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ANALYSIS OF EFFICIENCY AND RELIABILITY OF BLAST-FURNACE PROCESS WASTE HEAT RECOVERY SYSTEMS

Розглянуто систему утилізації теплоти димових газів доменних повітронагрівачів для підігріву їх повітря горіння. Описані аспекти визначення початкових даних та створення програмно-обчислювального комплексу для розрахунку рекуперативного утилізатора на основі авторської методики. Продемонстровано результати розрахунків при різних початкових параметрах повітря та отримано температурні діаграми поверхні теплообміну, на яких можна виявляти області корозії.

Ключові слова: *доменні повітронагрівачі, продукти згоряння, димові гази, утилізація теплоти, рекуператор.*

1. Introduction

To ensure the blast air heating at blast furnace, the unit, which consists of 3–4 hot blast stoves, is commonly used. Hot blast stoves are regenerative type heat exchangers that filled with checker-works with extended heat transfer surface. These devices work cyclically. During the first operation cycle, named the gas period, in the hot blast stove burner fuel is burned, waste gases pass through checker-work and heat it up. During the next operation cycle, named blast period, cold air passes in the opposite direction, takes away accumulated heat and then enters the blast furnace [1].

The hot blast stoves fuel is the blast furnace top gas, usually enriched by the additives of much higher calorific value, such as natural gas or coke oven gas. These additives are used to improve fuel energy value and rising the temperature under the hot blast stove dome to 1300–1450 °C. At the same time they are highly expensive fuel and energy resources, which consumption can be reduced through the waste heat recovery for the purpose of hot blast stoves combustion components preheating [2].

Development of methods and means of the hot blast stoves waste heat recovery equipment is an actual problem in terms of high cost of fuel and energy resources. In addition, using of heat recovery units is the key of negative effects of industry on the environment decreasing. Precise calculation methods of heat recovery units will improve their reliability and working time.

2. The object of research and its technological audit

The object of research is a hot blast generating system, which consists of three hot blast stoves with a remote combustion chamber and with sequential operation mode. The project temperature under the hot blast stove dome was 1350 °C. Excess air factor: $\alpha = 1{,}08$. The duration of heating cycle (gas period) was 1,83 hours, cooling cycle (blast period) – 1 hour [3].

The mixture of blast furnace top and coke oven gases was considered as fuel for hot blast stoves [4]. Hot blast stove fuel temperature was 50 °C. The compositions of blast furnace top and coke oven gases are contained in Tables 1, 2.

Table 1

Composition of dry blast furnace top gas

Composition of gas in volume ratio, %						Blast furnace top gas water content, g/m^3
CO_2	CO	H_2	N_2	O_2	CH_4	W
21	23	3	53	0	0	50

Table 2

Composition of dry coke oven gas

Composition of gas in volume ratio, %							Coke oven gas water content, g/m^3
CO_2	CO	H_2	N_2	O_2	CH_4	C_mH_n	W
2,6	7,1	58,4	3,2	1	24,8	2,9	50

One of the problem areas of the system is the presence of waste gases discharged after hot blast stoves with temperature 200÷400 °C. This heat can be recycled and used for combustion air or fuel preheating. Using waste gases heat potential, fuel consumption in cost of production and a negative burden on the environment can be reduced.

Though nowadays waste heat recovery systems are operating, but the methods of analysis of their performance, which must be suitable for their design, maintenance or upgrading stages, need for improvement and refinement.

3. The aim and objectives of research

The research aim is an improvement of hot blast stove efficiency via waste gases heat recovery for their combustion components preheating.

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To achieve this aim it is necessary to solve the following problems:

1. Determine the initial data for the calculation of waste heat recovery system.

2. Apply the author's mathematical model and create a software and computer complex for selected exchanger configuration and specified operating conditions.

3. Get a series of calculated results to assess the effectiveness and reliability of the chosen model of recuperative exchanger.

4. Research of existing solutions of the problem

Evaluating the potential of process sites for waste heat recovery is described in [5]. In addition to the above waste gases heat recovery is considered as one of the promising ways to develop the metallurgy industry [6]. 18 units for hot blast stoves waste gases heat recovery were installed in Europe [7]. The procedures and results of the evaluation of the effectiveness of the hot blast stoves waste gases heat recovery system based on the heat pipe heat exangers are described in [8]. Description of designing and analysis of waste heat recovery system, which is also based on using of the heat pipe heat exchangers can be found in [9], at the same time there observed that as hot blast stove waste gases heat recovery units can be used other various heat exchangers. For example, in [10] an application opportunity of compact regenerator as heat recovery unit is observed and calculation of such heat exchanger is provided. The comparative characteristic of miniregenerators with ball and tubular checker–works is performed in [11]. In the source [12] the latest model of the heat pipe heat exchanger is described, and in [13] performed and explored completely new cylindrical heat exchanger, comprising four coaxial tubes, this is a prospect model for waste heat recovery. [14] refers to the ability and efficiency of recuperative heat recovery units application.

Hot blast stove waste heat recovery system in Ukraine was implemented at the first time at the blast furnace number 2 of metallurgical plant «Zaporizhstal» [15]. The system consisted of tubular recuperators, the first of which was used for air preheating, and the second – for hot blast stove fuel preheating via their waste gases heat recovery. But significant drawback system implementation was the lack of air heat exchanger reliability in the winter due to acid corrosion [16]. This indicates the presence of inconsistencies in the design and calculation methods improvement of this kind of equipment. In addition, the investigated sources refer to waste heat recovery systems efficiency, but do not provide accurate algorithms and methods of calculation for hot blast stove waste gases heat recovery systems, used for combustion components preheating.

5. Methods of research

5.1. Determination of initial data. Necessary initial data for hot blast stoves waste gases heat recovery systems calculation include:

– Hot blast stoves block parameters and fuel parameters.
– Regime parameters and composition of waste gases.
– The necessary level of air combustion preheating.
– Characteristics of waste heat recovery heat exchanger.

Hot blast stoves block parameters can be found in item 2.

Percentage of coke oven gas in the fuel mix ranged within 0–16 %. A temperature of combustion air supplied to the hot blast stove was considered for summer and winter periods for climate zone in Ukraine (3 °C, 33 °C).

Based on the methodology provided in [17], fuel combustion in the hot blast stove was calculated and a valid combustion air volume and combustion products value, waste gases composition in fractions of components were received.

Then, knowing the temperature under the hot blast stove dome (1350 °C), the temperature of the fuel (50 °C) and air (3 °C, 33 °C), interdependence of combustion air preheating from the share of coke oven gas in fuel was obtained from the heat balance equation of fuel burning (considered cold and warm period). The method of calculation is presented in [18].

According to obtained data in [18], to provide the necessary calorimetric, and therefore the project, temperature under the hot blast stove dome, fuel with a share of 16 % coke must be burned.

With combustion air preheating, the share of coke oven gas can be reduced to 9–12 %. This requires combustion air preheating in the range of 178–224 °C. Since with combustion air preheating from 3 °C to 176 °C in the winter and from 33 °C to 222 °C in summer, coke oven gas share decreases from 16 % to 11 %. Stop using coke oven gas entirely due to combustion air preheating is not possible, because in this case air-preheating temperature should reach 780–953 °C.

In subsequent calculations considered fuel containing 10–12 % of coke oven gas.

Determination of the temperature and flow rate of waste gases and combustion components was conducted using the program «Regenerator», developed at the Department of Thermal Engineering and Energy Efficient Technologies of the National Technical University «Kharkiv Polytechnic Institute» (Ukraine) [19].

Waste gases temperature after one stove for all fuel composition is alike and ranges from 90 to 400 °C. Fuel consumption, air and waste gases rates for one hot blast stove are given in Table 3.

Table 3

Fuel consumption, air and waste gases rates for one hot blast stove

Coke oven gas share, %	Period	Fuel consumption rate, m^3/hour	Combustion air rate, m^3/hour	Waste gases rate, m^3/hour
10	Summer	74751,47	75274,73	139860,00
	Winter	73632,05	75178,32	139680,00
11	Summer	73906,66	77158,55	140940,00
	Winter	72595,66	76878,80	140400,00
12	Summer	72778,18	78745,99	141408,00
	Winter	71598,17	78543,20	141120,00

As noted above, hot blast stoves are regenerative type heat exchangers and in this case are in sequential mode, and one after another heat the blast air. It means that it necessary to determine the temperature and flow rate of waste gases in common flue. According to the method given in [20] waste gases regime parameters were obtained. Fig. 1 shows the waste gases temperature dependence on time after one hot blast stove and after mixing in common flue. Fig. 2 shows the waste gases rate dependence on time in common flue.

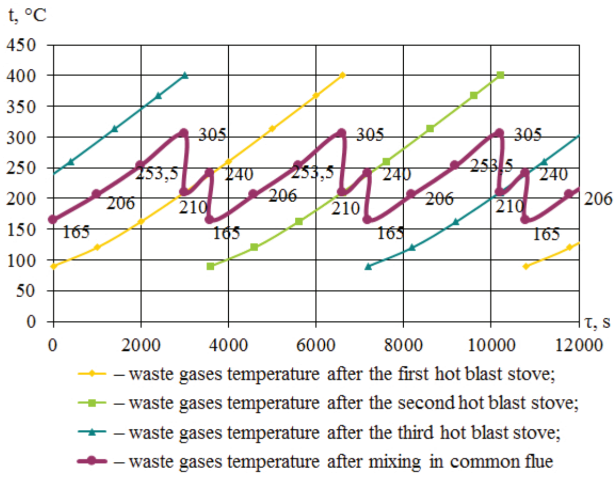

Fig. 1. The hot blast stoves waste gases temperature depending on time: *t* – temperature; τ – time

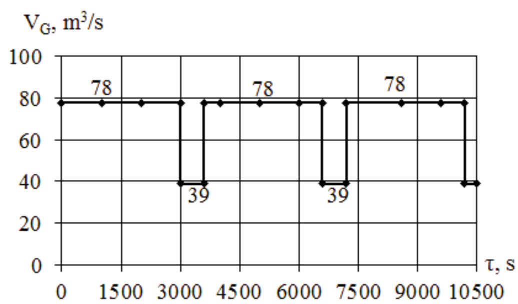

Fig. 2. Waste gases rate depending on time after three hot blast stoves: V_G – rate; τ – time

The average temperature of mixing is defined as the arithmetic mean of reference points of dust–like curve at Fig. 1, for waste gases with coke oven gas share of 11 % was 246 °C. Waste gases rate – 78 m/s.

5.2. Description of heat recovery unit configuration and fundamental principles of the mathematical model for its calculation. Bare-tube heat exchanger with the cross-countercurrent scheme of heat carrier medium movement was selected as the waste heat exchanger from a wide variety of heat exchange equipment, similar to that used at the first time in Ukraine. The heat exchanger is single-passed in the direction of waste gases flow and double-pass in the direction of air flow. The air is fed into the tubes, waste gases – between tubes. Heat exchanger scheme is shown in Fig. 3. Basic geometric characteristics of the surface heat exchanger are:

– outer diameter – 0,040 m;
– pipe wall thickness – 0,0016 m;
– tube spacing in rows – 0,070 m;
– tube raw spacing – 0,040 m;
– length of pipe of one pass – 3,52 m;
– number of tubes along tube nest length – 50;
– number of tubes along tube nest height of one pass – 50.

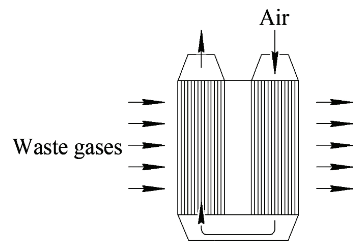

Fig. 3. Scheme of heat exchanger

Method and algorithm for discrete calculation were proposed to simplify the procedure of determining of the effectiveness of heat exchangers with complex mixed heat carrier mediums scheme and uneven distribution of heat transfer and heat interchange parameters [21]. This method assumes that the elements of which exchanger is composed, are simple cross-flow single-pass scheme with full cross-mixing heat carrier mediums in the direction of their movement.

The calculation of each element was conducted by P-NTU-method [22], taking into account the modes motion of heat carrier mediums and basing on a number of dimensionless values, the use of which leads to a reduction of variables, and hence to a more comfortable computing.

Each tube of each section was divided into 10 elements (micro heat exchangers). Calculation scheme is shown in Fig. 4.

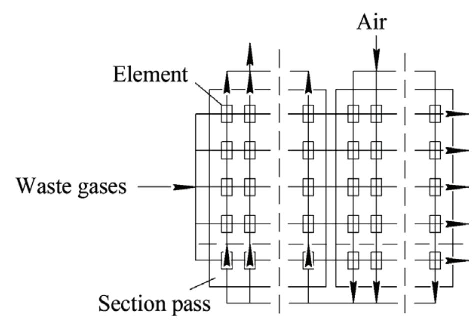

Fig. 4. Calculation scheme

Thermal-physical properties of each component of waste gases and air are usually selected from tables [23]. But for computer calculations it was necessary to determine the functional dependence of thermal-physical parameters of waste gases components and air on temperature. With Excel charts were built thermal properties depending on temperature. Polynomial trend lines were added to them, reflecting the functional dependence of thermal properties on temperature.

In the proposed method effectiveness of each cross-flow element from Fig. 4 (micro heat exchanger) and heat carrier mediums temperatures at the outlet of elements were calculated taking into account the known expression of efficiency [22] for classical cross-flow schematic with full cross-mixing heat carrier mediums:

$$P_{AIR}^{E}=\frac{1}{\dfrac{1}{1-e^{-NTU_2^E}}+\dfrac{R_{AIR}^{E}}{1-e^{-R^E\cdot NTU_2^E}}-\dfrac{1}{NTU_2^E}}. \qquad (1)$$

Temperatures at the outlet of the elements can be found from the equations (2), (3), °C:

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$$t^E_{AIR2} = t^E_{AIR1} + P^E_{AIR}(t^E_{GAS1} - t^E_{AIR1}), \tag{2}$$

$$t^E_{GAS2} = t^E_{GAS1} - P^E_{AIR} \cdot R_{AIR}(t^E_{GAS1} - t^E_{AIR1}). \tag{3}$$

Average temperatures in the element (local), C°:

$$\overline{t}^E_{AIR} = t^E_{AIR1} + \vartheta^E_{AIR} \cdot \left(t^E_{GAS1} - t^E_{AIR1}\right), \tag{4}$$

$$\overline{t}^E_{GAS} = t^E_{GAS1} - \vartheta_{GAS}^E \cdot \left(t^E_{GAS1} - t^E_{AIR1}\right), \tag{5}$$

where ϑ_{AIR}, ϑ_{GAS} – relative average temperatures of air and waste gases in the element respectively:

$$\vartheta_{AIR} = P^E \cdot \left(\frac{1}{1-e^{NTU_2^E}} - \frac{1}{NTU_2^E}\right), \tag{6}$$

$$\vartheta_{GAS} = P^E \cdot \frac{1}{1-e^{-NTU_2^E}}. \tag{7}$$

The number of heat transfer units from air and waste gases sides in accordance with [22]:

$$NTU_2^E = \frac{k \cdot F^E_{AIR}}{W^E_{AIR}}, \tag{8}$$

$$NTU_1^E = \frac{k \cdot F^E_{GAS}}{W^E_{GAS}}, \tag{9}$$

where F^E_{AIR}, F^E_{GAS} – heat transfer area from the side of the heat carrier medium, which is heated, and the heat carrier medium, that heats, m^2; W^E_{AIR}, W^E_{GAS} – heat capacity rate of the heat carrier medium, which is heated, and the heat carrier medium, that heats, J/(s·°C); k – heat transfer coefficient, W/(m^2·°C).

Characteristic parameters R and R were defined by equations:

$$P^E_{AIR} = \frac{t^E_{AIR2} - t^E_{AIR1}}{t^E_{GAS1} - t^E_{AIR1}}, \tag{10}$$

$$R^E_{AIR} = \frac{t^E_{GAS1} - t^E_{GAS2}}{t^E_{AIR2} - t^E_{AIR1}}. \tag{11}$$

It is impossible to make sequential element wise calculation of countercurrent scheme. Therefore refinement occurred simultaneously for all elements and values of temperature and pressure at the inlet of each element and the outlet of the exchanger. The interval-iterative method was applied.

6. Research results

Methodology, algorithms and software products created on the basis of a mathematical model allow to analyze processes in the heat exchanger for hot blast stoves combustion components preheating. Analysis of the effectiveness and reliability of the air preheater was performed at different initial temperatures of supplied air: +2 °C, +8 °C, +14 °C, +20 °C, +26 °C +34 °C.

Blocks of calculation results consisted of the values of final gases and air temperatures, the pipe wall surface temperature from the side of gases and air, the difference between the saturated vapor temperature of gases and wall temperature. These values were obtained for each element, in which heat exchanger was divided.

Based on these values, numerous surface temperature diagram have been built, the most important of them are shown in Fig. 5, 6. There were obtained resulting overall parameters characterizing the performance of the heat exchanger (Table 4).

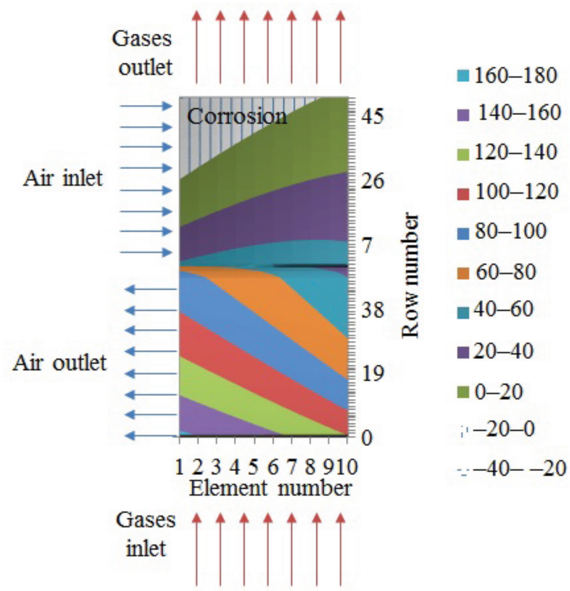

Fig. 5. The difference between the saturated vapor temperature of gases and wall temperature at initial air temperature of 2 °C

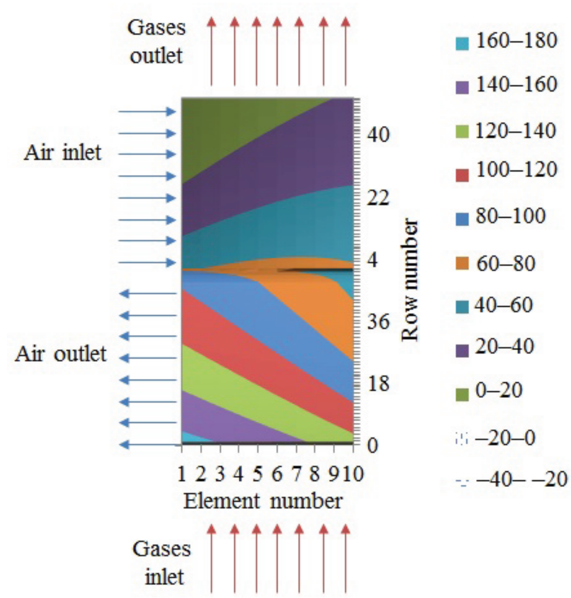

Fig. 6. The difference between the saturated vapor temperature of gases and wall temperature at initial air temperature of 26 °C

The methodology gave an opportunity to determine the temperature distribution in the walls at every point of the heat exchanger surface. Negative difference between the saturated temperature and the outer wall area temperature indicates condensate formation and corrosion of the surfaces in a given location (Fig. 5). The calculations showed that such area is present at values of supplied air temperature from +26 °C and below. Herewith waste gases final temperature was less than 80 °C, corresponding to the known value temperature at which corrosion occurs. The absence of sulfur components in the composition of fuel does not guarantee the absence of corrosion, since dust and impurities can get to the heat exchanger with combustion air.

Table 4

Some common results of calculation

The surface area of heat transfer, m^2	The air temperature at the inlet, °C	The air temperature at the outlet, °C	The gases temperature at the outlet, °C	The average temperature difference of heat carrier mediums, °C	Recovered heat, MJ/hour
2212	2	133,781	62,982	75,081	10575
2212	8	136,613	67,344	73,106	10328
2212	14	139,432	71,711	71,139	10080
2212	20	142,236	76,08	69,18	9833
2212	26	145,022	80,45	67,229	9585
2212	34	148,706	86,272	64,64	9255

As shown in Fig. 5, the area of condensate formation and corrosion of the surface is observed in the first pass in the direction of movement of air and near gases outlet. With supplied air temperature increasing, it decreases and disappears completely at the temperature of 26 °C and above (Fig. 6).

Thus, results of analysis based on using refined mathematical models pointed to the unreliability of the investigated model of heat exchanger. To solve this problem, consider the following options:

1) to preheat air previously in a separate heat exchanger to a temperature above that at which corrosion phenomena occur;

2) to redesign surface and change the heat carrier mediums scheme in the heat recovery unit;

3) to produce pipe nest of entire unit or only the first pass in the direction of air movement from corrosion resistant material such as stainless steel.

7. SWOT analysis of research results

Strengths. Implementation of hot blast stoves waste gases heat recovery systems for preheating of combustion components is energy-saving measure that aims at coke oven gas saving, and thus at reducing the total cost of pig iron production. The created calculation mythologies and recommendations concerning maximization of the heat exchangers efficiency can be used for modernization of waste heat recovery systems at existing hot blast stoves blocks and in the designing of new ones.

Weaknesses. A methodology and software can be used for recovery systems based on using recuperative heat exchangers type only. In addition, the implementation of hot blast stoves waste heat recovery systems requires additional material costs that have to be assessed in terms of payback period.

Opportunities. Updating of the software system will give the opportunity to calculate not only air heat exchanger, but blast furnace top gas heat exchanger too. The aggregate preheating of combustion components is a way to a significant coke oven gas economy and reducing of the payback period of energy-saving measures.

Threats. The risk of recovery system implementation is theoretically possible coke oven gas price reduction, which will increase the payback period of heat recovery system.

In addition, the increasing of blast temperature aimed at coke economy will change blast furnace material balance that will necessitate further research aimed at studying this factor in the context of changing parameters of blast generating system.

8. Conclusions

1. Using the developed methodology, parameters of hot blast stoves block waste gases (see item 5.1) and required combustion air flow rate were calculated. This data were used as initial parameters for the calculation and analysis of the recovery heat exchanger. When calculating the required combustion air preheating temperature was found that the increase in air temperature from 3 C° to 176 °C in winter and from 33 °C to 222 °C in the summer will reduce the share of coke oven gas in fuel from 16 % to 11 %. The methods, algorithms and software for discrete calculation based on the P-NTU-method for multisection bare-tube heat exchanger with the cross-countercurrent scheme of heat carrier medium movement were developed. Blocks of mediums and walls parameters distribution in terms of heat transfer area, result parameters at the heat exchanger outlet (gases temperature, air temperature, the temperature of the pipe wall surface from the side of gases, temperature of the pipe wall surface from the side of the air, difference between saturation vapor temperature in the gases and the temperature of the wall) that allow to analyze the effectiveness and reliability of heat exchanger were obtained.

2. On the basis of obtained data concerning the temperature distribution, areas with corrosion on the heat exchanger surface were detected in various modes. Areas of corrosion pitting occur at an initial air temperature below +26 °C, it made possible to make conclusion about the unreliability of selected modes of performance and heat exchanger design. To improve the reliability of heat recovery system offered a number of solutions, such as heat exchanger redesign, replacement of tube material or previous air preheating to a temperature at which there are no corrosive effects.

3. Developed methods and tools of analysis and synthesis of blast-furnace process waste heat recovery systems take into account the specific of thermal-physical properties distribution on the surface and operating factors and allow to develop new and improve existing systems that reduce fuel production consumption and negative impact on the environment.

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АНАЛИЗ ЭФФЕКТИВНОСТИ И НАДЕЖНОСТИ СИСТЕМ УТИЛИЗАЦИИ СБРОСНОЙ ТЕПЛОТЫ ДОМЕННОГО ПРОИЗВОДСТВА

Рассмотрена система утилизации теплоты дымовых газов доменных воздухонагревателей для подогрева их воздуха горения. Описаны аспекты определения исходных данных и создание программно-вычислительного комплекса для расчета рекуперативного утилизатора на основе авторской методики. Продемонстрированы результаты расчетов при различных начальных параметрах воздуха и получены температурные диаграммы поверхности теплообмена, на которых можно выявлять области коррозии.

Ключевые слова: доменные воздухонагреватели, продукты сгорания, дымовые газы, утилизация теплоты, рекуператор.

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