.9 | 3.9 | 3.2 |

The analysis of the research results shows that the use of a new heat-recovery scheme with heating of the combustion air by return heat network water before it enters the gas warm water heater of the boiler plant is characterized by a significantly lower relative metal capacity $M/Q$ of the system than in the case of using a gas warm plate air heater. In particular, the value of the studied parameter is 1.6–2.9 times smaller, which ensures a reduction in the total relative metal content of the proposed heat-recovery system by 1.4–1.7 times, depending on the boiler operating mode and the proportion of waste gas mixing. Larger values in the $M/Q$ differences relate to larger boiler loads, and smaller ones correspond to its small loads.

It should be emphasized that under conditions of heating the air with waste gases in air heater *3* (Fig. 1), in some modes condensation of steam from waste gases occurs, which requires its construction from anti-corrosion materials, in particular from stainless steel. Under conditions of heating the air with return heating network water, there is no problem of protection against corrosion.

The use of a water warm air heater due to the use of a developed heating surface in it ensures high compactness of this heat exchanger, which is essential in its design and manufacture, as well as placement in cramped conditions of modern boiler houses. In addition, the cost of such a heat exchanger is lower due to the use of the specified heating surface in comparison with a plate heat exchanger made of stainless steel. This is especially important for boilers with high heat output where the design, manufacture and installation of large heat exchangers is complicated.

Thus, the analysis of the obtained research results indicates a number of significant advantages of the developed new heat-recovery system over the known one under the conditions of application for boilers with waste gas recirculation. The use of the proposed heat-recovery system will provide boiler plants with increased environmental efficiency, reduced cost of heat recovery equipment, improved manufacturability of its manufacture, increased compactness, reliable operation and fuel savings.

**Originality.** The efficiency of a new complex heat-recovery system for heating boiler plants with recirculation of boiler exhaust gases into the combustion air are proposed and investigated for the first time.

**Practical value.** The obtained research results will be used in the design of waste gas heat-recovery systems for heating boiler plants to increase their environmental and thermal efficiency.

**Conclusions.** For heating gas-fired boilers, under the conditions of using the method of recirculation of waste gases into the combustion air, a new complex heat-recovery system is developed and, based on the results of a set of studies, an analysis was performed of its thermal efficiency, reliability, metal consumption, compactness and cost. It has been established that the applying of this system with the use of a water warm air heater provides:

Reliable operation of the air supply channels of the boiler plant due to heating of the supply air in the water warm air heater to 32–53 °C, which ensures the absence of condensation in these channels.

The resulting increase in boiler plant efficiency is 1.5–4.8 % due to the complex use of recovered heat for warming heating network water and combustion air. The efficiency value is determined taking into account heat losses for waste gas recirculation.

Reduction of the relative metal content $M/Q$ of heat exchangers (heat-recovery units) and increase of their compactness due to the developed heat exchange surface, which is composed of a bundle of finned bimetallic pipes. In particular, the value of $M/Q$ of a water warm air heater is 1.6–2.9 times smaller in comparison with the gas-warming analogue, which ensures reduction of the total relative metal content of the proposed heat-recovery system by 1.4–1.7 times depending on the boiler operating mode and the proportion of waste gas recirculation.

Diminution in the cost of a water warm air heater of a heat-recovery system compared to a gas-warming one due to reduced metal consumption, use of serially produced finned tubes, improved manufacturing processability, etc.

The obtained research results will be used when designing boiler plants using the considered method of their ecologization, when creating new effective heat-recovery systems with complex use of recovered heat for heating water and combustion air, as well as in the case of reconstruction of existing boiler plants in order to improve their environmental and energy performance.

Research data can also be used in educational processes when training specialists in heat and energy disciplines and environmental protection.

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## Нові комбіновані системи теплоутилізації екологоефективних котельних установок

*Н. М. Фіалко, Р. О. Навродська*, С. І. Шевчук, Г. О. Гнєдаш*

Інститут технічної теплофізики НАН України, м. Київ, Україна
* Автор-кореспондент e-mail: navrodska-ittf@ukr.net

**Мета.** Встановлення ефективності запропонованого нового технічного рішення малогабаритної та малометалоємної комбінованої теплоутилізаційної установки для газоспоживальних еколого-ефективних опалювальних котлів.

**Методика.** Використовувалися відомі методи теплового розрахунку котельних установок і дані експериментальних досліджень, отриманих авторами.

**Результати.** Запропонована для корисного використання скидної теплоти димових газів схема котельної установки із рециркуляцією газів і новою комбінованою теплоутилізаційною системою, призначеною для нагрівання таких теплоносіїв, як тепломережна вода й дуттьове повітря. Виконані розрахункові дослідження щодо основних показників теплової ефективності вказаної системи й тепловологісного стану в повітряних каналах котельної установки в різних режимах її експлуатації. Показано, що використання пропонованої системи забезпечує підвищення ККД котла та відсутність конденсатоутворення у вказаних каналах за умов рециркуляції димових газів. Одержані також показники відносної металоємності розглянутих теплообмінників-теплоутилізаторів. Виконане зіставлення розрахованих показників із відповідними показниками для відомої системи теплоутилізації з нагріванням вказаних теплоносіїв. Результати досліджень свідчать про те, що нова система із водогрійним повітронагрівачем характеризується значно меншою відносною металоємністю цього теплоутилізатора порівняно з відомою, яка комплектується газогрійним повітронагрівачем. Запропонований водогрійний повітронагрівач, завдяки застосуванню у ньому розвиненої поверхні нагрівання, є малометалоємним і висококомпактним, що є суттєвим при його конструюванні й виготовленні, а також розміщенні у стиснених умовах котелень.

**Наукова новизна.** Уперше запропонована та досліджена ефективність нової комбінованої теплоутилізаційної системи для опалювальних котельних установок підвищеної екологічності.

**Практична значимість.** Отримані результати досліджень будуть використанні для покращення екологічних і теплових характеристик котельних установок.

**Ключові слова:** *теплоутилізація, підігрівання води, дуттьове повітря, рециркуляція димових газів*

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