Application of mathematical modeling to optimize the operation of a tubular oil heating furnace

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Abstract. An energy balancing scheme has been developed for building a mathematical model of a tubular furnace for heating oil in accordance with the principle of its operation. This will allow taking into account all the heat fluxes, and the result of the work will be a reduction in fuel consumption for the tube furnace. 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 scientific novelty is that for a tubular heating furnace for the first time it is proposed to use the method of energy balances in the chambers of radiation and convection. The practical significance of the work is to reduce fuel consumption for a tube furnace, as well as the possibility of utilizing the heat of oil refining products when building a mathematical model of a distillation column. The calculation algorithm using the energy balances method for mathematical modeling of heat transfer processes allows balance equations for all furnace sections, including the radiation chamber and the convection chamber. After which several successive approximations are carried out using linear programming. In addition, there are technological solutions to optimize fuel use.

1. Introduction
Most processes in the oil refining industry use heating of the feedstock, as well as solvents, reagents, catalysts, etc. used in its processing. Obtained as a result of a particular technological process, the target products or semi-finished products usually need to be cooled to the temperature at which their storage and transportation are possible. In a modern oil refining factory, where deep oil refining is carried out, the production of heating and cooling equipment is spent up to 30% of the total consumption of materials on all technological installations [1-3]. High operation efficiency of such devices allows reducing the consumption of fuel and electricity spent on a particular technological process, and has a significant impact on its technical and economic indicators. Therefore, the study of the performance and operation of such devices, as well as the development of their calculation should be given special attention. The tube furnace is an apparatus designed to heat the product with heat released during the combustion of fuel directly in this apparatus. Tube furnaces are widely distributed in the oil refining and petrochemical industries; they are an integral part of many installations and are used in various technological processes, such as distillation and reforming, hydrotreating, etc. Tube furnaces are widespread due to their features [4,5]. Their work is based on the principle of single evaporation, which provides either a deeper heating of the raw material at a given temperature, or a given distillate at a lower heating temperature.

2. Description of the principle of operation of the tube furnace
The tube furnace has two chambers: radiation and convection (Figure 1). In the radiation chamber, where fuel is burned, a radiant surface is placed [6,7]. Heat is absorbed mainly due to radiation. In the convection chamber there are pipes that receive heat, mainly due to convection - when the flue gases come in contact with the heating surface. If the heat of the flue gases can be used for other purposes, for example, for heating air or for producing steam, then the presence of a convection surface is not necessary, or the dimensions of this surface can be significantly reduced.

![Figure 1. Schematic diagram of a tubular furnace with a double-row double-sided heating screen and a vertical arrangement of pipes: 1 – pipe coil, 2 – radiating wall, 3 – chimney, 4 – radiation chamber, 5 – convection chamber.](image)

In case of a small productivity, furnaces without a convection surface are sometimes used, which are simpler in a constructive aspect, but have a low efficiency. The paper proposes a version of the problem of mathematical modeling of a tube furnace in order to reduce fuel consumption. The fuel used is crude oil or natural gas [8,9].

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

In accordance with the operation principle of a tubular furnace for heating oil and its shortcomings, it is advisable to develop a mathematical model with the ultimate goal of reducing fuel consumption.

The scientific novelty is that for a tubular heating furnace for the first time it is proposed to use the method of energy balances in radiation and convection chambers.

The practical significance of the work is to reduce fuel consumption for a tube furnace, as well as the possibility of utilizing the heat of refined products when building a mathematical model of a distillation column.

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

The integral equation of temperature distribution in three coordinates is a generalized mathematical formulation of heat conduction problems. Integral expressions in it are often complex functions of coordinates [10,11]. Therefore, it is impossible to obtain an exact solution. As a rule, such equations are solved approximately. If the entire body area is conventionally divided into small volumes $\Delta V$ (elements) and thermophysical characteristics within these volumes for a sufficiently short period of time $\Delta \tau$ is considered unchanged, then for each element you can use the expression, replacing the integrals in it with finite sums:

\[ q_i \Delta V \sum_{i=1}^{N} q_i = C_p \Delta V \left( T^{r+\Delta \tau} - T^r \right) / \Delta \tau \]  

where $q_i$ – the power of the heat fluxes coming out of the element through its edges into the adjacent elements; $T^{r+\Delta \tau}, T^r$ – element temperature at time $r+\Delta \tau$; $T$ - element temperature at time $r$; $i$ – the number of current vector $q$ direction of normals to the corresponding edge of the element.

For parallelepiped shape element, $N=6$. Multiplying the left and right sides of the equation (1) by $\Delta \tau$:

\[ \Delta Q^r - \sum_{i=1}^{N} \Delta Q^r_i = \Delta Q^r \]  

where $\Delta Q^r$ – the heat fluxes coming out of the element through its edges into the adjacent elements; $\Delta Q^r_i$ – the heat fluxes coming out of the element through its edges into the adjacent elements; $\Delta Q^r$ – the heat fluxes coming out of the element through its edges into the adjacent elements; $\Delta Q^r_i$ – the heat fluxes coming out of the element through its edges into the adjacent elements; $\Delta Q^r$ – the heat fluxes coming out of the element through its edges into the adjacent elements.
where $\Delta Q_v$ – heat from internal sources over time interval $\Delta \tau$;

$$\sum_{i=1}^N \Delta Q_i = \text{the sum of heats released from the considered element in N directions;}$$

$\Delta Q_\tau$ – heat that went to increase the enthalpy of the element over a time period $\Delta \tau$.

If we assume that heat fluxes are included in the element from adjacent ones, then equation (2) takes the form:

$$\Delta Q_v + \sum_{i=1}^N \Delta Q_i = \Delta Q_\tau.$$  (3)

The use of a particular calculation scheme depends on the nature of the task and the features of the boundary conditions of heat transfer \[12,13\]. The main factors when choosing a calculation scheme are the accuracy and duration of the calculation. Then the standard procedure of mathematical modeling is applied using an explicit or implicit difference scheme.

For an explicit scheme, the terms of equation (3) are written as follows:

$$\Delta Q_i = \left[ \frac{T_i^\tau - T_i^{\tau+\Delta \tau}}{R_i^\tau} \right] \Delta \tau,$$

$$\Delta Q_v = \Delta Q_v^{\tau+\Delta \tau},$$

$$\Delta Q_\tau = C^\tau \left( T_\tau^{\tau+\Delta \tau} - T_\tau^\tau \right),$$  (4-6)

where $T_i^\tau$ – temperature of the adjacent element in the $i$-th direction at the moment of time $\tau$;

$R_i^\tau$ – thermal resistance of the considered element in the $i$-th direction;

$C^\tau$ – total heat capacity of the considered element.

Temperature of the calculated elements at time moment $\tau + \Delta \tau$ is defined as:

$$T_i^{\tau+\Delta \tau} = T_i^\tau + \Delta \tau \left( \frac{\sum_{i=1}^N (T_i^{\tau+\Delta \tau} R_i^{\tau+\Delta \tau})}{\sum_{i=1}^N 1/R_i^{\tau+\Delta \tau} + Q_v^{\tau+\Delta \tau}} \right).$$  (7)

Equation (7) makes it possible to determine the values of temperatures in the considered elements over a period of time $\Delta \tau$ with a known temperature distribution at the initial moment of time \[14,15\].

For the implicit scheme in equation (3), the components (4) and (5) will be written as:

$$\Delta Q_i = \left[ \frac{T_i^{\tau+\Delta \tau} - T_i^{\tau}}{R_i^{\tau+\Delta \tau}} \right] \Delta \tau,$$

$$\Delta Q_v = \Delta Q_v^{\tau+\Delta \tau} + \Delta \tau,$$  (8-9)

The result is a system of nonlinear algebraic equations, the number of which is equal to the number of elements with respect to unknowns $T_i^{\tau+\Delta \tau}$ \[16\]. This system can be solved by one of the iterative methods, for example, the Liebman method. In this case, the calculated dependence is converted to:

$$T_i^{\tau+\Delta \tau} = T_i^\tau \left[ \sum_{i=1}^N \left( T_i^{\tau+\Delta \tau} R_i^{\tau+\Delta \tau} \right) + \Delta Q_v^{\tau+\Delta \tau} + C^\tau / \Delta \tau \right] / \left[ C^\tau / \Delta \tau + \sum_{i=1}^N (1/R_i^{\tau+\Delta \tau}) \right].$$  (10)

5. Conclusion
The calculation algorithm using the energy balances method for mathematical modeling of heat exchange processes allows composing balance equations for all parts of the furnace, including the radiation chamber and the convection chamber. Several successive approximations are carried out using linear programming. In the end, such calculation algorithms make it possible to give recommendations on reducing heat losses in tube furnaces, as well as fuel consumption and optimization of the process of heating oil products.
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