Utilization of heat from gases leaving the waelz process is a promising way to increase its energy efficiency and environmental safety. Taking into account the gas dustiness, the most rational is the use of a loop air heater, which is a multi-pass and multi-section heat exchanger with a complex mixed scheme of coolant movement. In modern conditions, when the methods and means of calculation of such devices are simplified, the task of obtaining improved methods and means of calculation, determining the efficiency and reliability of their work is relevant.

Two mathematical models of the process of heat transfer and hydroaerodynamics in a multi-pass tubular air heater with a cross-circuit of coolants are used. The developed models for the loop air heater are based on the main methods of thermal calculation: a simpler method of correction factor to the average logarithmic temperature pressure and a discrete P-NTU method, which allows obtaining local thermal characteristics of the surface. Diagrams of distribution of heat transfer coefficients, heat transfer, local temperatures of flue gases, air and pipe walls are constructed. The influence of dust and dust particle size on heat transfer is determined. When the flue gas dust is 50 g/Nm³ and with a dust particle size of 1 µm, the heat transfer coefficient increases by 12 %. The application of the air heater design with different schemes of coolant movement is substantiated.

The developed universal methods allow determining the thermal productivity of heat exchangers and obtaining the distribution of local temperature characteristics on the heating surface. It is also possible to identify places of possible overheating of the heat exchange surface and the course of corrosion processes, taking into account the design of recuperators, operating conditions, operating modes and different schemes of coolant movement

Keywords: loop air heater (heat recovery), P-NTU-method, correction factor method, discrete (interval) calculation, cross-circuit of coolant motion, energy efficiency

IMPROVEMENT OF METHODS FOR CALCULATING THERMAL CHARACTERISTICS OF LOOP AIR HEATERS

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1. Introduction

Energy saving is a strategic task on a national scale [1]. Many companies have significant energy losses due to insufficient use of heat in technological processes. The heat of combustion products is either not used efficiently or not used at all, and high-temperature flue gases are emitted into the atmosphere. This leads to large energy losses in the volume of the enterprise, country, world, and also creates various environmental problems. This is especially true for high-temperature industries (1,000 °C or more), where energy losses are the greatest [2, 3]. The solution to this problem is the heat recovery of gases that leave the technological processes [4–6].

Numerous designs of regenerative air heaters and recuperators are used for the utilization of flue gas heat and air heating [7]. Their use for heating air with flue gases that do not contain dust was mastered many years ago. Problems arise when flue gases are products of technological productions in which a large amount of dust is formed. The processes in which dusty flue gases are formed include: ther- mal processing of solid household and industrial waste, steel smelting in arc and ferroalloy furnaces, waeltz processes, combustion of pulverized coal fuel and fuel with high ash content. The release of high-temperature gases with significant dust into the environment is prohibited.

The development of heat exchange equipment for the utilization of heat from gases with a significant concentration of dust prone to sticking, and methods for its calculation is an urgent task for a number of industries and environmental safety.

2. Literature review and problem statement

The recycling of waste containing heavy and non-ferrous metals is an important environmental aspect. For a long time, a large amount of waste from metallurgical production is stored in the sludge storages of specialized enterprises. Such wastes contain toxic components that have a negative impact on the environment. A number of technologies have been developed that involve the extraction of non-ferrous metals from

sludge. In particular, known patents of Russia RU 2280087, USA (19) (11) 6083295, Europe (19) (11) EP 0972849A1 and others. These technologies do not provide for the utilization of flue gases. High-temperature combustion products with a temperature of more than 500 °C are released into the atmosphere. Also, environmental safety is not observed due to the lack of utilization of harmful gaseous and dusty waste generated during the processing of sludge. Flue gases with significant dust are emitted into the environment. The high temperature does not allow directing gases on gas cleaning.

Employees of the heat and gas treatment department of UkrSTC "Energostal" developed the design of a loop air heater. The recuperator is four sections of pipes that hang freely from the pipe grids (Fig. 1), allowing shaking to clean the heating surface from dust. The installation of an air heater after the waeltz furnace as part of the equipment at the stage of the basic project on the work "Creation of production of utilization of intermediate products containing metal" is provided [8].

The main feature of the developed technology is the use of the original design of the loop air heater, which eliminates the shortcomings of similar complexes and raises it to a new level of application in the world.

Loop recuperators are widely used in metallurgy, energy, mechanical engineering, utilities (Fig. 1).
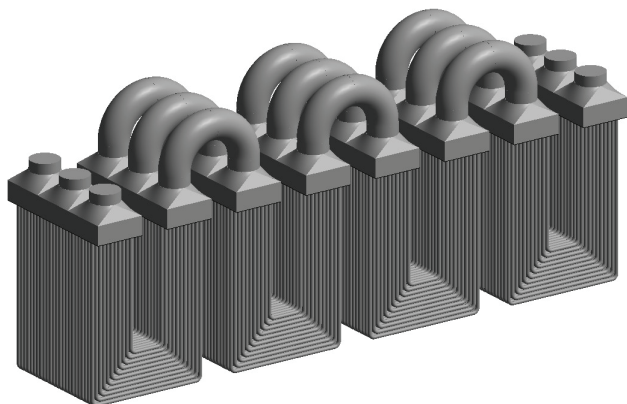

Fig. 1. 3D view of a tubular loop four-section air heater

Heat exchangers of this design have a mixed scheme of movement of heat carriers, where each course (section) is a complex scheme of cross-flow [9]. To calculate the temperature pressure in multi-pass heat exchangers, the method of correction factor to the average logarithmic temperature pressure at countercurrent (Ψ) is mainly used [10]. Dependencies for the correction factor are given in the form of graphs and nomograms, which are inconvenient to use in modern calculations. The intensity of heat transfer included in the calculations is averaged, which does not allow taking into account its local distribution and some features of the surface layout. This leads to significant errors in determining the average temperature pressure and the required surface area. Many variants of the solution by the method of correction factor to the average logarithmic temperature pressure are given in [11, 12].

To determine the performance of heat exchangers with the transverse motion of heat carriers in [13], a matrix approach is proposed, which is characterized by flexibility and can be used directly to calculate the temperatures of heat carriers between elements and rows of pipes.

The authors of [14–16] extend heat exchangers to a number of disk and simple single-pass "modified" transverse heat exchangers, in which the hot heat carrier moves and the cold one does not, taking into account their physical authorities.

In [17, 18], heat exchangers with complex cross-movement of heat carriers are considered, the formulas for calculating thermal characteristics and efficiency of which are described by simple systematized forms, for which an exact or approximate solution can be obtained. Also, examples of calculation of complex configurations of heat exchangers are given.

It is advisable to obtain more accurate and advanced methods and tools for research and analysis of multi-pass heat exchangers, which are loop air heaters.

3. The aim and objectives of the study

The aim of the study is to improve methods for calculating the thermal characteristics of the loop air heater for heat recovery of gases with a significant concentration of dust prone to sticking.

To achieve the aim, the following objectives were set:

– to analyze the influence of surface layout on the heat transfer process based on the method of correction factor;

– to analyze the influence of dustiness of gases and the size of dust particles on heat transfer using the method of correction factor;

– to identify areas of surface overheating and areas where corrosion will occur on the heating surface depending on the operation mode of the recuperator and its layout based on the discrete *P-NTU* method.

4. Materials and methods of research of thermal characteristics of loop air heaters

4. 1. Analysis of the design of loop air heaters and the choice of methods of thermal calculation

The design of a 4-section loop air heater with the cross-mixed movement of coolants allows calculations of the entire heat exchanger and each loop section or element. It is possible to create different schemes of coolant movement: direct flow (Fig. 2, *a*), countercurrent (Fig. 2, *h*) and combined (Fig. 2, *b–g*).

The scheme of movement of heat carriers in the air heater is complex mixed, where each course (section) is a complex scheme of cross-movement. The intertube coolant moves in separate jets along the entire length and does not mix between strokes. The tubular coolant moves in separate jets within one stroke, is completely mixed between the sections, and within the loop moves in separate jets. Each section consists of two moves.

The development of more advanced methods makes it possible to analyze the efficiency of both newly designed and existing heat exchangers, taking into account operational factors (pollution, corrosion and erosion wear, contact thermal resistances, etc.) and to optimize.

When using the *P-NTU* method, the heat transfer surface is broken down into individual elements in one go. The flow of dusty flue gases is directed into the intertube space, changing only the direction and order of the sections along which the air moves.
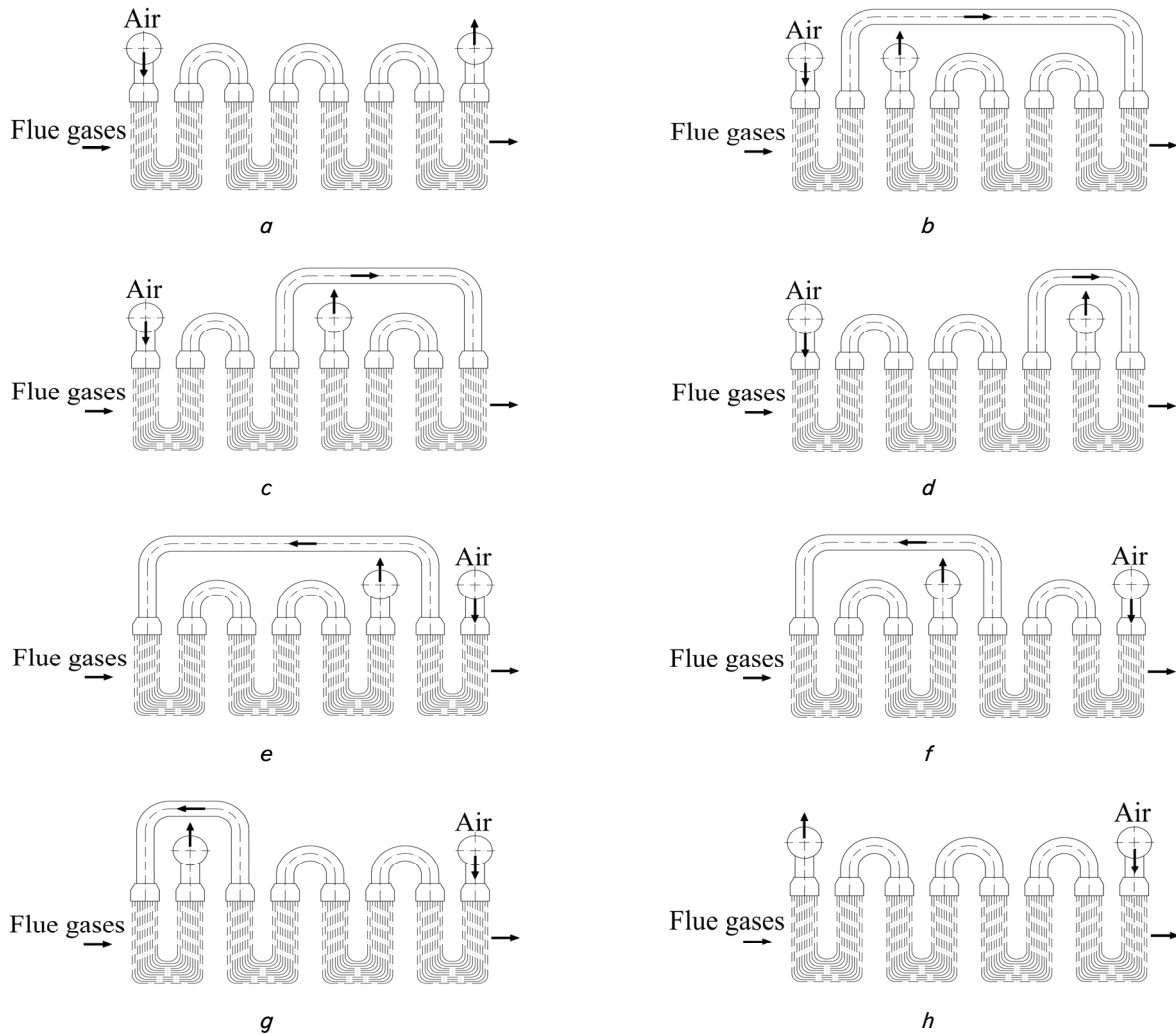
Fig. 2. Layout diagrams of the loop recuperator: *a* — direct flow; *b* — «1 direct flow - 3 countercurrent»; *c* — «2 direct flow — 2 countercurrent»; *d* — «3 direct flow - 1 countercurrent»; *e* — «1 countercurrent — 3 direct flow»; *f* — «2 countercurrent — 2 direct flow»; *g* — «3 countercurrent — 1 direct flow»; *h* — countercurrent

Taking into account the peculiarities of the design of loop air heaters, mathematical modeling of the heat transfer process and hydroaerodynamics is expediently carried out on the basis of two main methods of calculating recuperators: *P-NTU* method and correction factor method. Each method has its own characteristics, areas of application, advantages and disadvantages.

4. 2. Development of a mathematical model of a loop air heater based on the method of correction factor

The calculation by the method of correction factor is analytical and is carried out according to the recommendations [19] by successive calculations.

Solutions for increasing the convenience of application of modern engineering and practical calculations are offered. It is extremely inconvenient to use tables, graphs and nomograms in automated calculations.

In the recommendations [19], the functional dependences for the correction coefficient to the average logarithmic temperature pressure (Ψ), the correction to the heat transfer coefficients (C), the correction coefficients q_A, q_{FG} for calculating the heat content of flue gases and air, thermophysical characteristics of heat carriers are obtained.

The developed program allows carrying out thermal calculations of various designs of heat exchangers for many cases of their operation [20]. In it, you can set the following source data depending on the case:

– to carry out thermal calculations of various heating surfaces taking into account design features;

– to perform calculations for different heat carriers;

– to take into account the dust content of coolants and the size of dust particles.

The mathematical model of heat transfer in the recuperator is described by energy equations taking into account the initial conditions [21, 22]:

$$Cp_1 \cdot \rho_1 \cdot \left[\frac{\partial t_1}{\partial \tau} + \omega_{1X} \frac{\partial t_1}{\partial x} \right] =$$
$$= \frac{k(x, \tau)z(x)}{S_1(x)} \big[t_2(x, \tau) - t_1(x, \tau) \big], \qquad (1)$$

$$Cp_2 \cdot \rho_2 \cdot \left[\frac{\partial t_2}{\partial \tau} + \omega_{2X} \frac{\partial t_2}{\partial x} \right] =$$
$$= \frac{k(x, \tau)z(x)}{S_2(x)} \big[t_1(x, \tau) - t_2(x, \tau) \big], \qquad (2)$$

$$t_1(x,\,0)=A(x),\;\; t_2(x,\,0)=B(x), \tag{3}$$

where ρ_1, ρ_2 – coolant densities, kg/m^3; t_1, t_2 – coolant temperatures, °C; ω_1, ω_2 – heat carrier velocities, m/s.

Since the loop air heater is a structure with complex flows of coolants relative to each other, the model type (1)–(3) can be used as a model of modular elements.

The average temperature pressure $\overline{\Delta t}$ is defined as, °C:

$$\overline{\Delta t} = \psi \cdot \frac{\Delta t_2 - \Delta t_1}{\ln \dfrac{\Delta t_2}{\Delta t_1}}, \tag{4}$$

where Δt_1 – temperature pressure at the inlet to the air heater, $\Delta t_1 = t_{FG2} - t_{A1}$, °C; Δt_2 – temperature pressure at the outlet of the air heater, $\Delta t_2 = t_{FG1} - t_{A2}$, °C.

The correction factor Ψ to the average logarithmic temperature pressure is determined using a nomogram depending on the dimensionless parameters P and R and the number of strokes in the air heater n_S [19]. As noted, the corresponding nomogram was approximated and analytical representations of finding the correction factor Ψ were obtained.

Dimensionless parameters P and R are defined as:

$$P = \frac{t_{A2} - t_{A1}}{t_{FG1} - t_{A1}}, \tag{5}$$

$$R = \frac{t_{FG1} - t_{FG2}}{t_{A2} - t_{A1}}. \tag{6}$$

A detailed description of the calculation is given in [9, 19].

The mathematical model of the loop air heater based on the method of correction factor allows identifying the influence of different schemes of the loop air heater on the thermal characteristics and analyzing the influence of dust and dust particle size on heat transfer.

4. 3. Development of a mathematical model of a loop air heater based on the *P-NTU* method

The discrete *P-NTU* method is interval and is based on a number of dimensionless quantities, the use of which leads to a reduction in variables and more convenient calculations. This method takes into account the distribution of local temperature differences in the device. The initial system of equations of the mathematical model includes:

– heat balance and heat transfer equations for elementary areas (elements) of the surface;

– equations that take into account the peculiarities of the movement and connection of the flow of coolants, in particular, the number of rows of pipes in the section;

– schemes of combination of sections;

– schemes of coolant movement;

– taking into account mixing or not mixing of coolant flows.

The solution of the system of equations is complex, accompanied by iterations, recurrent calculation of integral transformations.

The discrete *P-NTU* method allows taking into account the nature of coolant movement. The intertube coolant is almost completely immiscible. The tubular coolant is mixed only in the transitions between successive sections, and in the transition from one course to another within the loop is not mixed.

To simplify the search for solutions of equations, the method of discrete (interval) calculation is used, where the elements of

which the heat exchanger is composed (Fig. 3) are the simplest schemes of single cross-flow with complete mixing of both coolants along the way. Rows for the flow of internal coolant can be multi-pass, there is a three-dimensional case [23].
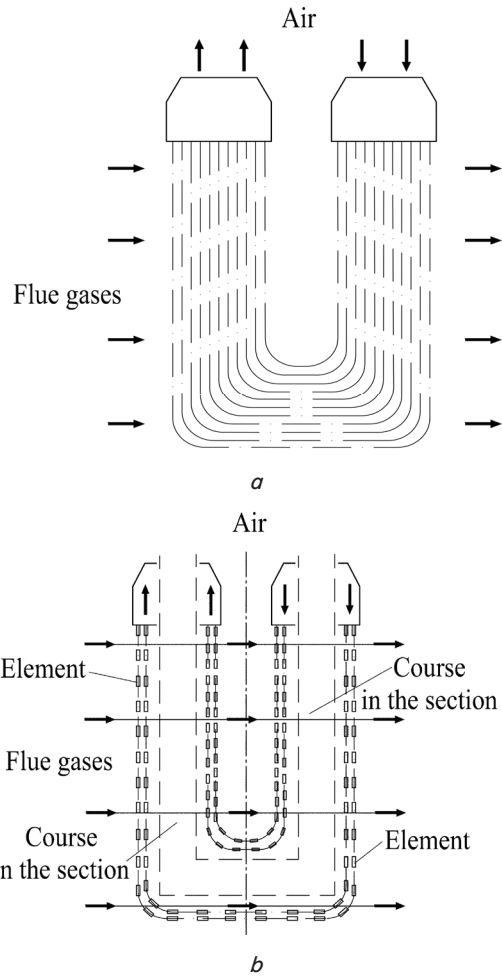
Fig. 3. Scheme of one section of the loop heat recovery unit: *a* — construction; *b* — calculation scheme

Each tube in one move *z* is divided into 10–20 elements (15 were accepted). The numbering of the elements begins with the direction of coolant movement in the pipe, also numbered rows of pipes *i*. The calculation scheme takes the form as in Fig. 3.

The method of correction factor is used to obtain the distribution of air temperatures, flue gases and heating surface only for the entire air heater or a separate loop section. In contrast, the results of the discrete *P-NTU* method are the distribution of air temperature, gases, pipe wall, the difference between the temperature of the outer wall and the vapor saturation temperature of the gases in each course with the division of the heat transfer surface into elements. The method developed by the authors allows taking into account any number of jets in the coolant and the factor of their mixing.

The efficiency of each cross-flow element from Fig. 3 and the temperature of the coolant at the outlet of the elements [12, 23]:

$$P_e = \frac{1}{\dfrac{1}{1-e^{-NTU_{2e}}} + \dfrac{R_e}{1-e^{-R_e \cdot NTU_{2e}}} - \dfrac{1}{NTU_{2e}}}, \tag{7}$$

$$t_{A2e} = t_{A1e} + P_e \cdot \left(t_{A1e} - t_{A1e}\right), \tag{8}$$

$$t_{FG2e} = t_{FG1e} + P_e \cdot R_e \cdot \left(t_{FG1e} - t_{FG1e}\right), \tag{9}$$

where «e» – the index that indicates that the parameters are defined in the element; «1, 2» – input and output of coolants, respectively; R – the ratio of water equivalents (heat consumption) of coolants:

$$R = \frac{C_A}{C_{FG}}; \tag{10}$$

NTU_2 – number of heat transfer units, which refers to the heated air [24]:

$$NTU_2 = \frac{k \cdot F}{C_A}, \tag{11}$$

k – heat transfer coefficient, W/m^2·°C; F – heat transfer area, m^2.

When compiling the algorithm for solving the system of equations (7)–(9) for each element of Fig. 3, the scheme of mutual connection and mixing of the heat carrier between courses and at an exit from the device is considered. The efficiency (degree of heating) of each element is determined taking into account the mixing at the outlet of the elements of the last stroke of the last section (7), the difference in properties of coolants and pipe wall materials, parameters characterizing heat transfer.

The use of the *P-NTU* method eliminates the use of empirical dependencies for calculation (except for dependences for heat transfer). The correction factor for temperature pressure is determined by the formula:

$$\psi = \frac{\Delta t_{mean}}{\Delta t_l} = \frac{1}{NTU_2 \cdot \delta}, \tag{12}$$

$$\delta = \frac{R-1}{\ln \dfrac{1-P}{1-PR}} \left(R \neq 1\right), \tag{13}$$

$$\delta = \frac{1-P}{P} \left(R = 1\right). \tag{14}$$

Some partial solutions for multi-pass circuits are based on the results [10]. For the scheme, where the tubular coolant moves in a single jet, the general formula has the form:

$$P = \frac{1}{R} \cdot \left(1 - \frac{1}{A}\right), \tag{15}$$

where A – the parameter that depends on the number of moves.

The mathematical model of the loop air heater based on the *P-NTU* method makes it possible to identify areas where corrosion will occur on the heating surface depending on the operation mode of the recuperator and its layout.

4. 4. Input data for calculations

Calculations were performed for a four-section tubular loop air heater with a pipe diameter of 89 mm and a heat transfer surface area of 2337.5 m^2. The initial temperature of dusty flue gases is 800 °C, the inlet air temperature is 12.6 °C with a relative humidity of 40 %.

Calculations based on the method of correction factor were performed for 8 layout schemes of the loop air heater

and allow determining the effect of dust and dust particle size on heat transfer.

Calculations based on the P-NTU method are performed for the countercurrent circuit and allow the detection of the area of corrosion of the heating surface.

5. Results of calculations of thermal characteristics of the loop air heater

5. 1. Influence of different layout schemes of a loop air heater on thermal characteristics

The calculation of the loop air heater based on the method of correction factor to the average logarithmic temperature pressure is carried out for 8 layout schemes.

It was found that the highest temperature of air heating is reached at the countercurrent scheme (Fig. 2, *h*). At the outlet of the recuperator, the air temperature is t_{A2}=482.46 °C. The flue gases are cooled to t_{FG2}=73.79 °C. The wall temperature in the first loop section is t_W=479.66 °C, which exceeds the operating temperature of carbon steel St20 t_{St20}=420 °C.

The lowest temperature of air heating is observed in the countercurrent scheme (Fig. 2, *a*). At the outlet of the recuperator, the air temperature is t_{A2}=326.1 °C. The flue gases are cooled to t_{FG2}=326.45 °C. The wall temperature of the pipes in the first loop section is t_W=370.7 °C.

When arranging the recuperator according to the scheme «1 direct flow – 3 countercurrent» (Fig. 2, *b*), the air is heated to t_{A2}=341.2 °C, and the flue gases are cooled to t_{FG2}=303.4 °C, the wall temperature in the first section is t_W=370.4 °C.

When arranging the recuperator according to the scheme «2 direct flow – 2 countercurrent» (Fig. 2, *c*), the air is heated to t_{A2}=327.4 °C, and the flue gases are cooled to t_{FG2}=324.2 °C, the wall temperature in the first section is t_W=370.4 °C.

When arranging the recuperator according to the scheme «3 direct flow – 1 countercurrent» (Fig. 2, *d*), the air is heated to t_{A2}=326.2 °C, and the flue gases are cooled to t_{FG2}=326.2 °C, the wall temperature in the first section is t_W=370.4 °C.

When arranging the recuperator according to the scheme «1 countercurrent – 3 direct current» (Fig. 2, *e*), the air is heated to t_{A2}=411.5 °C, and the flue gases are cooled to t_{FG2}=193.4 °C, the wall temperature in the first section is t_W=449.1 °C.

When arranging the recuperator according to the scheme «2 countercurrent – 2 direct current» (Fig. 2, *f*), the air is heated to t_{A2}=454.3 °C, and the flue gases are cooled to t_{FG2}=123.9 °C, the wall temperature in the first section is t_W=490 °C, in the second t_W=458.13 °C.

When arranging the recuperator according to the scheme «3 countercurrent – 1 direct flow» (Fig. 2, *g*), the air is heated to t_{A2}=476.3 °C, and the flue gases are cooled to t_{FG2}=87.5 °C, the wall temperature in the first section is t_W=520.4 °C.

Overheating of the pipe material is in places where the wall temperature exceeds the maximum operating temperature of carbon steel St20 t_{St20}=420 °C.

5. 2. Analysis of the influence of dust and dust particle size on heat transfer

Based on the results of the recuperator calculation by the method of correction factor to the average logarithmic temperature pressure, graphs are constructed that show the effect of flue gas dust on heat transfer coefficients (Fig. 4) and heat transfer in percent, flue gas temperature,

air and pipe walls. The calculation took into account the dust content of flue gases of 50 g/Nm^3 and without dust. The size of dust particles from 1 μm to 50 μm was set.

Heated dust particles to a temperature above 500–700 °C begin to glow and radiate more heat to the heating surface. Due to the increase of the heat transfer coefficient by radiation, the total heat transfer coefficient from the flue gases side and the total heat transfer coefficient, which determines the amount of heat transferred, will increase. The total heat transferred from the flue gases to the air, with a constant heat transfer area, affects the temperature of air heating and cooling of the flue gases. The smaller the particle size of the dust and the higher the concentration of dust in the gases, the higher the temperature of the heated air and the lower the temperature of the flue gases at the outlet of the heating surface.
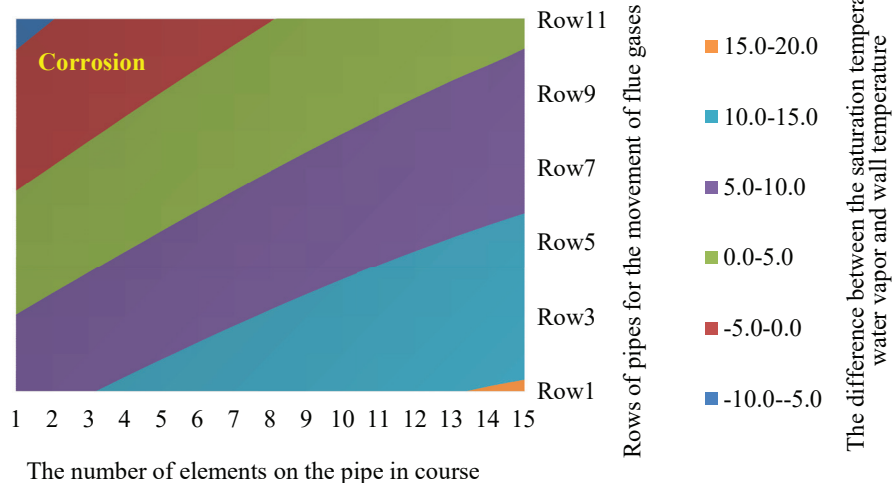

Fig. 5. Detection of the area of corrosion in the last course of the air heater

The method of discrete calculation was also tested for air cooling devices, heaters, air coolers, compressors, heat exchangers of heat supply and heating systems [23].
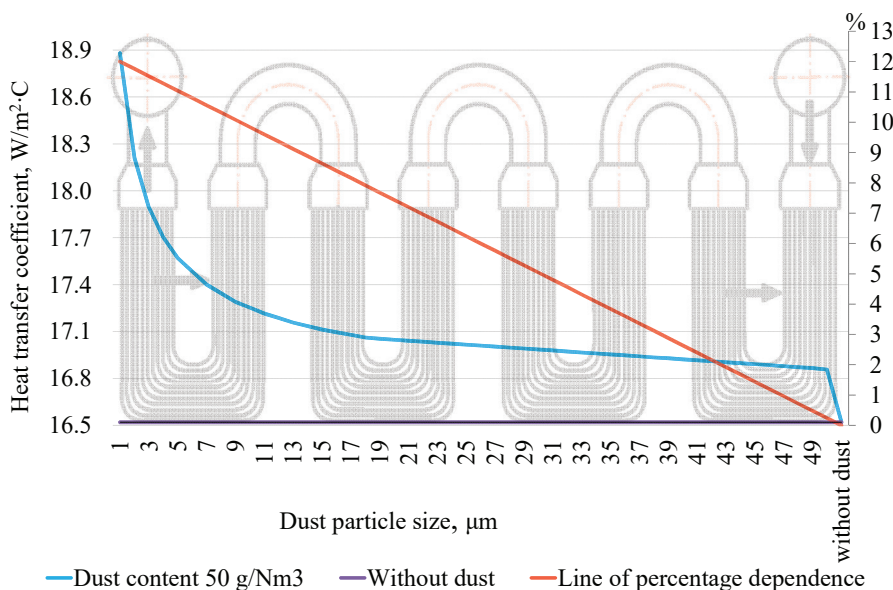

Fig. 4. Influence of dust and dust particle size on heat transfer coefficient in percent

The method of correction factor was tested for boilers, recovery boilers, superheaters, economizers, air heaters.

5. 3. Detection of the area of corrosion of the heating surface

Discrete calculation of the recuperator using the *P-NTU* method allows identifying areas where corrosion will occur on the heating surface.

Based on the calculation for the countercurrent flow of coolants, the air is heated to 550 °C, the gases are cooled to 52 °C. Under these conditions, in the first course of the air movement and the last in the movement of gases, there is an area where corrosion will occur. Depending on the operation mode of the recuperator, the corrosion area is transformed or disappears (Fig. 5).

Similar calculations were made for other parameters of coolants and surface size.

6. Discussion of the results of calculation of thermal characteristics of loop air heaters

The results of calculations of the parameters *P* and Ψ based on the *P-NTU* method from equations (7)–(9), (12)–(15) were compared with nomograms from [10, 12, 19, 24], which were developed based on the float method coefficient.

Fig. 6 compares the results of the calculation of the correction factor by the analytical (continuous curve) and discrete (intermittent curve) method for two sections (four strokes of air).

The practical coincidence of the parameters *P* and Ψ is noted. The error in the calculations is in the range of the correction factor Ψ from 0 to 0.5 and is 5–7 %, which indicates the reliability of the developed mathematical models and the efficiency of the applied methods and algorithms.

The main disadvantage of the calculation of heat exchangers by the method of correction factor compared to the *P-NTU* method – they are integrated (designed for the device as a whole). Due to this factor, the intensity of heat transfer is averaged in the calculations, and thus does not take into account its local distribution and some features of the surface layout. All this leads to a small difference in the obtained values and errors in determining the average temperature pressure and the required surface area.

When calculating by the correction factor to the average logarithmic temperature pressure, the original mathematical model is more maneuverable, allows you to change the initial data and perform thermal calculations of different heating surfaces (recuperative and regenerative) taking into account

design features (for various schemes of movement of heat carriers) in a shorter time.

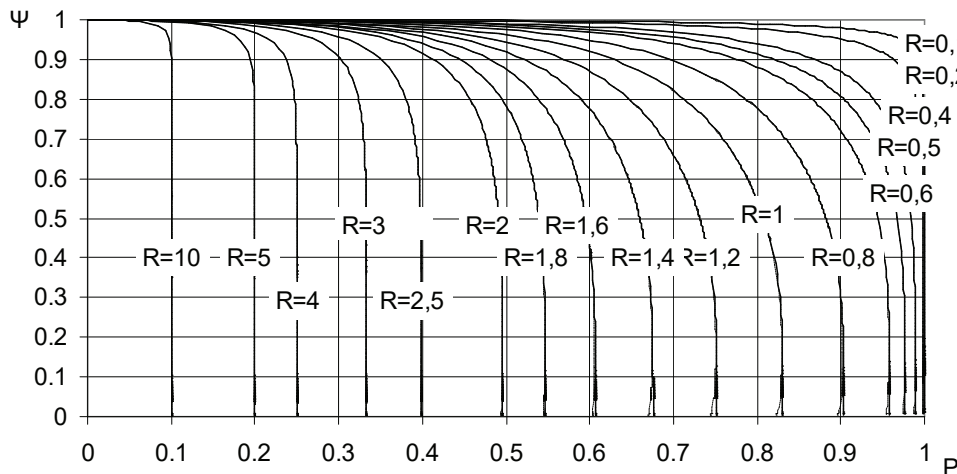The *P-NTU* method is limited to the use of cross-flow heat exchangers.

Fig. 6. Comparison of calculation results by the developed methods

carriers affect the thermal characteristics in the air heater. With the countercurrent scheme, it is possible to reach the highest temperature of air heating to 482.46 °C, and the temperature of flue gases decreases to 73.79 °C. In the direct-flow scheme, the heating temperature of the air is the lowest 326.1 °C, and the flue gases are cooled to 326.45 °C. The temperature characteristics of the combined circuits are intermediate between direct current and countercurrent. The places of possible overheating of the heat exchange surface were revealed, taking into account the design of the recuperator.

2. Based on the method of correction factor, the influence of dust and dust particle size on heat transfer is analyzed. It is determined that when the flue gas dust content is $50 \, \text{g/Nm}^3$ with a dust size of $1 \, \mu\text{m}$, the heat transfer coefficient increases by 12 %. Diagrams of distribution of coefficients on the heating surface of heat transfer coefficients, heat transfer, local temperature characteristics of flue gases, air and pipe walls are constructed.

3. Calculations based on the *P-NTU* method allow the detection of the area of corrosion on the heating surface. The area where corrosion will occur is located in the fourth section by the movement of flue gases (7–11 rows of pipes). The movement of air in the area is in the first course of the loop section.

Further development of the study can be aimed at developing mathematical models for other designs of recuperative heat exchangers with cross-movement of coolants.

7. Conclusions

1. Calculations based on the method of correction factor were performed for 8 layout schemes of the loop air heater and it was found that different schemes of movement of heat

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