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STATEMENT AND PERSONAL-COMPUTER-AIDED REALIZATION OF THE CONJUGATE PROBLEM OF HEAT TRANSFER IN A POWER-TECHNOLOGICAL BOILER WITH A MOVING BED OF DISPERSED HEAT-TRANSFER AGENT

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Consideration is given to the statement of the problem and principles of personal computer-aided realization of the thermal-calculation method for a steam generator-utilizer of the heat of high-temperature coke or other loose medium with known thermophysical properties.

One of the promising technologies in the by-product-coking industry is a combined process of thermal burden preparation and coke quenching [1] in which about a half of the heat of the hot coke that is produced from furnace chambers with a temperature of $1000 \pm 50^{\circ}C$ is used to dry and to prewarm the coal burden before carbonization. The remaining heat of the coke – in the high-temperature region of 1000 to $600^{\circ}C$ – is used as a secondary power source and must be recovered in a power-technological boiler (PTB) with production of steam of low grade (a pressure of 1.3 MPa and a temperature of $350-400^{\circ}C$). The steam is used for technological or central-heating purposes.

The PTB, which is designed to remove the excess heat of coke and to reduce its temperature before heat exchange with the coal burden is a vertical bin (shaft) of a rectangular cross-section with panels – the heating surfaces of the secondary heat transfer agent – liquid or steam – in a moving bed of coke (or any other dispersed medium) (Fig. 1).

The panels are arranged in several horizontal rows – in staggered order, i.e., with horizontal displacement of each subsequent row by a half step (see Fig. 1a) throughout the entire space with gaps (intervals) between the horizontal rows, in which, as calculations showed, an equalization of temperatures occurs in the coke bed.

The panels are flat surfaces formed by protective steel sheets welded tangentially to horizontal tubes (see Fig. 1b). Along the tubes, there flows a liquid heat-transfer agent, in our case, water or a steam-water mixture (evaporation panels) and superheated steam (steamsuperheating panels). These compound panels with flat outer surfaces and hence the internal cavities of irregular shape are designed to minimize wearing of the lumps of coke and eliminate bridging in the bed.*

To optimize the structure of the PTB for the number of steps and panels in each step, the number of tubes in a panel and their diameter as well as to choose the final dimensions of the boiler for the prescribed final temperature for the steam or, conversely, to determine the final temperature of the steam for the prescribed boiler structure, and, finally, to use the PTB in other technological processes, we developed a thermal-calculation method for the boiler that is realized in the present program using a computer.

* The PTB was designed on the request of the Eastern Research Coal-Chemical Institute by designers of the Joint-Stock Company "Belgorodenergomash" under the supervision of V. A. Gryaznov and L. M. Kapalet.

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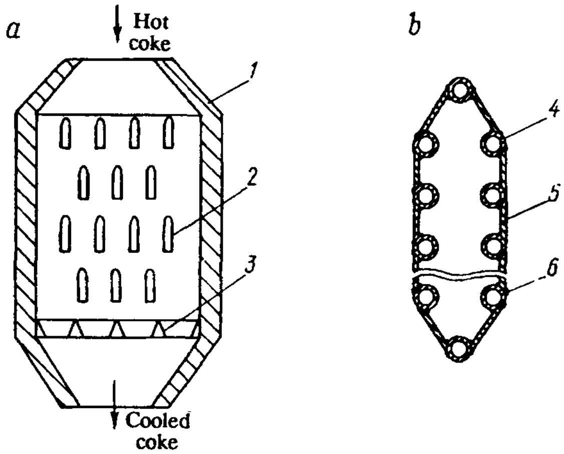

Fig. 1. Structure of PTB as a whole (a) and of an individual panel (b): 1) body, 2) panels, 3) discharging device, 4) tube, 5) sheet, 6) weld.

Statement of the conjugate problem of heat transfer: the stationary problem with a three-dimensional temperature field in a moving bed of a dispersed medium (a Cartesian coordinate system is tied to the fixed panels). In each cross-section, when $z = \text{const}$ the temperature field is constant with time. Heat transfer in the loose medium occurs in the joint action of the heat conduction of solid particles, free convection of gases, and radiation in interlump pores; for a material such as hot lump coke, the determining contribution to the overall heat transfer is made by radiation. This mechanism of heat transfer is realized in the program by using the effective thermal conductivity under the assumption of homogeneity of a loose-medium bed [2]. The temperature field of the liquid within steamsuperheater tubes is one-dimensional: $dT_{\text{liq}}/dx = \text{const}$. In evaporator tubes, the liquid temperature is taken to be constant and equal to the saturation temperature in all directions.

At the loose medium-panel metal boundary, the boundary conditions of the third kind are specified

$$q_{y=y_0} = \alpha_c(\overline{T}_c)(\overline{T}_c - T_w), \tag{1}$$

where the coefficient of the heat transfer from the coke to the flat surface $\alpha_c(\overline{T}_c)$ is determined from a table or a plot based on experiments conducted at the Eastern Research Coal-Chemical Institute on fixed and moving beds of coke [3]. The temperature field in the loose-medium bed is calculated from the stationary heat conduction equation in a nonlinear statement

$$\frac{\partial}{\partial x}\left(\lambda_{\text{eff}}(T_c)\frac{\partial T_c}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{\text{eff}}(T_c)\frac{\partial T_c}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_{\text{eff}}(T_c)\frac{\partial T_c}{\partial z}\right) = 0 \tag{2}$$

and the boundary condition at the boundary with the panel wall

$$\lambda_{\text{eff}}(T_c)\frac{\partial T_c}{\partial y} = \alpha_c(\overline{T}_c)(\overline{T}_c - T_w). \tag{3}$$

The heat flux from the coke follows two parallel pathways: most of the flux goes directly to the liquid through the front portion of the tube and adjacent portions of the sheet and weld (Fig. 2a) while the smaller share goes through the intermediate cavity (gaseous interlayer) from the open portion of the sheet to the lateral surface of the tube and weld and next to the liquid (Fig. 2b). Between these two fluxes, the heat flows by heat conduction along the sheet z-coordinatewise because of the large temperature gradient between the middle of the sheet and the weld.

According to this, we solve two auxiliary problems.

1. The temperature distribution in the weld and the adjacent portion of the tube is found by approximate analytical solution of the two-dimensional heat-conduction problem

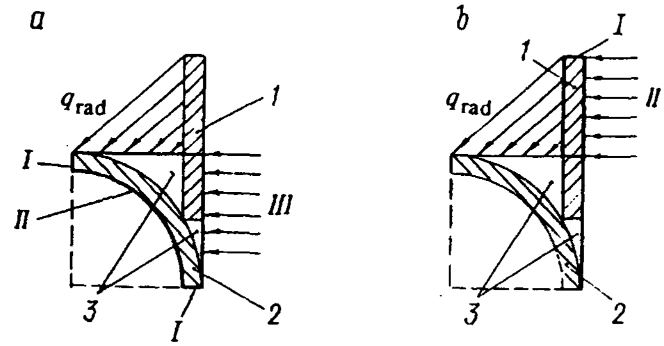

Fig. 2. Scheme of boundary conditions in auxiliary problems: a) problem 1 (I) $q = 0$, II) $q = \alpha_{liq}(T_{liq} - T_m)$, III) $q_y = \alpha_c(\overline{T}_c - T_m)$); b) problem 2 (I) $q_{z=0} = 0$, II) $q_y = \alpha_c(\overline{T}_c - T_{rad})$); 1) sheet, 2) tube, 3) weld.

$$\frac{\partial}{\partial z}\left(\lambda_m (T_m) \frac{\partial T_m}{\partial z}\right) + \frac{\partial}{\partial y}\left(\lambda_m (T_m) \frac{\partial T_m}{\partial y}\right) = 0 . \tag{4}$$

We disregard the temperature drop in the evaporator metal along the x-coordinate since the metal temperature is similar to the constant-along-the tube temperature of the liquid.

Forced convection within the tube is prescribed in the form of criterial dependences of the heat exchange in the tube for a turbulent regime of single-phase liquid flow or in pool boiling of a two-phase liquid [4, 5].

2. To determine the temperature field in the protective sheet, we solve analytically the system of one-dimensional heat conduction and heat transfer equations

$$\delta \frac{\partial}{\partial z}\left(\lambda_m \frac{\partial T_m}{\partial z}\right) = q_1 (T_m) - q_2 (T_m) , \tag{5}$$

$$q_2 (T_m) = \varphi \varepsilon_{red}\, \sigma_0 \left[\left(\frac{T_m}{100}\right)^4 - \left(\frac{T_t}{100}\right)^4\right] , \tag{6}$$

$$q_1 (T_m) = \alpha_c (\overline{T}_c) (\overline{T}_c - T_m) \tag{7}$$

with the following boundary conditions: at equal distance from the tube in the middle of the sheet $dT_m/dz = 0$; at the boundary with the weld, the metal temperature is set equal to the weld temperature $T_m = T_w$.

In Eq. (6), the radiation in the intermediate cavity from the sheet surface to the lateral surface of the tube and weld is calculated by the Stefan–Boltzmann law with determination of the radiation slopes for mutually perpendicular flat walls from the table of [6]. We can disregard free convection in the intermediate cavity ($\alpha_{conv} < \alpha_{rad}$ by a factor of 10 and more).

When solving these auxiliary problems we assume that the $\overline{T}_c$ value obtained in the previous segment in height to be fixed. Then, with allowance made for the determined temperature field of the wall, we calculate the temperature distribution in the coke on this segment.

In the steam-superheater stage, we mate the metal and coke temperatures with the steam temperature, which varies along the x-coordinate. Furthermore, in the second subproblem, we determine the maximum temperature of the metal sheet, which affects the choice of panel material. In each stage, the equation of the heat balance between the coke and the steam-vapor mixture (steam – in the steamsuperheater) is employed.

Differential equations were solved by the finite-difference method.

The results of the calculation of the basic thermal characteristics for the boiler are produced on a printer (display) in tabulated form. An example for one of the variants of calculation of a PTB with an output of 100 t of coke per hour is presented below.

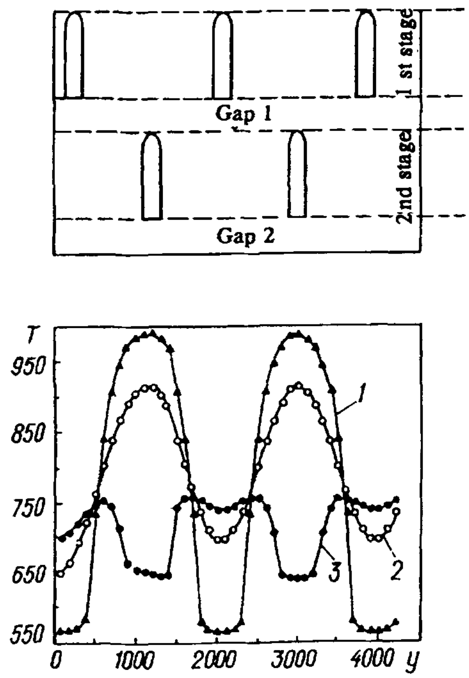

Fig. 3. Coke temperature field: at the outlet from the first stage (1); at the inlet to the second stage (2) and at the outlet from it (3). T, °C; g, mm.

TABLE 1. Results of Calculation

Stage No.	Heat absorption, kW	Outlet coke temperature, °C		
		average	maximum	minimum
1	8540	811	915	648
2	4081	717	755	683
3	646	702	724	608
4	2740	635	689	578
5	2220	579	612	530
Maximum vapor temperature is 329°C				
Logarithmic mean temperature head is 441°C				
Average vapor velocity is 19.1 m/sec				
Maximum temperature of tubes in evaporator is 253°C				
Maximum temperature of a sheet in steam superheater is 343°C.				

A fragment of the temperature field for the coke in arbitrarily chosen channels constructed by numerical data is given in Fig. 3.

An interactive visualization subsystem for the temperature field of a loose medium is obtained in the form of a plot of the temperature over the width of each channel and over the width of the entire unit in the intervals between stages and at the outlet from the last stage with a mark for the value of the heat-flux density at the loose medium-panel boundary. The subsystem makes it possible to rapidly examine on the display screen the $T_c(y)$ plots in arbitrary cross-sections of any channel and select the desired graphical materials for subsequent printing in graphical or numerical form.

To solve a specific problem, we need to specify the following initial data:

• The geometric characteristics of the boiler: the dimensions of the heat exchanger in plan, the number of panels per stage, the height of the panels and intervals between the stages, the number of tubes, their diameter and the distance between them in a panel; the thicknesses of the tube wall and the sheet.

• The flow rates of the heat-transfer agents and their initial temperatures.

• The thermophysical properties of the loose medium: $\alpha_c(\overline{T}_c)$ and $\lambda_c(T_c)$ in the form of tables (see, for example, λ_{eff} for a coke bed [25], heat capacity in the form of an interpolation formula (for coke, see [7]), the bulk density.

• The thermophysical properties of the liquid (water, steam) as functions of temperature in tabulated form: heat capacity, thermal conductivity, density and viscosity as well as the Prandtl number.

The disagreement of the heat absorptions of the panels that are calculated by the program with the results of nonatomated calculations strictly by the standard procedure [4] does not exceed 8%. We should note that in the latter case, it is impossible to obtain the sheet temperature (the maximum temperature of metal) and the temperature distribution in the coke bed.

The program for solving the conjugate problem of heat transfer is used in technical design of power-technological boilers of different structures for three promising technological processes in the by-product-coking industry. When some calculation techniques are used in specification of the initial data the program can be applied to simpler heating surfaces with flat or tube elements.

NOTATION

T, temperature, $^{\circ}$C; λ_{eff}, effective thermal conductivity; α, heat-transfer coefficient; q, heat flux density; ε_{red}, reduced emissivity factor for metal; φ, slope of radiant heat transfer; σ_0, Stefan-Boltzmann constant; x, y, z, Cartesian coordinate system: x, along panel tubes; y, over channel width; z, vertically; δ, sheet thickness. Superscripts and subscripts: c, coke (loose medium); liq, liquid; w, wall; m, sheet and tube metal; rad, radiant; conv, convection; t, tube; w, weld; 1 and 2, inner (in the panel) and outer surfaces of sheet; overscribed bar, average value of the quantity.

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