The use of a combined scheme of mathematical modeling for the continuous heating furnace of metallurgical production

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Abstract. In this paper, it is proposed to put the finite volume method into the basis of a mathematical model of a heating furnace. The finite volume method is used in modern computer programs for calculating gas-dynamic flows. It is advisable to use a combined scheme when building a mathematical model in accordance with the results of data analysis of the continuous heating furnace of the metallurgical rolling production and its disadvantages. The novelty lies in the fact that for the first time it is proposed to use a finite volume method with a combined difference scheme for the heating zones of a continuous furnace of a metallurgical rolling manufacture for calculating a furnace. Such calculation algorithms make it possible to give recommendations on reducing heat losses in a furnace. Mathematical model building can lead to a significant reduction in fuel consumption and an increase in economic efficiency when using heating continuous furnaces of metallurgical rolling production.

1. Introduction
Continuous furnace is used to heat metal billets before pressure treatment. Feedthrough furnace is such a continuous furnace, in which the heated billet moves along the furnace, moved by the pusher, roller conveyor or other mechanisms. Loading and unloading of the feedthrough furnace is done through windows in the end walls of the furnace or in the side walls near the ends. Billets are usually moved towards the movement of combustion products in a continuous furnace. A high degree of utilization of heat supplied to the furnace is achieved with such countercurrent motion. There are direct current furnaces and direct countercurrent furnaces. Billets pass successively three thermal zones: preheating zone, heating zone and temperature equalization zone. At the same time, heating furnaces have their drawbacks. For example, it is increased specific fuel consumption for tempering the metal. The paper proposes the option of using a combined scheme for the problem of mathematical modeling of a heating continuous furnace to reduce fuel consumption.

2. Description of the principle of the continuous furnace operation
A continuous furnace is a unit of continuous action, although the billets are fed into it with a certain interval. The scheme of the continuous furnace is shown in Fig.1. The principle of operation is as follows. The pusher moves heated metal through water-cooled pipes. The fuel is burned with burners located above and below the surface of the metal. The products of combustion move along the working space of the furnace in two streams - upper and lower. They move in the opposite direction to the movement of the metal, i.e. countercurrent. Combustion products are removed through the smoke channels into the furrow and out of it through the heat exchanger and the chimney into the atmosphere.
The heated metal gets on the roller conveyor through the window of the material output and along the roller conveyor to the metallurgical rolling machine.

**Figure 1.** Schematic diagram of a three-zone heating furnace method: 1, 2, 3 – the first, second and third continuous zones, respectively

There are several types of continuous furnaces, which differ in the number and location of zones. Let us consider the most common option. This is a three-zone furnace with three upper zones. In the three-zone mode, a higher temperature is maintained in the welding zone (second) than in the temperature equalization zone (third). The third zone is used to equalize the temperature over the cross section of the metal after forced heating in the welding zone. However, a significant cooling of the combustion products in the billets preheating zone is not economically justified. The temperature of gases can reach 1000°C in modern continuous furnaces. Most of the heat of combustion of fuel is lost with the heat of exhaust gases. Such loss reduction methods as recuperators, waste heat boilers and energy technology complexes based on heating furnaces are currently used. Heat utilization of flue gases is carried out together with their purification from harmful impurities and solid particles. Gases that do not harm the environment and humans should be released into the atmosphere. The emissions of gases are monitored, their number is regulated. Recuperators can be divided into radiation and convective according to the principle of action. In the first case, the main part of the heat is transferred by thermal radiation of flue gases. Such heat exchangers are installed above the furnace in zones with a temperature of 1000 K and above. Triatomic gases contained in the combustion products emit and absorb energy in the form of electromagnetic waves with the greatest intensity at such temperatures. Radiation heat exchangers are made in the form of annular channels. Flue gases pass in the center channel of annulus and heated air in the boundary channel. The second type of heat exchangers is convective. They are installed in the ducts behind the furnace. The temperature in them should be less than 1000 K, and the main part of the heat is transferred by convection. Intensification of heat transfer is possible by increasing the flow rate of flue gases in such recuperators. Convection heat exchangers are made in the form of curved pipes; coils of these pipes are suspended in the duct.

3. Setting a research problem. Scientific novelty. Practical significance.

It is advisable to use a combined scheme when building a mathematical model in accordance with the results of data analysis of the continuous heating furnace of the metallurgical rolling production and its disadvantages. In this paper, it is proposed to put the finite volume method into the basis of a mathematical model of a heating furnace. The finite volume method is used in modern computer
programs for calculating gas-dynamic flows.

The novelty lies in the fact that for the first time it is proposed to use a finite volume method with a combined difference scheme for the heating zones of a continuous furnace of a metallurgical rolling manufacture for calculating a furnace.

The practical significance of the work is to reduce the fuel consumption of the heating furnace. Fuel consumption for heat generation depends on the type of fuel being burned. It can be natural gas or coke oven gas. Also fuel consumption depends on the possibility of utilizing the heat of combustion products. Mathematical model building can lead to a significant reduction in fuel consumption and an increase in economic efficiency when using heating continuous furnaces of metallurgical rolling production. Such calculation algorithms make it possible to give recommendations on reducing heat losses in a furnace.

4. The main provisions of the scientific part of the study

The finite volume method is used to calculate gas-dynamic flows and fuel combustion processes. The method can be applied using explicit and implicit difference schemes depending on the specific physical characteristics of the flow itself and the geometric characteristics of the channel in which this flow occurs. Therefore, it is proposed to apply a combined scheme when calculating continuous heating furnaces in a particular case.

The combined scheme consists of explicit and implicit schemes, taken with a certain weight. It is obtained by introducing some coefficient \( \theta \) (0 \( \leq \theta \leq 1 \)). As a result, the equation takes the form:

\[
\Delta Q_i = \left[ \frac{T_i^\tau - T_i^\tau + \Delta T}{R_i^\theta} + \frac{T_i^{n+\Delta T} - T_i^\tau + \Delta T}{R_i^{n+\Delta T}} \right] \Delta \tau. \tag{1}
\]

\[
\Delta Q = \Delta Q_i^\theta (1 - \theta) + \Delta Q_i^{n+\Delta T} \theta \tag{2}
\]

Then the main calculated dependence can be written as:

\[
T^{\tau+\Delta T} = \left[ \frac{\sum_{i=1}^{N} T_i^\tau - T_i^\tau + \Delta T}{R_i^\theta} + \sum_{i=1}^{N} T_i^{n+\Delta T} \right] (1 - \theta) + \left( \sum_{i=1}^{N} T_i^{n+\Delta T} + \Delta Q_i^\theta (1 - \theta) + \Delta Q_i^{n+\Delta T} \theta \right) + \frac{C_T^n T^\tau}{\Delta \tau} \tag{3}
\]

The equation (3) takes the form that characterizes the explicit scheme with \( \theta = 0 \). And this equation becomes analogous to the implicit scheme with \( \theta = 1 \).

The system of nonlinear algebraic equations (3) for unknown \( T^{\tau+\Delta T} \) is solved by an iterative method. The use of a particular calculation scheme depends on the nature of the task and the features of the boundary conditions of heat transfer. The main factors when choosing a calculation scheme are the accuracy and duration of the calculation.

The disadvantage of explicit schemes is the restriction imposed on the choice of the time interval \( \Delta \tau \) for calculation. Allowable value \( \Delta \tau \) is determined from external and internal conditions of heat exchange of elementary volume. The limit value \( \Delta \tau \) is determined by the formula [2]:

\[
\Delta \tau_{lim} = \frac{\Delta V C_T}{\rho_T \sum_{i=1}^{N} \frac{1}{R_i}} \tag{4}
\]

where \( C_T \) - specific mass heat capacity of the element; \( \rho_T \) - element density.

It follows from formula (4) that the value of \( \Delta \tau_{lim} \) depends not only on the volume of the element, but also on its thermophysical properties. The value of \( \Delta \tau_{lim} \) will vary with changes in thermophysical properties that are temperature dependent. Therefore, it is necessary to calculate the limit values of time intervals at each calculated moment of time for all elements \( \Delta \tau \) to select the counting time interval and choose the smallest value of the time interval. They can be calculated by the formula (4):

\[
\Delta \tau \leq \Delta \tau_{lim} \tag{5}
\]
In some cases, the interval $\Delta \tau_{lim}$ may have a small value and the solution of the problem will take a long time. The error in calculating the implicit scheme increases with increasing time step. The convergence of the iterative process is also deteriorating. The iterative cycle is performed at each step of calculating $\Delta \tau$ according to an implicit scheme as long as the condition for the given accuracy of convergence of the iteration process is not satisfied.

An implicit scheme is often not economical due to repeated traversal of the nodal points of elements. The choice of the time step depends on the nature of changes in the boundary conditions and thermal characteristics of the body. The magnitude of their change over time $\Delta \tau$ must be related to the value of $\varepsilon$.

5. Conclusion
The finite volume method is used in modern computer programs. It can be supplemented with a developed combined difference scheme. The mathematical model of building can lead to a significant reduction in fuel consumption and increase economic efficiency when using heating continuous furnaces of metallurgical rolling production.

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References
[1] Ba A, Cissou A, Marcano N, Panier F, Tsiava R, Cassarino G, Ferrand L and Honore D 2019 Oxyfuel combustion and reactants preheating to enhance turbulent flame stabilization of low calorific blast furnace gas Fuel 242 211-221
[2] Gicquel O, Vervisch L, Joncquet G, Labegorre B and Darabiha N 2003 Combustion of residual steel gases: Laminar flame analysis and turbulent flamelet modeling Fuel 82 (8) 983-991
[3] Wang Y, Huang J, Su C and Li H 2019 Furnace thermal efficiency modeling using an improved convolution neural network based on parameter-adaptive mnemonic enhancement optimization Applied Thermal Engineering 149 332-343
[4] Xu Z, Kong W and Wang M 2019 Multi-model modeling of heating furnace system based on FCM and GA optimization ElasticNet-SVR Lecture Notes in El. Engineering 529 1-10
[5] Fu Z, Yu X, Shang H, Wang Z and Zhang Z 2019 A new modelling method for superalloy heating in resistance furnace using FLUENT International Journal of Heat and Mass Transfer 128 679-687
[6] Kumbhar S V and Sonage B K 2019 Enhancement of thermal efficiency and cost effectiveness by development of melting furnace by revamping and troubleshooting fuel-fired furnace Heat Transfer - Asian Research 48(1) 164-181
[7] García, A M and Amell A A 2018 A numerical analysis of the effect of heat recovery burners on the heat transfer and billet heating characteristics in a walking-beam type reheating furnace International Journal of Heat and Mass Transfer 127 1208-1222
[8] Mehta N, Varia R, Vasani S and Varma R 2018 Development of solar heating furnace International Journal of Mechanical Engineering and Technology 9 762-768
[9] Gerhardter H, Prieler R, Mayr B, Tomazic P and Hochenauer C 2018 Assessment of a novel numerical model for combustion and in-flight heating of particles in an industrial furnace Journal of the Energy Institute 91(6) 817-827
[10] Liu X, Worl B, Tang G, Johnson K and Zhou C Q 2018 A numerical model to predict scale formation in an industrial reheat furnace Iron and Steel Technology 15(12) 62-70