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INCREASING FUEL EFFICIENCY OF WASTE INCOMBUSTION BOILER PLANTS

Purpose. The goal is to increasing the thermal efficiency of a water heating boiler burning solid household waste or fuels made from it.

Methodology. Known and developed by the authors, methods for thermal calculation of heat exchangers were used.

Findings. The modern heat-recovery technology based on the use of a complex system has been proposed for the useful use of waste heat from combustion products of household waste incineration plants and fuels based on it. This system is designed to heat combustion air and heating network water in the corresponding modular heat exchangers-heat recovery units. Original technical solutions for these heat-recovery units have been developed with the possibility of operation on dusty gas flows. Calculation studies have been carried out on the effectiveness of the use of the specified system. The patterns of changes in the main characteristics of the heat-recovery system have been determined, namely: its heat productivity, final temperature levels of the used heat-transfer agents and the volumes of condensate formed during deep cooling of waste gases. The level of flue gas temperature reduction in the entire heat-recovery system is 126.9–197.1 °C. Therefore, the use of the proposed heat-recovery system and the equipment used is an effective measure to significantly increase the efficiency of incineration of solid household waste and fuels based on it.

Originality. First proposed, a complex heat-recovery system designed to heat combustion air and heating water has been proposed for a waste incineration boiler, and its energy efficiency has been investigated.

Practical value. The obtained research results will be used to increase the efficiency of incineration of solid household waste and fuels from it in relevant installations.

Keywords: *household waste, heat-recovery, thermal efficiency, condensation mode, reliability*

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Introduction. Incineration of household waste, the so-called solid household waste (SHW), or artificial fuels (AF) from them, is the most effective way to combat their accumulations to avoid a possible environmental threat [1, 2]. The tasks of construction and safe operation of waste incineration plants, as well as the effective use of heat from SHW combustion are practically solved in developed countries of the world [3, 4]. However, it should be noted that the material costs for the construction and maintenance of these enterprises are significantly higher compared to the construction and operation of landfills and waste processing plants. One of the ways to reduce capital costs for the maintenance of enterprises for the incineration of SHW and AF from them is to increase the energy efficiency of these installations. In particular, this increase can be implemented, for example, by using (recovering) the waste heat of exhaust flue gases [5, 6]. Recovery can simultaneously solve two problems: cleaning unrefined and irrational waste; and generating a large amount of energy to meet the needs of consumers [7, 8]. In the created heat-recovery systems of the existing technologies of thermal disposal of household waste, various heat-recovery equipment is used [9, 10]. The effectiveness of the specified technologies, as is known, is associated with the depth of cooling

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of exhaust gases, namely with the level of reduction of the thermal potential of waste heat, which in turn depends on the temperature and humidity of the outgoing flue gases (after heat-recovery exchangers). The highest efficiency of the heat-recovery technology is achieved in the case of reducing the temperature of the outgoing gases below the dew point of the water vapor contained in the gases and using the heat of the phase transition of condensed steam [11, 12]. Deep cooling of exhaust gases is usually implemented in complex heat-recovery systems using different coolants with different temperature potentials.

Literature review. The waste heat from waste thermal treatment plants can be used in boilers designed to produce steam, hot water or thermal energy in the form of another coolant [13, 14]. The boilers used can be divided into the following categories: a hot water boiler designed to heat the process water of the boiler house, water for the heating system, or another liquid heat-transfer agent; a steam boiler used to produce saturated or superheated steam, as well as to heat water [14, 15].

The creation of appropriate equipment for heat-recovery systems for waste incineration plants is problematic due to the presence of chemically aggressive compounds in the exhaust gases of these plants and a significant amount of solid waste in the form of dust. In particular, according to the identified information sources, the combustion products of fuels based on SHW contain such harmful compounds in the gas phase as ammonia, fluorine, nitrogen, chlorine, etc., as well as various chemical and fractional compositions of dust compounds.

Analysis of research on the use of these technologies also showed that an important factor in the development of these technologies and appropriate equipment is the morphological and granulometric composition of waste, as well as its thermal characteristics, in particular, the heat of combustion, humidity, etc. It is these characteristics and features of waste incineration that affect the composition of combustion products, which contain the above-mentioned harmful and chemically aggressive compounds in the gas phase and solid technological waste in the form of dust of various fractional spectra.

At of complete combustion of the fuel, this is when the combustion reaction occurs with sufficient air for combustion, the combustible components of SHW are transformed into water vapor, carbon dioxide and solid residues in the form of ash and slag. With a lack of oxygen, a process of incomplete combustion occurs, as a result of which other potentially harmful substances are formed. The most dangerous such formation is carbon monoxide CO, as well as carbon in the form of solid particles – soot, smoke and some types of resins. For any combustion process, the formation (types and concentrations) of harmful pollutants and their content in the composition of flue gases depends on the combustion conditions, type of AF, features of the process and the selected equipment for processing SHW into energy. Pollutants can enter the exhaust gases in three ways. The first way is that these harmful substances (or their components) were already in the composition of the waste. The second is the formation of harmful substances during combustion under conditions of incomplete oxidation of the fuel, due to the lack of the required amount of oxygen. The third way of formation is as a result of cooling of exhaust gases.

It is a common occurrence when the combustion products of waste incinerators include acid gases. Their danger lies in the fact that when combined with water, they form acids that are dangerous to the environment and human health. For example, when burning plastic, hydrogen chloride (HCl) is formed, which, when in contact with moisture, turns into hydrochloric acid. When burning rubber and paper, sulfur dioxide (SO_2) is formed, which, when reacting with water vapor, forms sulfurous acid. This acid is the main component of acid rain. Also, acid gases include nitrogen oxides, hydrogen bromide, hydrogen fluoride and hydrogen iodide.

The technological exhaust of waste incineration plants, as already noted, also includes solid particles, which are formed mainly from non-combustible substances contained in exhaust gases and incomplete combustion products, which exist in solid or aerosol form. The concentration of solid particles in waste gases in the absence of control devices usually varies from 180 to more than 46,000 mg per dry standard cubic meter.

In addition to the negative impact on the environment, the chemical aggressiveness and dustiness of waste gases complicate the operation of various equipment of waste incineration plants and can even lead to its inoperability. In view of this, the main prerequisite for the development and application of waste heat-recovery systems of gas emissions at SHW and AF incineration plants is the use of special heat-recovery equipment (heat-recovery units) in these systems. Such equipment should provide high energy efficiency, protection of its critical elements from mechanical erosion and chemical corrosion of exhaust gases. In addition, the design of such heat-recovery units and their operating parameters should facilitate self-removal of dust deposits from the heat exchange surface during operation. Heat-recovery units should also provide for the possibility of forced cleaning of this surface.

One of the types of equipment used in heat-recovery technologies of waste incineration plants is air heaters of various designs and functional purposes. For example, these are air heaters based on thermosyphons [16], or surface heat exchangers-recuperators, which are made depending on their application from ceramic, metal or other heat-resistant materials [17, 18]. Such air heaters are also stationary regenerative heat exchangers using modern storage materials with high heat capacity [17]. A type of regenerative equipment is rotating regenerators, which operate similarly to stationary devices under the conditions of heat transfer through a porous heat wheel between hot and cold heat flows [19, 20]. There are also isolated developments of other heat exchange devices for heating air by recovering waste heat from waste gases.

In [21], a new technical solution for air-heating heat-recovery equipment for the useful use of waste heat from combustion products of a waste incineration plant is proposed. The proposed modular panel heat-recovery device is designed to heat combustion air by recovering the heat of exhaust gases leaving after the turbine or boiler.

Calculation studies have been carried out on the energy efficiency of the proposed air heating equipment under the conditions of its use for the recovery of waste

heat from waste-based fuel combustion plants. The studies were carried out in different operating modes of this equipment during the year. When performing the studies, the following were varied: the initial temperature of the heated air, the temperature and humidity of the exhaust gases, the excess air coefficient, the level of dust deposits on the heat exchange surface, etc. Analysis of the research results showed that due to the structural features of the proposed air heating heat-recovery device, it is characterized by high thermal performance, resistance of working surfaces to corrosive wear and tear and the possibility of forced cleaning of these surfaces from dust contamination. The critical level of surface contamination at which it is necessary to carry out forced removal of dust deposits is determined by the operating parameters of the heat-recovery unit (temperature and velocity of waste gases, the amount of solid technological waste in them, its dispersed composition, the required level of final air temperature, etc.), as well as the technical feasibility and specific conditions for implementing the cleaning process.

The results of the studies performed in [21] show that under the considered conditions, the value of the initial moisture content of waste gases does not affect their final moisture content. That is, in the process of heat-recovery, such deep cooling of gases is not realized, during which moisture falls out of them and water condensate is formed, in which part of the corrosive compounds contained in the exhaust gases dissolves. This protects the working surfaces of the proposed heat-recovery unit from the corrosive action of condensate during operation.

Regarding the use of heat-recovery equipment for deep cooling of exhaust gases of waste incineration plants, no relevant information was found in the literature. The relevance of this work lies in the creation and implementation of research on a new heat-recovery plant and the corresponding heat exchange equipment of high and operational efficiency, which will ensure deep recovery of waste heat from combustion products of enterprises incinerating SHW and AF from them.

Purpose. The aim of the work is to develop a new complex heat-recovery system and corresponding equipment with deep cooling of exhaust gases for water heating boiler operating on solid household waste or fuels from them, and to study their efficiency.

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

- development of a new heat-recovery scheme for a water-heating waste burning boiler using recovered heat for heating the combustion air and return heat network water of the boiler house in the corresponding heat exchangers – heat-recovery units;

- establishment of patterns of changes in the defining indicators of the proposed heat-recovery system and its elements under different boiler modes during the operational period.

Methodology. To determine the main characteristics of heat-recovery systems, known methods of thermal calculation of heat exchange equipment and the results of our own experimental studies of heat and mass transfer processes and aerodynamics in water-heating heat exchangers of waste heat-recovery systems of combustion products of industrial glass-melting furnaces of various types were used [22].

In the work for the useful use of heat from exhaust gases of a heating waste incineration boiler, a scheme of a modern complex heat-recovery system was proposed (Fig. 1). In this system, the recovered heat is used for preheating the combustion air and return water of the boiler house heating network before these heat-transfer agents enter the boiler.

Calculation studies were performed for a boiler with a complex heat-recovery system, in which the heat from waste incineration heats the return water of the heating system. The waste consumption in nominal mode is 5 t/h.

The initial data (Table 1) for performing thermal calculations of the proposed heat-recovery system for the studied waste incineration boiler were taken in their practical range based on 1 t/h of SHW combustion. The temperature parameters of the direct and return water entering the boiler house from the heating network were taken according to the standard thermal performance of the heating system.

The dustiness coefficient indicated in the table determines the level of reduction in the heat transfer coefficient of the heat exchange surface of the heat exchanger in the presence of dust deposits.

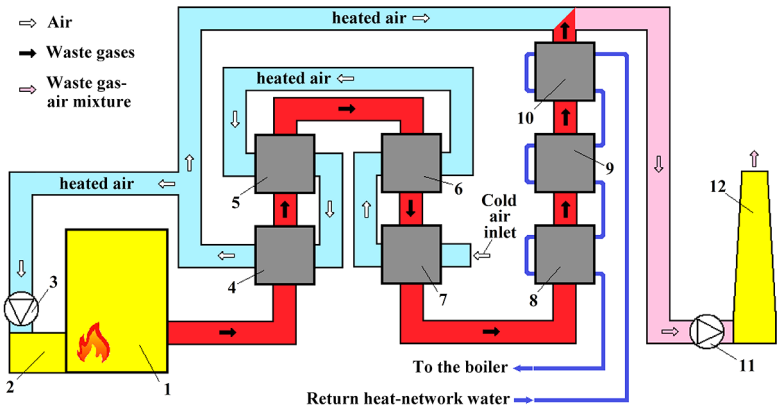

Fig. 1. Schematic circuit of a complex heat-recovery system:

1 – water heating boiler; 2 – gas burner; 3 – combustion air fan; 4, 5, 6, 7 – first, second, third and fourth modules of the air-heating heat-recovery exchanger, respectively; 8, 9, 10 – first, second and third modules of the water-heating heat-recovery exchanger, respectively; 11 – exhauster; 12 – chimney

Table 1

Output data

Characteristic name, dimension	Value
Flow rate of exhaust gases from the boiler, kg/s	1.8–0.6
Excess air ratio in the exhaust gases	1.5–2.0
Inlet temperature of exhaust gases, °C	200–250
Inlet temperature of ambient air, °C	–20–10
Inlet temperature of heat-network water, °C	35–70
Temperature difference of the heating system heat-transfer agent, °C	25
Estimated ambient air temperature for the heating system, °C	–20
Moisture content of waste gases, kg/kg of dry matter	0.15–0.25
Heat exchange surface area of the air-heating heat-recovery exchanger, m^2	90.4
Heat exchange surface area of the water-heating heat-recovery exchanger, m^2	54.5
Dustiness coefficient of the heat exchange surface	0.5–1.0

In the proposed heat-recovery system, exhaust gases after the boiler first enter the air-heating heat-recovery exchanger, in which the combustion air is heated before it enters the boiler. The waste gases partially cooled in the air heater are sent to the water-heating heat-recovery exchanger, designed to preheat the return heating network water before it enters the boiler for reheating. In the water-heating heat-recovery exchanger, in some boiler operating modes, deep cooling of waste gases can be implemented (cooling below the dew point of water vapor contained in the exhaust gases).

The air-heating heat-recovery exchanger in the above scheme was a modular panel heat exchanger proposed in [21] (Fig. 2). The heat exchange surface of the heat exchanger is composed of steel panels formed from pipes and membranes. The surface of the panels on the gas side, if necessary, can be protected with a specially developed anti-corrosion coating. The pipes used in the panels are covered with annular flow turbulators (Fig. 2, *b*) of the required geometric parameters. The annular turbulators contribute to the intensification of heat exchange and increase the heat transfer coefficient inside the pipes by 1.4–1.8 times under the conditions of an allowable increase in aerodynamic resistance, compared to other methods of intensification of heat exchange. In the heat exchanger, cross-flow movement of coolants is implemented during air flow into the pipes, and waste gases in the interpanel space. The passage of air from the tube bundle of one module to another is implemented in the collector chambers (Fig. 2, *a*). The design of the heat-recovery unit provides special openings with hatches for organizing, if necessary, forced cleaning of the heat exchange panels on the gas side with compressed air. The use of this method of cleaning the working surfaces of the heat-recovery equipment has achieved a positive result under the conditions of recovery of waste heat from the exhaust gases of fuel-consuming installations of glass-making production. At the same time, the experimentally established cleaning efficiency is approximately 95 %.

The water-heating heat-recovery exchanger used in the proposed scheme was also assembled from structurally similar panels and consisted of three modules of the same type (Fig. 3). In order to prevent operational wear of the panels in the corrosive environment of waste gases, they can be made of specially alloyed steel or have an appropriate protective coating.

The design of the water-heating heat recovery exchanger, as well as in the air-heating one, provides for the possibility of forced removal of dust deposits with compressed air or other means. The design of the heat exchange panels used and the operating parameters of the heat-recovery exchanger contribute to reducing the intensity of the dusting process of the panels during operation.

Findings. The results of thermal calculations of the proposed scheme of heat-recovery of a waste incineration boiler in the absence of dust on the heat exchange

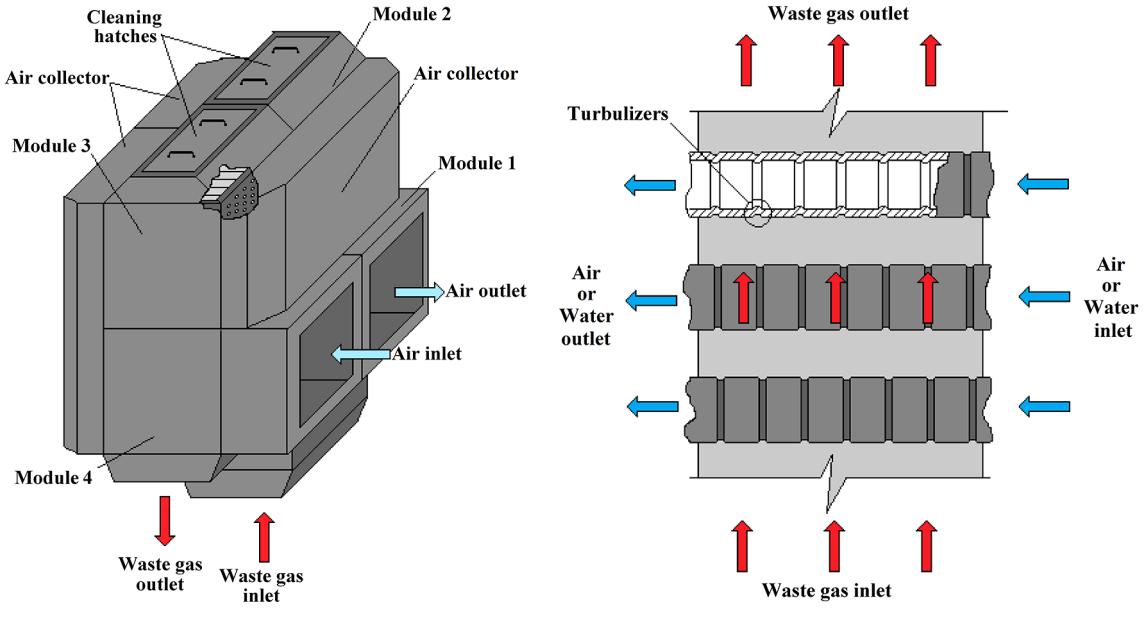

Fig. 2. Design of an air-heating heat-recovery unit: general view (a) and coolant flow circuit (b)

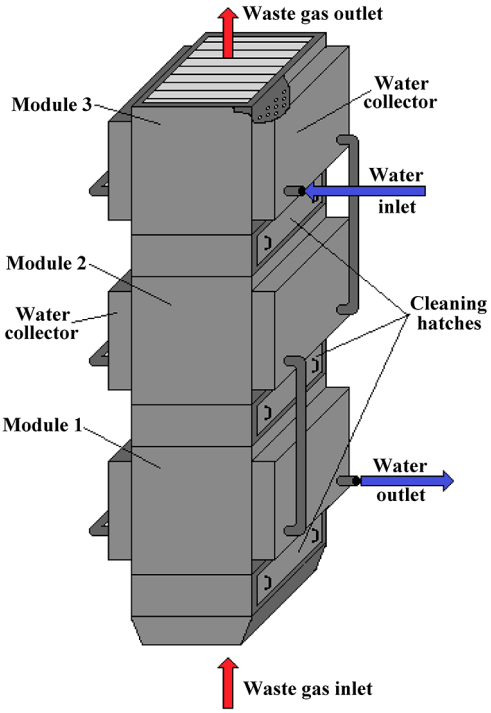

Fig. 3. Design of a water-heating heat-recovery unit consisting of three modules

surfaces of the used heat-recovery exchangers are given in Fig. 4–6 and Tables 2, 3.

The results of on the change in the temperature indicators of boiler exhaust gases during the recovery of their heat in a complex heat-recovery system for different initial conditions and boiler modes during the heating period are shown in Fig. 4.

The results of the studies show that under the considered conditions, a more intensive decrease in the temperature of the gases is realized in air-heating heat-recovery equipment than in a water-heating one. Thus, the value of the difference $\Delta t = t_g^{in} - t_g^{out}$ is within the range of 120.9–123.3 °C for the air heater and 75.7–51.1 °C for the water heater at the initial temperature of the waste gases t_g^{in} = 250 °C and, respectively, 96.1–100.5 and 51.4–6.4 °C for the temperature t_g^{in} = 200 °C.

According to the obtained calculation results, the total decrease in the temperature of the exhaust gases Δt in the heat-recovery system corresponds to the values of 126.9–197.1 °C depending on the boiler mode and the initial values of the temperature and moisture content of these gas emissions.

At the same time, the results of the performed studies have established the absence of the influence of the con-

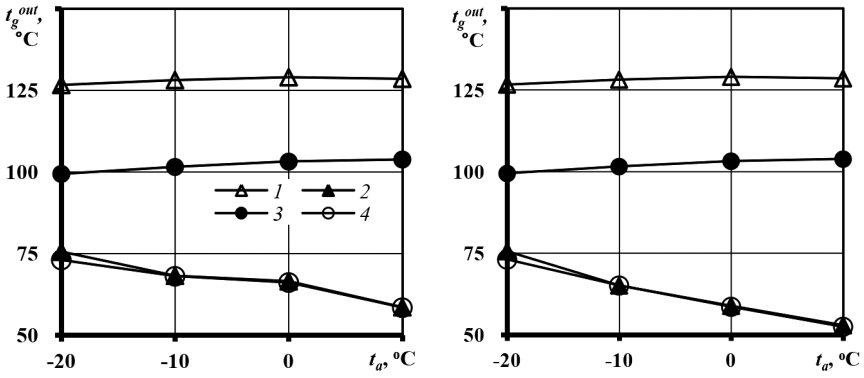

Fig. 4. Dependence of the temperature t_g^{out} of waste gases at the outlet of the air heater (1, 3) and water heater (2, 4) on the ambient temperature t_a at different temperatures t_g^{in} and moisture content X_g^{in} of exhaust gases at the inlet:
a – X_g^{in} = 0.25 kg/kg d.g.; b – X_g^{in} = 0.15 kg/kg d.g.;1, 2 – t_g^{in} = 250 °C; 3, 4 – t_g^{in} = 200 °C

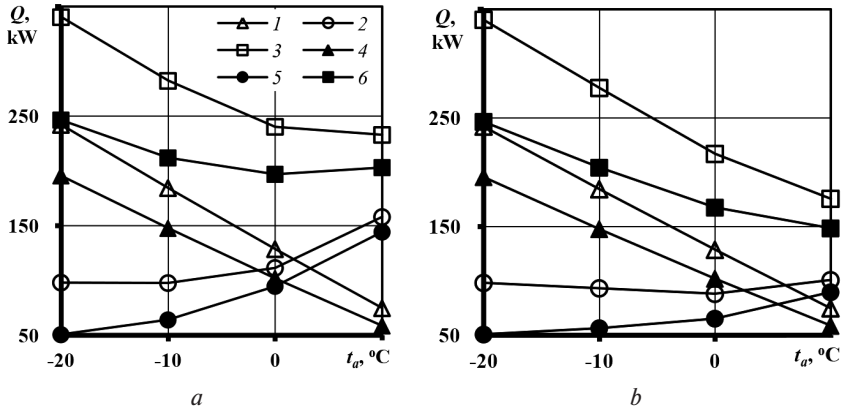

Fig. 5. Dependence of the heat output Q of the air heater (1, 4), water heater (2, 5) and the total (3, 6) on the ambient temperature t_a at different waste gas inlet temperatures t_g^{in} and the initial exhaust gas moisture content X_g^{in}:
a – X_g^{in} = 0.25 kg/kg d.g.; b – X_g^{in} = 0.15 kg/kg d.g.; 1–3 – t_g^{in} = 250 °C; 4–6 – t_g^{in} = 200 °C

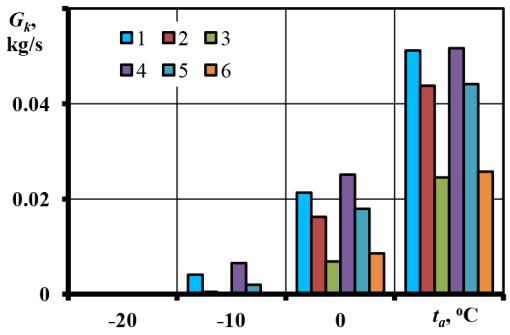

Fig. 6. Dependence condensate consumption G_k of the water heating heat-recovery unit at different temperatures t_g^{in} and moisture content X_g^{in} of waste gases at the inlet on the ambient temperature t_a:

1, 4 – X_g^{in} = 0.25 kg/kg d.g.; 2, 5 – X_g^{in} = 0.2 kg/kg d.g.; 3, 6 – X_g^{in} = 0.15 kg/kg d.g.; 1–3 – t_g^{in} = 250 °C; 4–6 – t_g^{in} = 200 °C

Table 2

Air temperature at the outlet of the air-heating heat-recovery unit depending on the ambient temperature at different inlet temperatures and moisture content of the waste gases

Initial moisture content of waste gases X_g^{in}, kg/kg d.g.	Temperature of heated air t_{air}^{out}, °C at different values of ambient temperature t_a, °C and at different temperatures of waste gases at the inlet t_g^{in}, °C			
	–20	–10	0	10
t_g^{in} = 250				
0.25–0.15	180.9	188.2	196.5	206.8
t_g^{in} = 200				
0.25–0.15	143.0	149.4	156.6	165.2

Table 3

Water temperature at the outlet of the water heating heat-recovery unit depending on the ambient temperature at different inlet waste gas temperatures and moisture content

Initial moisture content of waste gases X_g^{in}, kg/kg d.g.	Water temperature t_w^{out}, °C at different values of ambient temperature t_a, °C and at different temperatures of waste gases at the inlet t_g^{in}, °C			
	–20	–10	0	10
t_g^{in} = 250				
0.25	71.4	61.4	50.2	37.4
0.20	71.4	61.4	50.1	37.1
0.15	71.4	61.3	49.9	36.6
t_g^{in} = 200				
0.25	70.7	60.9	50.0	37.2
0.20	70.7	60.9	49.8	37.0
0.15	70.7	60.8	49.5	36.4

sidered values of the moisture content of waste gases on their temperature indicators in the air heating equipment. According to the performed calculations, only in the water-heating heat-recovery exchanger does the moisture content of gases change during the heat-recovery process. This is explained by the fact that the air heater does not cool the waste gases below their dew point. The condensation mode occurs only in the water heater and only in certain boiler modes. These modes are inherent in relatively small boiler loads, which correspond to positive ambient temperatures in the heating period, under which, according to the considered thermal schedule, the temperature of the return heating network water in the boiler house main decreases below 50 °C.

In accordance with the described operating features of the two types of heat-recovery equipment considered in the complex recovery system, the patterns of changes in their heat productivity are also explained (Fig. 5).

In particular, according to the results of the performed studies, the heat output Q of the air heater is 75–242 kW, and of the water heater 98–158 kW under the conditions of the initial temperature of the waste gases t_g^{in} = 250 °C. The values of Q decrease to 59–196 kW in the air heater and 51–145 kW in the water heater under the conditions of t_g^{in} = 200 °C. Higher values of Q, other things being equal, correspond to boiler loads close to the nominal ones, which are realized at the lowest ambient temperatures during the heating period. Lower values of Q occur at relatively high ambient air temperatures, respectively, at minimum boiler loads.

The graphs shown in Fig. 5 demonstrate that the heat output levels are generally somewhat higher in an air heater than in a water heater. Only in the condensation mode at low boiler loads is the heat output of a water-heating heat-recovery unit higher than that of an air-heating one. The influence of the waste gas moisture content on the Q value occurs, as noted, only in water-heating equipment. According to the results of the studies, the total heat output of the heat-recovery system is at an initial moisture content of X_g^{in} = 0.25 kg/kg d. g. and an initial waste gas temperature of t_g^{in} = 250 °C – 233–341 kW. The Q value at t_g^{in} = 200 °C decreases to values of 203–247 kW. In the case of operating the heat-recovery system at a lower initial moisture content (X_g^{in} = 0.20 kg/kg d. g.), the total heat output of the system also decreases slightly, namely to values of 217–341 kW at an initial waste gas temperature of t_g^{in} = 250 °C and 188–247 kW at a t_g^{in} = 200 °C.

Fig. 6 illustrates the patterns of changes during the heating period in the volume of condensate formed in the water heater of the proposed heat-recovery system. As the results of the research show, under the considered conditions, the volume of G_k of the formed condensate varies within 0.001–0.05 kg/s depending on the boiler mode during the specified period.

The results obtained show that in boiler modes close to nominal (at the lowest ambient temperatures) there is no condensation of water vapor from exhaust gases due to the high temperature of water in the boiler return line ($t_w \approx$ 50–70 °C). Condensation of moisture from gases occurs under conditions of a decrease in the boiler heat output below 77–31 % of the nominal, which corresponds to an ambient temperature $t_a \geq$ –10 °C and a boiler return water temperature below 50 °C. In particular, the minimum value of G_k is 0.01 kg/sat an initial moisture content of waste gases X_g^{in} = 0.25 kg/kg d. g.

and an ambient temperature $t_a = -10$ °C. Under conditions of a decrease in the initial moisture content to values $X_g^{in} = 0.15$ kg/kg d. g. the value of G_k decreases to values of 0.005 kg/s.The largest values of the volume of condensate formed G_k correspond to the lowest boiler loads (approximately 30 %), i.e. at positive atmospheric air temperatures, at which the water temperature in the boiler house return line is the lowest, close to 30 °C. Under these conditions, more intensive condensation of water vapor from combustion products is realized. And the higher the moisture content of these products, the higher the level of condensate formation in the water heater and, accordingly, in the entire heat-recovery system. In particular, at the initial moisture content of waste gases $X_g^{in} = 0.25$ kg/kg d. g. and at the highest temperature of the heating period (+10 °C), the value of G_k reaches a maximum value of – 0.05 kg/s. At a lower value of the initial moisture content of gases ($X_g^{in} =$ = 0.15 kg/kg d. g.), the values of G_k decrease to values of 0.02 kg/s.

As for the temperature values of the heat-transfer agents which heated by heat recovery, the relevant information is given in Tables 2, 3.

As can be seen from the results of the studies presented in the tables, under the considered operating conditions of the waste incineration boiler, the combustion air in the heat-recovery system is heated from –20 to 206.8 °C at the initial temperature of the exhaust gases $t_g^{in} = 250$ °C. A lower level of air heating (from –20 to 165.2 °C) naturally occurs at $t_g^{in} = 200$ °C. At the same time, the return heating network water is heated from 35.1 to 71.4 °C at the values $t_g^{in} = 250$ °C. Lower temperatures of the heated water (from 35.1 to 70.7 °C) correspond to the lower inlet temperature of the waste gases ($t_g^{in} = 200$ °C).

The results of the research presented in Figs. 4–6 and in Tables 2 and 3 concerned the operation of the heat exchange equipment in question in the absence of a layer of contaminants on its heat exchange surface. The work also included research on the influence of the level of dust on the efficiency of waste gas heat recovery. The research was carried out in the range of values of the dust coefficient k from 0.5 to 1. The value of $k = 0.5$ corresponds to a decrease in the heat transfer coefficient of the heat exchange surface of the heat exchanger by half, other things being equal.

Analysis of the results obtained on the influence of dust deposits on the intensity of heat recovery shows that the final temperature of the heated air at values of $k = 0.5$ decreases by 1.3–1.4 times and its minimum value is 96 °C. Under these conditions, the temperature of the waste gases at the outlet of the air heater increases by 1.1–1.2 times to a maximum value of 245 °C. The indicated decrease in the temperature of the heating air and the increase in the final temperature of the waste gases indicates an insufficient level of use of their heat due to dustiness of the heat exchange surface. This indicates the need for forced removal of dust contamination from the heat exchange surface. According to the technical solution of the heat exchanger, cleaning of its working surfaces can be carried out through the corresponding holes with compressed air or other means.

Table 4

Heat productivity of an air-heating heat-recovery unit at different ambient and waste gas inlet temperatures, and at different heat exchange surface contamination coefficients at an excess air coefficient $\alpha = 2.0$

Dustiness coefficient k of the heat exchange surface	Heat productivity of the air heater Q, kW at different values of ambient temperature t_a, °C and at different temperatures of waste gases at the inlet t_g^{in}, °C			
	–20	–10	0	10
$t_g^{in} = 250$				
1.0	193.7	186.7	179.7	172.7
0.7	167.7	161.6	155.5	149.4
0.5	141.6	136.4	131.2	126.1
$t_g^{in} = 200$				
1.0	156.6	149.6	142.6	135.5
0.7	135.7	129.5	123.4	117.3
0.5	114.6	109.4	104.2	99.0

Table 4, for example, shows the results of studies on the dependence of the heat productivity Q of an air-heating heat exchanger on the level of dustiness of heat exchange surfaces according to the coefficient k. The results correspond to different values of the input temperatures of the heat transfer agents (waste gases and combustion air), as well as the ratio of excess air in the waste gases $\alpha = 2.0$.

The results of the performed calculation studies on the influence of dustiness of the heat exchange surface on the efficiency of heat recovery show that under the considered conditions in the process of formation of a dust layer on the heat exchange surface, the value of heat productivity Q decreases from 193.7 to 99.0 kW. And this value is the greater, the lower the level of dustiness of the surface, the lower the inlet temperature of the heated air, the higher the initial temperature of the waste gases and the higher the excess air coefficient.

For example, in the case of $\alpha = 2.5$, the value of Q during the operation of the heat-recovery unit and the corresponding dustiness of the surface decreases to 85 kW. Therefore, to increase the heat efficiency Q, it is necessary to perform periodic cleaning of the working surfaces of the heat-recovery unit. The permissible level of reduction in heat productivity Q, at which it is advisable to carry out forced removal of dust deposits, is determined by the specific operating conditions of the boiler. In particular: the required level of its heat efficiency in a certain period in accordance with the need for heat energy in accordance with the ambient temperature, the required level of final temperatures of the heat transfer agents used, the conditions of technical implementation of the cleaning process, etc. The time period between cleanings depends on the intensity of contamination of the working surface, which in turn depends on the characteristics of the fuel consumed from solid household waste and the operating mode of the heat-recovery units. These factors mainly determine the rate of dusting of the heat exchange surface of the heat-recovery equipment and the possibility of its partial self-cleaning during operation.

Originality. For the first time, a new heat-recovery system with deep cooling of waste gases has been pro-

posed and researched for a heating boiler operating on solid household waste through the use of special air and water heating heat-recovery exchangers designed for operation on dusty gas flows.

Practical value. The proposed technical solutions for heat-recovery units and the obtained research results will be used in the creation of heat-recovery systems for exhaust gases from solid waste incineration plants.

Conclusions. The efficiency of a latest complex heat-recovery system with deep cooling of exhaust gases and the possibility of operation on dusty flue gases, developed for a waste incineration heating boiler, was investigated and analyzed. In particular:

1. The author's technical solutions of the system elements – water and air heating heat-recovery units of panel type, intended for heating the return heating network water and combustion air, are proposed. The design of the heat-recovery units promotes self-cleaning of heat exchange surfaces from dust deposits during operation and provides the possibility of forced removal of these deposits.

2. The regularities of changes in the main thermal indicators (thermal efficiency, temperatures of heated heat transfer agents and volumes of condensate formation) depending on the boiler operating mode during the heating period were determined for the developed heat-recovery system and its elements. It was established that due to the use of the proposed system, deep cooling of waste gases with condensation of steam in a water-heating heat-recovery exchanger is implemented, which is installed after the air-heating exchanger in the course of exhaust gases. It was shown that in the heat-recovery system the temperature of these gases decreases by 120.9–123.3 °C depending on the boiler mode and the initial temperatures and moisture contents of the exhaust gases adopted in the studies.

3. The analysis of the influence of the level of contamination of the heat exchange surface of the air-heating heat-recovery exchangers on the efficiency of waste heat recovery was performed. It was shown that under the conditions of a halving of the heat transfer coefficient of the studied heat exchange surface, the final temperature of the heated air decreases by 1.3–1.4 times. At the same time, the final temperature of the waste gases increases by 1.1–1.2 times. The permissible level of final temperatures at which it is advisable to carry out forced removal of dust contamination is determined by the specific operating conditions of the boiler and the corresponding heat-recovery equipment.

The obtained research results will be used in the creation of heat-recovery units for waste incineration boilers, as well as other solid waste incineration units.

The research results will also be used in educational processes in the training of specialists, bachelors, masters and scientific degrees in the field of heat power engineering and environmental protection.

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Підвищення ефективності використання палива сміттєспалювальних котельних установок

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Мета. Підвищення ефективності водогрійного котла, що працює на твердих побутових відходах, або палив із них.

Методика. Використовувались відомі методики теплового розрахунку теплообмінних апаратів і результати власних експериментальних досліджень теплообміну й аеродинаміки при запилених газових потоках.

Результати. Запропонована для корисного використання скидної теплоти продуктів згоряння установок спалювання побутового сміття й палив на його основі сучасна теплоутилізаційна система із глибоким охолодженням димових газів. Ця система призначена для нагрівання дуттьового повітря й тепломережної води у відповідних теплообмінниках-теплоутилізаторах модульного типу. Розроблені оригінальні технічні рішення цих теплоутилізаторів із можливістю експлуатації на запилених газових потоках. Виконані розрахункові дослідження щодо ефективності застосування вказаної системи. Визначені закономірності зміни основних характеристик системи, а саме: її теплопродуктивності, кінцевих температурних рівнів застосовуваних теплоносіїв та обсягів утворюваного при глибокому охолодженні димових газів конденсату. Рівень зниження температури димових газів у всій теплоутилізаційній системі становить 126,9–197,1 °С. Отже, використання пропонованої системи теплоутилізації та застосовуваного устаткування є ефективним заходом щодо суттєвого підвищення ефективності спалювання твердих побутових відходів і палив на його основі.

Наукова новизна. Уперше запропонована й досліджена для опалювального котла, що працює на твердих побутових відходах, нова теплоутилізаційна система з глибоким охолодженням димових газів завдяки використанню спеціальних повітрой водогрійного теплоутилізаторів, призначених для експлуатації на запилених газових потоках.

Практична значимість. Запропоновані технічні рішення теплоутилізаторів та отримані результати досліджень використовуватимуться при створенні систем рекуперації скидної теплоти димових газів установок спалювання твердих побутових відходів.

Ключові слова: *побутові відходи, утилізація теплоти, теплова ефективність, конденсаційний режим, надійність*