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The heat-transfer system modelling of the convective heating surfaces of a TP-92 steam boiler

Abstract: The relevance of the subject of research is determined by the need to develop and subsequently implement a mathematical model and the corresponding structural scheme of the convective heating surfaces of the TP-92 steam boiler. The purpose of this research work is to directly model the heat-transfer system of the convective heating surfaces of this boiler, designed for effective use in real conditions. The basis of the methodological approach in the research work is a combination of methods of the system analysis of the key principles of constructing mathematical models of heat-transfer systems of modern steam boilers with an experimental study of the prospects for creating a mathematical model of a heat-transfer system of the convective heating surfaces of a TP-92 steam boiler.

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In the course of the study, the results were obtained and presented in the form of a mathematical model of a convective heat-transfer system. It allows for making effective mathematical calculations of the main operating modes of the TP-92 steam boiler and calculating the dependences of the temperature and thermal modes of its operation on the change of incoming parameters of the used heat carriers, changes in the heating surface area and the relative flow rate of the heat carriers over the time of their use. The results obtained in the study, including the conclusions formulated on their basis, are of significant practical importance for the designers of steam boilers. The results also are useful for maintenance personnel, whose immediate responsibilities include determining the real possibilities of improving the convective heat-transfer system, based on the known parameters of the temperature of the coolant at the entrance to the system and at the exit from it.

KEYWORDS: mathematical model, flue gases, coolant temperature, heat-transfer system, surface temperature regime

Introduction

During the operation of the main technological equipment of the thermal power plant, and the research and commissioning of thermal power equipment, it is necessary to periodically determine the degree of influence on the modes of operation of the equipment of the current changes in the mode of its operation and the main performance indicators of various units and units of this equipment (Sparrow et al. 2016). In some cases, it is necessary to solve interrelated regime tasks. In particular, it concerns working situations related to changes in the main regime operational indicators of the functioning of thermal power equipment, and changes in the temperature of heat carriers at the entrance to the system and at the exit from it (Galyanchuk and Kravets 2020). In this context, it may sometimes be necessary to perform a number of routine tasks related to the need to determine the most likely causes of the development of deviations of the main temperature indicators from those nominally stated at the design and debugging stage of the technological equipment of modern thermal power plants (Balaji et al. 2020).

There are tasks associated with involving the consistent establishment of specific indicators that are significant from the standpoint of determining the main operating modes of thermal power equipment. The solution of such regime tasks is traditionally carried out experimentally, using equipment of a specific type (Zaporozhets et al. 2021). In certain cases, practical experiments are associated with significant technological difficulties. They are conditioned upon the high cost of technological equipment used during the experiment and the significant complexity and high cost of the main experimental studies conducted (Redko and Redko 2021). All of the above can be rightfully attributed to steam boilers of type TP-92, with an estimated capacity of 150 MW, which is equipped with the Dobrotvorskaya TPP. The practical application of a number of techniques, both project, and design, including some mathematical calculations, raises doubts about their complex effectiveness in solving a number of typical tasks. Such calculations are conditioned upon the mandatory use of a significant amount of information for this, which can be very difficult to obtain and is explained by the significant technological deterioration of the equipment used (Galyanchuk et al. 2015). In addition, the actual conditions for the practical use of this technological equipment may significantly differ from those that were originally laid down when drawing up an approximate plan for the implementation of a technical project (Sheikholeslami and Ganji 2017). These factors explain the need for the consistent development of special methods of mathematical calculations sufficient for the qualitative determination of key parameters of regime dependencies and involving the use of minimal amounts of available information for this purpose (Mysak et al. 2016). The results of the practical application of such computational mathematical models are undergoing a stage of generalization and systematization. It is necessary to carry out some improvements that can give the results a convenient form from the standpoint of subsequent practical application (Zhang et al. 2016).

In this study, the practical task is to consistently develop a specific mathematical model, and the corresponding structural scheme of convective heating surfaces of a steam boiler of type TP-92, with the aim of the subsequent practical application of the results obtained. It is important to ensure high accuracy of the parameters of technological regime calculations and studies of this type of heating surfaces, and this fully applies to individual nodes of thermal exchange and to their entire totality in structural interaction. In the course of this study, it is first of all necessary to determine the dependence of the power parameters of heat carriers transmitted between individual technological nodes with the temperature values at the entrance to the heat exchange surface and at the exit from it. The parameters of heat transfer losses and temperature changes of convective heat exchange surfaces are also evaluated. The main information practically used in the process of creating this mathematical model is parameters of the temperature of the heat carriers at the entrance to the system under study and at the exit from it with a known, established mode of operation of the heat exchange surfaces. At the same time, the absolute values of the heat exchange surface area and the volume of consumption of the used heat carriers can remain unchanged.

1. Materials and methods

The methodological approach in this research work is based on a combination of methods of system analysis of the key principles of constructing mathematical models of heat-transfer systems of modern steam boilers. The presented approach is associated with an experimental study of the prospects for creating a mathematical model of a heat-transfer system of convective heating surfaces of a TP-92 steam boiler. A schematic diagram of the heat-transfer system of convective heating surfaces of a TP-92 type steam boiler is presented with an indication of all the main subsystems, the basic mathematical equations of the key elements of heat transfer. The averaged parameters of the key elements of heat transfer are also given. The theoretical basis of this research is the development of Ukrainian and a number of foreign authors who have studied the problematic issues of creating mathematical models of heat-transfer systems of the convective surfaces of steam boilers. The practical application of these models for calculating the basic parameters of the functioning of heating surfaces of modern steam boilers was also in the interest of the scientists (Vakkilainen 2016). This study was carried out in several stages. At the first stage of the research, a theoretical base was prepared, intended for the direction of the main research works. In addition, at this stage of research, based on this database, a systematic analysis of the key principles of constructing mathematical models of the heat-transfer systems of modern steam boilers was carried out. This was of fundamental importance from the standpoint of subsequent research. The main operating factors that cause changes in temperature parameters at the entrance to the subsystems of the steam boiler and at the exit from them and the peculiarities of changes in the reliability and efficiency of the operation of the steam boiler depending on these factors were investigated.

At the next stage of this study, an experimental study of the prospects for creating a mathematical model of the heat-transfer system of the convective heating surfaces of the TP-92 steam boiler was carried out. The steam boilers with an estimated capacity of 150 MW, which are equipped with Dobrotvorskaya TPP, were adopted as an experimental model. The initial information, which is of key importance for the qualitative creation of the desired mathematical model, is presented in the form of a schematic diagram of a heat-transfer system of the convective heating surfaces of a steam boiler of type TP-92. This diagram includes a display of the main subsystems that collectively make up the convective heating surface of a steam boiler. The computational mathematical model is created in several main stages, in compliance with the necessary sequence of displaying the results. The key operating coefficients of the mathematical model of the heat-transfer system of the convective surface of the boiler of the type under consideration are presented in the corresponding tables. The final equations describe the relationship of the temperatures of the elements of the model of the heat-transfer system of the convective heating surfaces of the steam boiler are given. In addition, at this stage of the research, an analytical comparison of the results was performed with the results and conclusions of related studies of problematic issues of constructing mathematical models of heat-transfer systems of the convective surfaces of steam boilers, including that which is related to the stated subject of this study (Zhang et al. 2021). At the final stage of the research, based on the obtained results, final conclusions were formulated describing the computational capabilities obtained as a result of the development of the desired mathematical model. This serves as a final display of the results and also summarizes the entire research.

2. Results and discussion

A key feature of an effective convective heat-transfer system is the technological possibility of a sequential passage through any of the subsystems of flue gases that perform the function of the main heating coolant. At the same time, steam, air, and water can be used as heated heat carriers. Each of the subsystems has two inputs and two outputs for the heat carriers used. In the event that the solution of a key regime problem involves the need to solely determine the relationships, and the mutual influence of the functioning subsystems, each of the subsystems used, if necessary, can be replaced by a heat exchanger. Such an exchanger should be selected in accordance with the parameters of the original mode. It is important to note that the mentioned exchange will be possible in a case in which there is no analysis of direct current changes in the subsystems themselves. The temperature parameters at the inlet and outlet of such a heat exchanger should be similar to the corresponding values of the temperatures of entry into and exit from the subsystem. A typical diagram of the heat-transfer system of convective heating surfaces of the type TP-92 steam boiler is shown in Figure 1.

Figure 1 schematically shows:

- A – air heater,
- B – water economizer,
- C – intermediate superheater,
- D – screens of the rotary chamber.

From the diagram shown in Figure 1, it follows that there is a significant impact of the operating and object parameters in the air heater exclusively on the temperature parameters at the entrance to this object and at the exit from it. At the same time, these parameters, including their

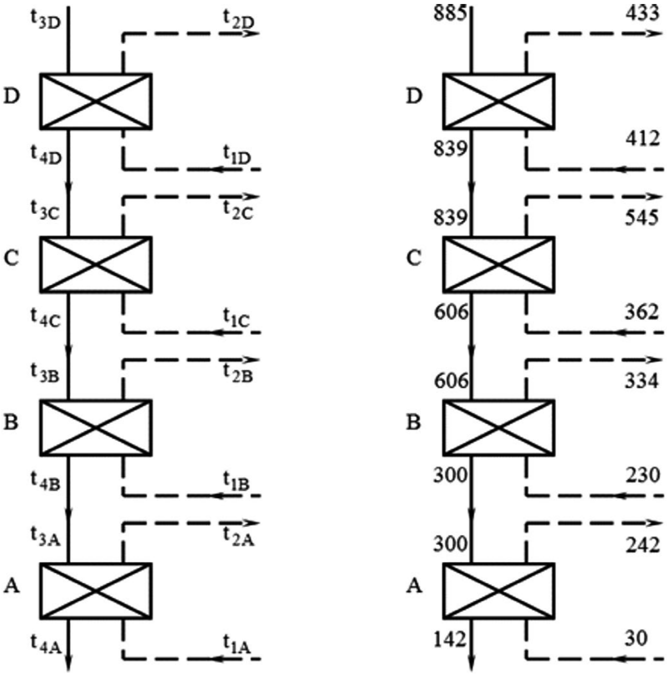

Fig. 1. Schematic diagram of the heat-transfer system of convective heating surfaces of a type TP-92 steam boiler

Rys. 1. Schemat ideowy układu wymiany ciepła konwekcyjnych powierzchni grzewczych kotła parowego typu TP-92 changes, have no effect on the objects presented in this diagram as B, C, and D (water economizer, intermediate superheater, and screens of the rotary chamber). Current changes in the key parameters in the secondary superheater have a direct impact on temperature changes at its inlet and on changes in the temperature parameters in objects B and A. There is no significant effect on the temperature regime in object D. The current changes in the operating and object parameters in the screens of the rotary chamber have a direct effect on the parameters of the coolant temperature at the inlet to it. The parameters of the coolant temperature at the inlet to the intermediate superheater and temperature changes in all other subsystems are also influenced by them. The mathematical model of the scheme of the heat-transfer system of the convective heating surfaces of the TP-92 steam boiler assumes mandatory calculation of the operating coefficients of the primary state of the system. The equation of the key elements of the heat-transfer system is as follows:

$$t_{2n} = (1 - W_{2n}) \cdot t_{1n} + W_{2n} \cdot t_{3n}; \; t_{4n} = (1 - W_{4n}) \cdot t_{1n} + W_{4n} \cdot t_{3n} \qquad (1)$$

where n is {A, B, C}.

The equation of the connection of the specified elements of the heat-transfer system is:

$$t_{3C} = t_{4d}; \; t_{3B} = t_{4C}; \; t_{3A} = t_{4B} \qquad (2)$$

The averaged parameters of the key elements of the heat-transfer system have the form:

$$W_{2n} = (t_{2n} - t_{1n})/(t_{3n} - t_{1n}); \; W_{4n} = (t_{4n} - t_{1n})/(t_{3n} - t_{1n}) \qquad (3)$$

The calculation of the key parameters of the operating coefficients of the heat-transfer system of convective heating surfaces of a TP-92 type steam boiler for the primary state of the system can be represented as: for the screen of the rotary camera (subsystem D): $W_{2D} = (433 - 412)/(885 - 412) = 0.0444$; $W_{4D} = (839 - 412)/(885 - 412) = 0.9027$. For the secondary superheater (subsystem C): $W_{2C} = (545 - 362)/(839 - 362) = 0.3836$; $W_{4C} = (606 - 362)/(839 - 362) = 0.5115$. For the water economizer (subsystem B): $W_{2B} = (334 - 230)/(606 - 230) = 0.2766$; $W_{4B} = (300 - 230)/(606 - 230) = 0.1862$. For the air heater (subsystem A): $W_{2A} = (242 - 30)/(300 - 30) = 0.7852$; $W_{4A} = (142 - 30)/(300 - 30) = 0.4148$. In general, the mathematical model of the heat-transfer system of the convective heating surfaces of the TP-92 steam boiler can be represented as follows:

$$t_{in} = K_{in1A} \cdot t_{1A} + K_{in1B} \cdot t_{1B} + K_{in1C} \cdot t_{1C} + K_{in1D} \cdot t_{1D} + K_{in3D} \cdot t_{3D} \qquad (4)$$

$$Dt_{in} = K_{in1A} \cdot \Delta t_{1A} + K_{in1B} \cdot \Delta t_{1B} + K_{in1C} \cdot \Delta t_{1C} + K_{in1D} \cdot \Delta t_{1D} + K_{in3D} \cdot \Delta t_{3D} \qquad (5)$$

Here, i is the index of the outgoing flow (“2”, “4”) in a particular subsystem; n is the name of the subsystem (A, B, C, D); 1A is the index of the incoming flow of subsystem A; 1B, 1C, 1D, 3D are similar indicators for other subsystems; K is the mode coefficient. The mathematical model of the heat-transfer system of convective surfaces of the TP-92 steam boiler can be presented in the following form:

The mathematical model of the screen of the rotary camera (subsystem D) is:

$$\begin{gathered} t_{2D} = (1 - W_{2D}) \cdot t_{1D} + W_{2D} \cdot t_{3D}; \\ t_{4D} = (1 - W_{4D}) \cdot t_{1D} + W_{4D} \cdot t_{3D} = t_{3C} \end{gathered} \tag{6}$$

The mathematical model of the intermediate superheater (subsystem C) is:

$$\begin{gathered} t_{2C} = (1 - W_{2C}) \cdot t_{1C} + W_{2C} \cdot t_{3C} = \\ = (1 - W_{2C}) \cdot t_{1C} + W_{2C} \cdot [(1 - W_{4D}) \cdot t_{1D} + W_{4D} \cdot t_{3D}] = \\ = (1 - W_{2C}) \cdot t_{1C} + W_{2C} \cdot (1 - W_{4D}) \cdot t_{1D} + W_{2C} \cdot W_{4D} \cdot t_{3D}; \end{gathered} \tag{7}$$

$$\begin{gathered} t_{4C} = (1 - W_{4C}) \cdot t_{1C} + W_{4C} \cdot t_{3C} = \\ = (1 - W_{4C}) \cdot t_{1C} + W_{4C} \cdot [(1 - W_{4D}) \cdot t_{1D} + W_{4D} \cdot t_{3D}] = \\ = (1 - W_{4C}) \cdot t_{1C} + W_{4C} \cdot (1 - W_{4D}) \cdot t_{1D} + W_{4C} \cdot W_{4D} \cdot t_{3D} = t_{3B} \end{gathered}$$

The mathematical model of the water economizer (subsystem B) is:

$$\begin{gathered} t_{2B} = (1 - W_{2B}) \cdot t_{1B} + W_{2B} \cdot t_{3B} = \\ = (1 - W_{2B}) \cdot t_{1B} + W_{2B} \cdot [(1 - W_{4C}) \cdot t_{1C} + W_{4C} \cdot [(1 - W_{4D}) \cdot t_{1D} + W_{4D} \cdot t_{3D}]] = \\ = (1 - W_{2B}) \cdot t_{1B} + W_{2B} \cdot (1 - W_{4C}) \cdot t_{1C} + W_{2B} \cdot W_{4C} \cdot \\ \cdot (1 - W_{4D}) \cdot t_{1D} + W_{2B} \cdot W_{4C} \cdot W_{4D} \cdot t_{3D}; \\ \\ t_{4B} = (1 - W_{4B}) \cdot t_{1B} + W_{4B} \cdot t_{3B} = \\ = (1 - W_{4B}) \cdot t_{1B} + W_{4B} \cdot [(1 - W_{4C}) \cdot t_{1C} + W_{4C} \cdot [(1 - W_{4D}) \cdot t_{1D} + W_{4D} \cdot t_{3D}]] = \\ = (1 - W_{4B}) \cdot t_{1B} + W_{4B} \cdot (1 - W_{4C}) \cdot t_{1C} + W_{4B} \cdot W_{4C} \cdot (1 - W_{4D}) \cdot \\ \cdot t_{1D} + W_{4B} \cdot W_{4C} \cdot W_{4D} \cdot t_{3D} = t_{3A} \end{gathered} \tag{8}$$

The mathematical model of the air heater (subsystem A) is:

$$\begin{gathered} t_{2A} = (1 - W_{2A}) \cdot t_{1A} + W_{2A} \cdot t_{3A} = = (1 - W_{2A}) \cdot t_{1A} + W_{2A} \cdot \\ \cdot [(1 - W_{4B}) \cdot t_{1B} + W_{4B} \cdot [(1 - W_{4C}) \cdot t_{1C} + W_{4C} \cdot [(1 - W_{4D}) \cdot t_{1D} + W_{4D} \cdot t_{3D}]]] = \\ = (1 - W_{2A}) \cdot t_{1A} + W_{2A} \cdot (1 - W_{4B}) \cdot t_{1B} + W_{2A} \cdot W_{4B} \cdot (1 - W_{4C}) \cdot t_{1C} + \\ + W_{2A} \cdot W_{4B} \cdot W_{4C} \cdot (1 - W_{4D}) \cdot T_{1D} + W_{2A} \cdot W_{4B} \cdot W_{4C} \cdot W_{4D} \cdot t_{3D}; \\ \\ t_{4A} = (1 - W_{4A}) \cdot t_{1A} + W_{4A} \cdot t_{3A} = (1 - W_{4A}) \cdot t_{1A} + W_{4A} \cdot \\ \cdot [(1 - W_{4B}) \cdot t_{1B} + W_{4B} \cdot [(1 - W_{4C}) \cdot t_{1C} + W_{4C} \cdot [(1 - W_{4D}) \cdot t_{1D} + W_{4D} \cdot t_{3D}]]] = \\ = (1 - W_{4A}) \cdot t_{1A} + W_{4A} \cdot (1 - W_{4B}) \cdot t_{1B} + W_{4A} \cdot W_{4B} \cdot (1 - W_{4C}) \cdot t_{1C} + \\ + W_{4A} \cdot W_{4B} \cdot W_{4C} \cdot (1 - W_{4D}) \cdot T_{1D} + W_{4A} \cdot W_{4B} \cdot W_{4C} \cdot W_{4D} \cdot t_{3D} \end{gathered} \tag{9}$$

When compiling a mathematical model of the heat-transfer system of the convective heating surfaces of the TP-92 steam boiler, the parameter of the mode coefficient K_{in} of this mathematical model is of particular importance (Table 1).

The main parameters of this coefficient are presented in Table 2. They are presented depending on temperature conditions and are of key importance from the standpoint of constructing the desired mathematical model.

TABLE 1. Operating coefficients K_{in} models of the heat-transfer system of the convective heating surfaces of the TP-92 boiler

TABELA 1. Współczynniki pracy K_{in} modeli układu wymiany ciepła konwekcyjnych powierzchni grzewczych kotła TP-92

t_{in}	K_{in1A}	K_{in1B}	K_{in1C}	K_{in1D}	K_{in3D}
t_{2D}	0	0	0	$1 - W_{2D}$	W_{2D}
t_{4D}	0	0	0	$1 - W_{4D}$	W_{4D}
t_{2C}	0	0	$1 - W_{2C}$	$W_{2C} \cdot (1 - W_{4D})$	$W_{2C} \cdot W_{4D}$
t_{4C}	0	0	$1 - W_{4C}$	$W_{4C} \cdot (1 - W_{4D})$	$W_{4C} \cdot W_{4D}$
t_{2B}	0	$1 - W_{2B}$	$W_{2B} \cdot (1 - W_{4C})$	$W_{2B} \cdot W_{4C} \cdot (1 - W_{4D})$	$W_{2B} \cdot W_{4C} \cdot W_{4D}$
t_{4B}	0	$1 - W_{4B}$	$W_{4B} \cdot (1 - W_{4C})$	$W_{4B} \cdot W_{4C} \cdot (1 - W_{4D})$	$W_{4B} \cdot W_{4C} \cdot W_{4D}$
t_{2A}	$1 - W_{2A}$	$W_{2A} \cdot (1 - W_{4B})$	$W_{2A} \cdot W_{4B} \cdot (1 - W_{4C})$	$W_{2A} \cdot W_{4B} \cdot W_{4C} \cdot (1 - W_{4D})$	$W_{2A} \cdot W_{4B} \cdot W_{4C} \cdot W_{4D}$
t_{4A}	$1 - W_{4A}$	$W_{4A} \cdot (1 - W_{4B})$	$W_{4A} \cdot W_{4B} \cdot (1 - W_{4C})$	$W_{4A} \cdot W_{4B} \cdot W_{4C} \cdot (1 - W_{4D})$	$W_{4A} \cdot W_{4B} \cdot W_{4C} \cdot W_{4D}$

TABLE 2. Key parameters of the operating coefficient K_{in} depending on temperature indicators

TABELA 2. Kluczowe parametry współczynnika eksploatacyjnego K_{in} w zależności od wskaźników temperatury

T_{in}	K_{in1A}	K_{in1B}	K_{in1C}	K_{in1D}	K_{in3D}
T_{2D}	0	0	0	0.9556	0.0444
T_{4D}	0	0	0	0.0972	0.9028
T_{2C}	0	0	0.6164	0.0373	0.3463
T_{4C}	0	0	0.4885	0.0497	0.4618
T_{2B}	0	0.7234	0.1351	0.0138	0.1277
T_{4B}	0	0.8138	0.0909	0.0093	0.0860
T_{2A}	0.2148	0.6390	0.0714	0.0073	0.0675
T_{4A}	0.5852	0.3376	0.0377	0.0038	0.0357

The key relationship of the model elements of the heat-transfer system of the convective heating surfaces of the TP-92 steam boiler in accordance with the equations of the system (4) has the form:

- For the air heater (subsystem A):

$$\begin{aligned} t_{2A} &= 0.2148 \cdot t_{1A} + 0.6390 \cdot t_{1B} + 0.0714 \cdot t_{1C} + 0.0073 \cdot t_{1D} + 0.0675 \cdot t_{3D}; \\ t_{4A} &= 0.5852 \cdot t_{1A} + 0.3376 \cdot t_{1B} + 0.0377 \cdot t_{1C} + 0.0038 \cdot t_{1D} + 0.0357 \cdot t_{3D} \end{aligned} \tag{10}$$

- For the water economizer (subsystem B):

$$\begin{aligned} t_{2B} &= 0 \cdot t_{1A} + 0.7234 \cdot t_{1B} + 0.1351 \cdot t_{1C} + 0.0138 \cdot t_{1D} + 0.1277 \cdot t_{3D}; \\ t_{4B} &= 0 \cdot t_{1A} + 0.8138 \cdot t_{1B} + 0.0909 \cdot t_{1C} + 0.0093 \cdot t_{1D} + 0.0860 \cdot t_{3D} \end{aligned} \tag{11}$$

- For the secondary superheater (subsystem C):

$$\begin{aligned} t_{2C} &= 0 \cdot t_{1A} + 0 \cdot t_{1B} + 0.6164 \cdot t_{1C} + 0.0373 \cdot t_{1D} + 0.3463 \cdot t_{3D}; \\ t_{4C} &= 0 \cdot t_{1A} + 0 \cdot t_{1B} + 0.4885 \cdot t_{1C} + 0.0497 \cdot t_{1D} + 0.4618 \cdot t_{3D} \end{aligned} \tag{12}$$

- For the screen of the rotary camera (subsystem D):

$$\begin{aligned} t_{2D} &= 0 \cdot t_{1A} + 0 \cdot t_{1B} + 0 \cdot t_{1C} + 0.9556 \cdot t_{1D} + 0.0444 \cdot t_{3D}; \\ t_{4D} &= 0 \cdot t_{1A} + 0 \cdot t_{1B} + 0 \cdot t_{1C} + 0.0972 \cdot t_{1D} + 0.9028 \cdot t_{3D} \end{aligned} \tag{13}$$

The interdependence of temperature changes in the heating surfaces of the elements of the heat-transfer system of the convective heating surfaces of the type TP-92 steam boiler under consideration in accordance with equation (5) has the form:

$$\begin{aligned} \Delta t_{2A} &= 0.2148 \cdot \Delta t_{1A} + 0.6390 \cdot \Delta t_{1B} + 0.0714 \cdot \Delta t_{1C} + 0.0073 \cdot \Delta t_{1D} + 0.0675 \cdot \Delta t_{3D}; \\ \Delta t_{4A} &= 0.5852 \cdot \Delta t_{1A} + 0.3376 \cdot \Delta t_{1B} + 0.0377 \cdot \Delta t_{1C} + 0.0038 \cdot \Delta t_{1D} + 0.0357 \cdot \Delta t_{3D}; \\ \Delta t_{2B} &= 0 \cdot \Delta t_{1A} + 0.7234 \cdot \Delta t_{1B} + 0.1351 \cdot \Delta t_{1C} + 0.0138 \cdot \Delta t_{1D} + 0.1277 \cdot \Delta t_{3D}; \\ \Delta t_{4B} &= 0 \cdot \Delta t_{1A} + 0.8138 \cdot \Delta t_{1B} + 0.0909 \cdot \Delta t_{1C} + 0.0093 \cdot \Delta t_{1D} + 0.0860 \cdot \Delta t_{3D}; \\ \Delta t_{2C} &= 0 \cdot \Delta t_{1A} + 0 \cdot \Delta t_{1B} + 0.6164 \cdot \Delta t_{1C} + 0.0373 \cdot \Delta t_{1D} + 0.3463 \cdot \Delta t_{3D}; \end{aligned} \tag{14}$$

$$\Delta t_{4C} = 0 \cdot \Delta t_{1A} + 0 \cdot \Delta t_{1B} + 0.4885 \cdot \Delta t_{1C} + 0.0497 \cdot \Delta t_{1D} + 0.4618 \cdot \Delta t_{3D};$$

$$\Delta t_{2D} = 0 \cdot \Delta t_{1A} + 0 \cdot \Delta t_{1B} + 0 \cdot \Delta t_{1C} + 0.9556 \cdot \Delta t_{1D} + 0.0444 \cdot \Delta t_{3D};$$

$$\Delta t_{4D} = 0 \cdot \Delta t_{1A} + 0 \cdot \Delta t_{1B} + 0 \cdot \Delta t_{1C} + 0.0972 \cdot \Delta t_{1D} + 0.9028 \cdot \Delta t_{3D}$$

Thus, using the created mathematical model of the heat-transfer system of convective heating surfaces of the TP-92 steam boiler, it is possible to determine the nature of the change in the temperature of the gases at the outlet depending on the change in the temperature of the air at the inlet to the air heater. When the cold air temperature parameter drops by 15°C ($\Delta t_{1A} = -15$°C), there is a decrease in the temperature of the exhaust gases by 8.78°C ($\Delta T_{4A} = -8.78$°C). In the event that by the same value ($\Delta t_{3D} = 15$°C) the temperature of flue gases at the entrance to the heat-transfer system increases, there is an increase in the temperature of gases at the exit from the heat-transfer system by 0.54°C ($\Delta t_{4A} = 0.54$°C). According to the results obtained during experimental studies of the functioning of the TP-92 steam boiler superheater, the error between the calculated model indicators and the data obtained directly during the experiment was 2.7%. Recently, in order to ensure the high quality of technological heat supply to various production facilities that operate under conditions of variable or intermittent load, ram-flow steam boilers are increasingly used in practice. Additionally, such boilers are used in the case of insufficient benefit of disposing of the steam boilers in hot reserve, and in cases where excessively frequent technological shutdowns and restarts become necessary (Xu et al. 2020). Steam boilers are placed in close proximity to the end user, which allows for consistently reducing heat loss during steam transportation to the minimum possible values. There is an additional opportunity to expand the functional purpose of individual key elements of a steam boiler, which are of no small importance from the standpoint of providing additional safety measures for its practical use.

The functioning of steam boilers of small sizes is ensured by the method of forced circulation. Therefore, to ensure the full functioning of these devices, a consistent clarification of the mutual influence of regime and design features is required. In particular, along the steam-water path, it is necessary to determine the corresponding heat supply to the heating surface to its volume per unit of time which is required for the same period of time for in order to qualitatively heat the feed water to a temperature several degrees below the boiling point, with its further boiling, including evaporation on the evaporation surface (Laubscher and Rousseau 2019). Steam boilers which are currently installed at modern thermal power plants can be divided into three main types: direct-flow boilers, boilers with forced and natural circulation. Direct-flow boilers have become the most widespread among the units of the first group. At the same time, the main differences between the boilers of these two types lie in the features of the device of the evaporation surface (Zainullin and Galyautdinov 2016).

The energy sector is the basis of the security of any modern state, the main task of which is the uninterrupted supply of energy to citizens in an amount that meets their daily needs. Moreover, the quality of the energy supplied and the maximum efficiency of its receipt should be given paramount importance. In the energy sector, significant savings in financial resources can be achieved by improving the technology of energy production, transmission, and conversion. In general, this also contributes to the more rational use of available natural resources (Panov et al. 2015). In this context, the improvement of modern technological devices for industrial heat exchange is of key importance in improving modern energy production technologies for their subsequent practical application to meet the urgent needs of the population. The principles used to date for calculating heat exchange processes in furnaces and convective heating surfaces of steam boilers are often generally empirical in nature. As a result, the final accuracy of calculating heat exchange parameters reduced significantly. This results in significant deviations from the design parameters directly during the operation of steam boilers and heat exchangers. The result is often that a large amount of time is spent on further adjustment of boiler units (Baubekov et al. 2018). The mathematical generalization of the results of debugging the thermal modes of operation of modern steam boilers clearly indicates that the key factor that has a direct impact on reducing the reliability of their operation is the high level of maximum heating temperatures of the convective surfaces of the steam boiler, including the high temperatures of combustion products. The high level of maximum heating temperatures of the convective surfaces of the steam boiler often leads to the failure of these units. These factors often become the main cause of the formation of metal corrosion which occurs when a high burning temperature is reached, the rupture of radiation pipes, and the occurrence of a number of other problems with the integrity of the boiler equipment used.

Many modern boiler houses are equipped with steam boilers that perform the function of providing steam to functioning industrial plants and heating workshops. At the same time, when industrial enterprises are idle, there is a significant decrease in the need for the generated steam, which limits its further use to only heating. Most often, steam in water-type heaters is used to prepare a network heating system and is also used in steam heating systems. In such cases, it is recommended to carry out a series of measures aimed at improving the efficiency of the use of steam boilers, and the accumulated practical experience allows us to conclude that these measures, subject to a significant increase in the profitability of the boiler house, pay off within a period not exceeding one and a half years (Medyanin et al. 2018). Reducing the temperature of the exhaust gases reduces the overall level of heat loss in the boiler room conditioned upon the need to isolate the surface of the boiler chimney. An increase in the efficiency of steam boilers can be achieved by gradually switching them to a hot-water mode, while the mains water can be heated directly in the boiler itself. Measures of this kind should be implemented at the same time and systematically with the forces of specific, responsible organizations, or a boiler company upon receipt of all necessary recommendations. Modern boiler houses are complex technological systems in which the process of obtaining steam or hot water takes place by burning various types of fuel. Steam boilers are the most important industrial facilities of modern boiler houses, they are successfully used in power units of thermal power plants, as well as in thermal centers of industrial facilities (Sakar 2016). Steam boilers and functional boiler equipment have their own characteristic features peculiar to complex energy systems. The criterion of reliability of steam boilers is an integral criterion of their operation, which is of key importance from the standpoint of the efficiency of the use of steam boilers. During a given service life of boiler equipment, the reliability criterion of a steam boiler is considered as its ability to maintain all the specified functions that are required for high-quality compliance throughout this period with all established operating modes, operational conditions, and technical conditions.

Managing the functioning of complex modern technological systems presupposes the presence of some uncertainty in the initial data, system parameters, and unclear goals and management tasks. Managing the operation of a steam boiler is a kind of fuzzy task, the qualitative solution of which requires the objective consideration of a whole set of parameters that are of fundamental importance from the standpoint of the final provision of the efficiency of the boiler unit. At the same time, the preparation of a qualitative mathematical model of individual steam boiler systems and the relationship with various parameters is essential from the standpoint of ensuring the reliability of operation and compliance with all specified standards of operational use. These steps are of key importance from the standpoint of ensuring the reliable functioning of the boiler unit throughout its operational life (Khan et al. 2021). Modeling the heat-transfer system of convective heating surfaces of a steam boiler is of key importance from the point of view of assessing the safety of the operational use of boiler units and increasing their service life in general. The creation of a mathematical model describing all the key features of the functioning of the quality of the flow of the processes of thermal conductivity, convection, and heat exchange on various parts of the heating surfaces of boiler units is extremely important. It enables the qualitative determination of the main operating parameters that are important from the point of view of the efficiency of the use of a steam boiler and an estimate of the estimated period of its operational use (Milicevic et al. 2021). In this context, the accuracy of the created model and its ability to consider all the features of the flow of the technological process is crucial.

The durability, reliability, and economic efficiency of the operation of steam boilers are largely determined by the amount of scale that forms on the heating surfaces of the steam boiler throughout its operational use (Duroudier 2016). Depending on the specific parameters of thermal conductivity, the occurrence of a scale with a thickness of several millimeters can lead to a significant increase in the temperature of the pipe walls, which in the future can cause them to burn out. Another consequence of this phenomenon may be increased fuel consumption during the operation of a steam boiler, which in some situations can reach 5–6% of the nominal value as determined by the technical conditions of operation. The operation of steam boilers for a long time inevitably leads to the development of scale directly on the convective heating surfaces, which in the future leads to premature wear of boiler equipment and boiler failure before the deadline. Carrying out high-quality and timely mathematical modeling of the heat-transfer system of the convective heating surfaces of a steam boiler in combination with regular prevention can prevent the development of these negative consequences and contribute to an increase in the period of the trouble-free operation of modern steam boilers.

Conclusions

A study of the principles of modeling the heat-transfer system of convective heating surfaces of a TP-92 steam boiler has led to the following conclusions. In the course of this article, the practical possibility of carrying out effective calculations of the parameters of the heating surface of used steam boilers at known temperatures of heat carriers in the established mode of operation of thermal equipment has been demonstrated. The values of the total heating surface area of the steam boiler, and the amount of coolant flow immediately before the construction of the calculated mathematical model remained unknown. The practical possibility of constructing a computational mathematical model, including a scheme for carrying out mathematical calculations of key parameters of the convective heat-transfer system in relation to steam boilers of the TP-92 type installed and successfully operating at the Dobrotvorskaya TPP is proven. The resulting mathematical model is designed to carry out specific mathematical calculations of the actual operating modes of steam boilers of the specified type in real conditions.

In the course of this study, it was found that for a specific convective heat-transfer system, a decrease in the air-temperature parameter at the entrance to the system itself by 15°C will lead to a decrease in the temperature of the exhaust gases at the outlet by 8.78°C. If there is an increase in the temperature of the flue gases at the entrance to the calculation system by 15°C, there will be an increase in the temperature of the exhaust gases at its outlet by 0.54°C. The error value between the experimental calculated parameters and those obtained as a result of the practical application of the developed mathematical model was 2.7%. Thus, modeling of the heat-transfer system of convective heating surfaces of the TP-92 steam boiler can be successfully implemented in the conditions of the practical operation of this kind of unit. The resulting computational mathematical models can be successfully applied to obtain the calculated parameters of the air temperature at the entrance to the heat-transfer system and at the exit from it.

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Modelowanie systemu wymiany ciepła konwekcyjnych powierzchni grzewczych kotła parowego TP-92

Streszczenie

O trafności przedmiotu badań decyduje potrzeba opracowania, a następnie wdrożenia modelu matematycznego i odpowiadającego mu schematu konstrukcyjnego konwekcyjnych powierzchni grzewczych kotła parowego TP-92. Celem pracy badawczej jest bezpośrednie zamodelowanie układu wymiany ciepła konwekcyjnych powierzchni grzewczych tego kotła, zaprojektowanego do efektywnego wykorzystania w warunkach rzeczywistych. Podstawą podejścia metodologicznego w pracy badawczej jest połączenie metod analizy systemowej kluczowych zasad budowy modeli matematycznych układów wymiany ciepła nowoczesnych kotłów parowych z eksperymentalnym badaniem perspektyw stworzenia modelu matematycznego układu wymiany ciepła konwekcyjnych powierzchni grzewczych kotła parowego TP-92. Uzyskane wyniki zaprezentowano w postaci modelu matematycznego konwekcyjnego układu wymiany ciepła. Pozwala to na wykonanie efektywnych obliczeń matematycznych głównych trybów pracy kotła parowego TP-92 oraz obliczenie zależności temperatury i trybów cieplnych jego pracy od zmian parametrów wejściowych stosowanych nośników ciepła, zmian powierzchni grzewczej oraz względnego natężenia przepływu nośników ciepła w czasie ich użytkowania. Uzyskane w pracy wyniki, w tym sformułowane na ich podstawie wnioski, mają duże znaczenie praktyczne dla projektantów kotłów parowych. Są one również przydatne dla personelu utrzymania ruchu, do którego bezpośrednich obowiązków należy określenie realnych możliwości udoskonalenia konwekcyjnego układu wymiany ciepła, w oparciu o znane parametry temperatury chłodziwa na wejściu do układu i na wyjściu z niego.

Słowa kluczowe: model matematyczny, spaliny, temperatura płynu chłodzącego,
system wymiany ciepła, reżim temperatury powierzchni