Simulation of heat transfer in fire-tube and fire-tube-contact water heaters

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Abstract. A mathematical model is proposed for calculating the constructive and operational characteristics of fire-tube and fire-tube-contact storage heaters used in the industrial, potable and firefighting water processing and storage units. The mathematical model includes equations for calculating heat balance, heat transfer, radiant heat transfer, and physical and chemical properties of substances. The heat transfer in fire tubes is calculated using a generalized process characteristic that is a function of structural and parametric indicators and heat engineering criteria. An example of application of the simulation software package for designing water heaters and conducting numerical experiments in order to draw up process flow diagrams accounting for variation of operational parameters and composition of fuel gas, is presented.

1. Introduction
The current trend in improving methods for calculating heat transfer in heat engineering equipment with fire-tubes involves creating experimental-analytical models that are maximally adapted for simulating equipment of a certain configuration, power and technological purpose [1–3]. This is due to the fact that there are few standard databases of thermal calculations for contemporary fire-tube boilers with a capacity of 1 to 4 MW, as well as corresponding process flow evaporators and heaters. The applicable standards for the thermal calculation of boiler units [4], firstly, require knowledge of a number of empirical corrections, and secondly, provide only approximate description of the heat transfer process in the combustion chambers of the fire-tube equipment. For example, the results of experimental and theoretical studies of the operating modes of a 3 MW fire-tube boiler described in [1] showed that the fire tube and the flue receive significantly more heat than expected, while the convective component of heat transfer within the fire tube may reach 30% of the total heat transfer. Similar results are provided in [5], where it is shown the gas flow is highly turbulized due to the conditions of gas flow within the fire tube, therefore, the coefficient of heat transfer coefficient between the gas and the walls of the fire tube is significantly higher than the calculated value determined in accordance with the standard [4].

A review of Russian and foreign works on heat transfer issues in fire-tube equipment showed that development of engineering methods of numerical simulation of modern devices that also improve existing methodology for simulating screened furnaces of boiler units [4] requires corrections in finding values for the following parameters and coefficients [1–3, 5, 6]:
- a parameter characterizing the nature of the temperature distribution in the furnace;
- average value of thermal efficiency coefficients of screens;
- effective thickness of the radiating layer;
- heat transfer coefficient from gases in convective heating surfaces.
When creating a model for calculating heat transfer and structural characteristics of fire-tube water heaters, the authors used the method for calculating cylindrical tube furnaces [7] and experimental data for adjusting the final temperature function.

2. The device schematic and mathematical description of the process of calculation of structural and operational characteristics

Fire-tube and fire-tube-contact storage heaters are used in the industrial, potable and firefighting water processing and storage units operated in regions with cold and temperate climates. They can also be used in autonomous heat supply systems for hot water supply and heating.

The water heater (RU 46340) contains the following main components (Figure 1): a cylindrical heat-insulated tank 1 with a capacity of 100 to 2000 m³ (equipped with a heat-insulated roof 2); burner piping systems 3 located in a thermally insulated cover 4; fire-tubes 5 (with deflectors 6 installed into the upper part of tubes) built into the tank and equipped with burners; skylight 7.

![Diagram of fire-tube water heater](Image)

1 – tank; 2 – roof; 3 – burner piping systems (shown conditionally); 4 – shelter for burners; 5 – fire-tube; 6 – deflector; 7 – skylight; I – fuel gas supply; II – air inlet; III – water supply; IV – water withdrawal; V – flue gas outlet.

**Figure 1.** Scheme of a fire-tube water heater (view A is rotated and reduced).

In fire-tube-contact water heaters, the exhaust fumes resulting from complete combustion of gaseous fuel contact the surface of the heated water at the outlet of the fire tubes. This heating method is acceptable if there are no specific requirements for increased quality of the heated water and if it is necessary to ensure a higher value of thermal efficiency.

Constructive and operational characteristics of water heaters are determined by a modeling algorithm that reflects the block structure of the mathematical calculation model (Figure 2, [8]).
Figure 2. Diagram of water heater simulation algorithm.

The input data block 1 includes parameters that vary during operation including the flow rate of circulating water \( G \) and its temperature at the inlet \( t_1 \) and outlet \( t_2 \) of the water heater; chemical composition of fuel gas \( \beta_c \) and outdoor temperature \( \theta \). Air flow coefficient \( \alpha \) is assigned a value specific to the known design of the burners.

Block 2 consists of the following preset structural characteristics of the water heater: tank diameter \( D \); quantity of fire-tubes \( n \), their outer diameter \( d \) and wall thickness \( \delta \); the height of the vertical part \( H \) of fire tubes that contacts water, and the length of the horizontal part \( L \) of the fire-tubes. These parameters are used to calculate:

- internal heat transfer surface \( F_R = (H + L)\pi dn \);
- internal volume of fire-tubes \( V_T = 0.25\pi n(H + L)(d - 2\delta)^2 \);
- water surface area (for simulations of fire-tube-contact water heater) \( F_{mw} = 0.785(\pi D^2 - \pi d^2 n) \);
- effective thickness of the emitting layer of flue gases within the fire-tubes \( S = 3.6V_T F_R^{-1} \).
It should be noted that in the developed software package (RU 2012612727) the preset design characteristics of the fire tubes are checked for the possibility of water vapor condensation within them in operating conditions. Therefore, the length of the horizontal section must meet the anti-condensation criteria (for the calculated heat transfer coefficient $k$ and the temperature of the fire-tube wall $t_w$).

$$L = \left( Gc(t_2 - t_1)n^{-1} - \pi kDh(t_w - 0.5(t_2 - t_1)) \right) / \left( \pi kD(t_w - 0.5(t_2 - t_1)) \right). \quad (1)$$

In block 3 utilizes the known dependencies [4, 7] to calculate the following variables of the combustion process:

- theoretical and actual air volume ($V_0$ and $V$);
- volumes of combustion products – water vapor $V_{H_2O}$, triatomic gases $V_{RO_2}$, nitrogen $V_{N_2}$, and flue gases $V_g = V_{H_2O} + V_{RO_2} + V_{N_2} + (\alpha - 1)V_0$;
- partial and total pressure of combustion products – water vapor $r_{H_2O}$, triatomic gases $r_{RO_2}$, total $r = r_{H_2O} + r_{RO_2}$;
- calorific value of fuel gas (lower, working) calculated on the basis of known calorific value of the corresponding component $Q_{Lc}$: $Q_L = 0.01 \sum \beta_iQ_{Lc}$;
- available heat introduced into fire tubes by fuel and air is calculated as: $Q_L = Q_L^0 + 0.01 \sum \beta_iL_c + \alpha V_0 \delta c_A$; where $L_c$ are the enthalpies of the fuel gas components and $c_A$ is the heat capacity of air at temperature $\gamma$;
- adiabatic combustion temperature is a function of previously calculated variables determined by the following equation:

$$t_a = Q_L^0 \left[ V_{N_2}c_{N_2}(t_a) + V_{RO_2}c_{RO_2}(t_a) + V_{H_2O}c_{H_2O}(t_a) + (\alpha - 1)V_0c_A(t_a) \right]^{-1}. \quad (2)$$

where heat capacities of combustion products ($c_{RO_2}, c_{H_2O}, c_{N_2}$) and air ($c_A$) are determined as a second-order polynomial function of temperature $(t=t_0)$:

$$c = a_0 + a_1t + a_2t^2. \quad (3)$$

Values of polynomial indexes $a_0, a_1$ and $a_2$ used for calculating the volumetric heat capacity of gases in the 300–2200 K temperature range are provided in Table 1 [8, 10].

| Gas   | $a_0$    | $a_1$    | $a_2$    |
|-------|----------|----------|----------|
| CO$_2$| 1.6365   | 0.0007   | -2.10$^{-7}$|
| SO$_2$| 1.7284   | 0.0008   | -3.10$^{-7}$|
| N$_2$ | 1.2799   | 0.0001   | -5.10$^{-9}$|
| H$_2$O| 1.4698   | 0.0003   | -3.10$^{-9}$|
| Air   | 1.2818   | 0.0001   | -2.10$^{-8}$|

In block 3 also calculates useful heat output according to preset initial data and designed values of water heat capacity: $Q = 4.186G(t_2 - t_1)$.

Blocks 5–12 consist of iterative calculations of the heat balance and simulation of heat transfer from the flue gas.

The preceding block 4 sets the initial minimal value of flue gas temperature (usually $t_{g_{\text{min}}} = 100^\circ$C). Calculation functions of blocks 5–7 and 11 utilize the following parameters (their values are fully adjustable within the software) and constants:

- black body emissivity coefficient $\sigma_0 = 5.67 \cdot 10^{-8}$ Bt/m$^2$K$^4$;
- the degree of screening of the fire-tubes (equivalent of the degree of screening of furnaces and boilers) $\chi_f = 1$;
- fire-tube emissivity factor $A_T \approx 0.80...0.85$;
- heat leakage to the environment $q_5 = 0.02Q_L^0$;
- thermal resistance of fire-tubes pollutants $\varepsilon = (2.7–3.1) \cdot 10^6$ (m$^2$·K)/kBt;
heat transfer coefficient to water $\alpha_w = 0.28$–0.35 kBt/l(m$^2$·K);
thermal conductivity of tube material $\lambda = 0.032$ kBt/(m·K).

Block 5 includes known dependencies for calculating heat transfer in fire-tubes and utilizes the procedure described in [7] to calculate the following variables:

- enthalpy of combustion products at the fire-tubes outlet
  \[ I_g = V_{N_2} I_{N_2}(t_g) + V_{RO_2} I_{RO_2}(t_g) + V_{H_2O} I_{H_2O}(t_g) + (\alpha - 1) V_{O} I_{A}(t_g); \]
  \[ (4) \]
  where the enthalpies of combustion products ($I_i$) calculated at the gas temperature $t_g$ by a simulation subprogram using the data base of RU 2012612727 [9] software package;
- thermal efficiency
  \[ \eta = 1 - I_g(Q_f - q_s)^{-1}; \]
  \[ (5) \]
- fuel gas consumption
  \[ B = Q(Q_f \eta)^{-1}; \]
  \[ (6) \]
- coefficient of convective heat transfer from flue gases to the heat-receiving surface
  \[ \alpha_c = 0.002(T_g - T_w)^{1/4}, \]
  \[ (7) \]
  where $T_g = t_g + 273$; $T_w = t_w + 273 = 333$ K (accepted for methane);
- summary heat transfer coefficient
  \[ k = (\alpha_w^{-1} + \delta \lambda^{-1} + \varepsilon)^{-1}. \]
  \[ (8) \]

Blocks 6 and 7 calculate the following characteristics of radiant heat transfer using the dependencies supplemented by experimental coefficients and adjusted for specific water heaters:

- Boltzmann criterion
  \[ B_o = 10^3(Q_f - I_g)(T_a - T_g)^{-1} B(F_r \sigma_0 T_a^3)^{-1}, \]
  \[ (9) \]
  where $T_a = t_a + 273$;
- attenuation coefficient of rays by triatomic gases
  \[ K_g r = r \left( (0.78 + 1.6r_{H_2O}) r S^{1/2} - 0.1 \right)(1 - 0.37 T_g \cdot 10^{-3}); \]
  \[ (10) \]
- integral coefficient of thermal radiation
  \[ a_\phi = 1 - \exp(-K_g r S); \]
  \[ (11) \]
- absorption capacity of fire-tubes (physical absorption capacity accepted equal to relative absorption capacity)
  \[ a_T = \left( A_T^{-1} + \chi_f (a_\phi^{-1} - 1) \right)^{-1}; \]
  \[ (12) \]
- relative temperature of flue gases
  \[ \theta_g = T_g T_a^{-1}; \]
  \[ (13) \]
- reductive characteristic of heat transfer in fire tubes
  \[ k_T = a_T(\theta_{gf}^4 - \theta_g^4) + \alpha_c \sigma_0^{-1} T_g^{-3}(1 - \theta_g), \]
  \[ (14) \]
  where, the closing function of the temperature $\theta_{gf}$ is equal to 1.33 (according to experimental data for a given condition of the tube wall temperature $T_e$ exceeding 333 K);
- the calculated value of the relative temperature at the fire tubes outlet is determined by solving the equation with respect to $\theta_{gf}$.
\[ k_T B_0^{-1} = \left(1 - \theta_{gc}\right)\left(\theta_{gc}\right)^{-4}; \]

- design temperature of flue gas at the outlet
  \[ T_{gc} = \theta_{gc} T_a; \]
- heat transferred by flue gases to water
  \[ Q_{gc} = B(\dot{Q}_f^\gamma - I_g - q_5). \]

Block 8 verifies the condition for convergence for the iterative calculation of heat transfer within a water heater by estimating the accuracy of calculated temperature of the flue gas (\(\Delta_t\)), which is assumed to be \(1\)–\(1.5^\circ C\). At the same time, the iteration step in block 10 should be less than the accepted error: \(s_T = (0.3 \div 0.5)\Delta_T\). Verification for temperature \(t_g\) exceeding its maximum value \(t_{g_{\text{max}}}\) is performed in block 9. The value of \(t_{g_{\text{max}}}\) is usually set in the range of 600–700°C.

In the last calculation block 11, two variables are defined:
- average heat tension of tubes
  \[ q_r = Q_{gc} F_R^{-1}; \]
- average temperature of the tube wall from the flue gas side
  \[ t_{wc} = 0.5(t_1 + t_2) + q_r k^{-1}. \]

In block 12, the calculated value of the temperature of the tube wall is compared with the minimum value corresponding to situation when there is no condensation of water vapor inside the tube: \(t_{wc} < t_{w_{\text{min}}}\). The value of \(t_{w_{\text{min}}}\) is advised to be assumed as the dew point temperature for flue gases generated during the combustion of the corresponding fuel.

The simulation software developed according to this algorithm allows one to perform calculations for water heaters of a certain design and evaluate the characteristics of variable operating conditions.

### 3. Numerical experiments and performance charts of the fire-tube water heater

The operational characteristics of a water heater of a given design vary during its operation as a result of affecting factors listed in the input data block. In general, performance charts are representations of dependencies of the required fuel consumption – \(B = f(G, t_3, t_2, \beta_C, \vartheta)\).

This article presents the results of creating a two-parameter performance chart for a fire-tube water heater in the form of a phase field in the \(B - G - Q_f^\gamma (\beta_C)\) coordinates as shown in Figure 3 [8].

Design characteristics of a water heater are as follows:
\[ D = 10.43 \text{ m}; \ n = 3; \ d = 0.2 \text{ m}; \ \delta = 0.009 \text{ m}; \ H = 8.1 \text{ m}; \ L = 3.6 \text{ m}. \]

The following operational parameters are accepted as constants:
\[ t_1 = 5^\circ C; \ t_2 = 15^\circ C; \ \vartheta = -20^\circ C; \ \alpha = 1.1. \]

The composition of the fuel gas used in the calculations and corresponding calorific values are shown in Table 2.

It should be noted that composition \(\beta_{c1}\) corresponds to the average gas composition in the local gas pipeline of a gas production facility. Compounds \(\beta_{c6}\) and \(\beta_{c7}\) are mixed and secondary raw materials from cracking plants for oil and gas condensate refineries, respectively. Composition \(\beta_{c2}\) is a very close representation of a standard composition of natural gas. Natural fuel gas from various gas pipelines is represented by compositions \(\beta_{c3}\) and \(\beta_{c4}\), and associated petroleum gas – by composition \(\beta_{c5}\).
Figure 3. Dependence of fuel gas consumption on two operational variables.

Table 2. The compositions of the fuel gases, % by volume.

| Components of the gases | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\beta_4$ | $\beta_5$ | $\beta_6$ | $\beta_7$ |
|------------------------|----------|----------|----------|----------|----------|----------|----------|
| CH$_4$                 | 62.4     | 97.7     | 85.0     | 93.8     | 35.0     | 7.4       | 14.9     |
| C$_2$H$_6$             | 3.6      | 0.03     | 1.0      | 2.0      | 15.0     | 13.6      | 10.8     |
| C$_3$H$_8$             | 2.6      | 0.01     | 3.0      | 0.8      | 10.0     | 29.8      | 25.8     |
| n-C$_4$H$_{10}$        | 0.5      | 0.01     | 1.0      | 0.2      | 7.0      | 13.4      | 14.9     |
| i-C$_4$H$_{10}$        | 0.4      | 0.0      | 0.5      | 0.1      | 8.0      | 19.2      | 20.6     |
| C$_5$H$_{12}$          | 0.1      | 0.0      | 0.5      | 0.1      | 10.0     | 0         | 0        |
| C$_6$H$_{14}$          | 0.1      | 0.0      | 0.0      | 3.0      | 0        | 0         | 0        |
| C$_7$H$_{16}$          | 0.0      | 0.0      | 0.0      | 0.0      | 2.0      | 0         | 0        |
| H$_2$                  | 0.0      | 0.0      | 0.0      | 0.0      | 16.6     | 13.0      | 0        |
| CO                     | 0.0      | 0.0      | 0.0      | 0.0      | 0        | 0         | 0        |
| H$_2$S                 | 0.0      | 0.0      | 0.0      | 0.0      | 0.3      | 0         | 0        |
| CO$_2$                 | 0.1      | 1.0      | 1.0      | 0.4      | 3.0      | 0         | 0        |
| N$_2$                  | 30.2     | 1.25     | 8.5      | 2.6      | 6.7      | 0         | 0        |
| Q$^L_s$, MJ/m$^3$       | 28.6     | 35.1     | 35.9     | 36.2     | 73.8     | 80.5      | 81.4     |

For practical application by the control systems of industrial enterprises, we propose presenting the dependence of fuel gas consumption in the simulated water heater by the following polynomial:

$$B = c_1 + c_2 Q^L_s + c_3 (Q^L_s)^2 + c_4 (Q^L_s)^3 + c_5 (Q^L_s)^4,$$  \hspace{1cm} (20)

where the coefficients $c_i = f_i(G)$ are also determined by the following polynomial:

$$c_i = d_1 + d_2 G + d_3 G^2 + d_4 G^3.$$ \hspace{1cm} (21)

The values of the coefficients are given in Table 3.

Table 3. Coefficients $d_i$ in (21).

| Coefficient $c_i$ | $d_1$   | $d_2$   | $d_3$   | $d_4$   |
|------------------|---------|---------|---------|---------|
| $c_1$            | -214.46 | 144.46  | -27.75  | 1.8845  |
| $c_2$            | 19.311  | -12.775 | 2.5302  | -0.1707 |
| $c_3$            | -0.6107 | 0.4022  | -0.081  | 0.0054  |
| $c_4$            | 0.058   | -0.0038 | 0.0008  | -0.00005|
| $c_5 \times 10^7$| -8.0    | 7.0     | 0       | 0       |
Thus, mathematical model and developed software package [9] for calculating fire-tube water heaters allows us to determine the main thermal and technical characteristics of devices of a given design: the useful heat output; the thermal efficiency; fuel gas consumption; the heat transferred in the fire tubes; the average heat tension of the heat transfer surface; and the average temperature of the fire tube wall. The proposed algorithm takes into account the variable operating modes and forms the required dependencies of fuel gas consumption on influencing factors.

4. References
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