Thermal plants operational efficiency improvement

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Abstract. The thermal plants operational efficiency improvement study relevance is associated with the temperature influence of heating the air required for the fuel burning and economic feasibility. The paper objective is to define the optimal value of the recuperator air heating temperature and to study the given temperature impact on the high-temperature unit operating efficiency. The recuperator air heating optimal temperature defining algorithm deriving appears to be the problem solving. The methods of the heat exchange equation mathematical modelling, optimization problem numerical solution, non-linear programming, and modern methods of the technical and economic assessment were used in the paper. The computational investigation results of the temperature influence of heating the air required for the radiant tube fuel burning on the thermal plant technical and economic efficiency are presented.

Key-words: temperature, radiant tube, thermal plant, recuperator, efficiency.

1. Introduction
Heat-treatment plants, where fuel is burned in radiant tubes which makes it possible to reduce the metal losses from oxidation [1] and to improve the processing procedure efficiency [2] are used in machine building for the parts and assemblies thermal treatment.
The heat-treatment plants efficiency improving known solutions mainly refer to the heating machines of the metal industry [3]. The research revealed the current insufficiency of special studies focused on the thermal plants in machine building. This is a major deterrent against their efficiency and economy improving.

2. Problem statement
One of the tasks of the given plants is the new technologies implementation with minimum expense. [4]. Addressing the challenge provides the fuel and energy resources consumption reducing [5]. The exhaust gases thermal energy application at the air high-temperature heating in the recuperator is one of the measures of improving the high-temperature plants efficiency [6]. However, it results in the recuperator costs increase, therefore it is appropriate to calculate the fuel combustion air heating optimal temperature.

3. Theory
The high-temperature thermal plant comprising the radiant tubes and recuperator "BIRLEC" R18 (figure 1) was chosen for the study: 1 is the exhaust gases pipe; 2 is the heat recovery unit; 3 is the fan; 4 is the lining; 5 is the batch; 6 is the pushing mechanism; 7 is the batch guide; 8 is the supply air pipe; 9 is the protective atmosphere input; 10 is the heated air feeding pipe; 11 is the radiant tube; 12 is the burner device; 13 is the fuel supply pipe; 14 is the burner assembly.
The high-temperature plant is divided into four zones: the first zone is heating the metal to 870 °C; the second and third ones are cementation; the fourth one is the stabilization zone where the parts are evenly heated up. The given plant capacity is 400 kg/h in burning the natural gas with the calorific
value of 35.4 MJ/m³, the gas consumption is 0.0014 m³/s, the efficiency is 17% with the air heating temperature of up to 100 °C, the first zone metal heating time is not more than 3 hours.

The temperature field in the metal heating chamber is conducted by the ceramic U-shaped radiant pipes (figure 2): 1 is the plate; 2 is the duct; 3 is the radiant tube body; 4 is the pipe bend; 5 is the gas pipe; 6 is the insulating packing; 7 is the packing seal; 8 is the nozzle; 9 is the air swirler; d₀=0.012 m; d₁=0.1 m; D₁=0.12 m; r=0.05 m; R=0.16 m; l₁=0.7 m.

The design of the recuperator required for heating the air by means of the radiant tube exhaust gases (figure 3) has the following main dimensions: δ=0.05 m; dₑ=0.3 m.

Figure 1. The high temperature thermal plant including the radiant tubes and recuperator.

Figure 2. The ceramic U-shaped radiant tube.
The air heating optimal temperature is defined on the basis of the minimal discounted investments in the recuperator and fuel. Having expressed the recuperator parts heating and heating surface fuel consumption from the heat balance of the plant working area and heat exchange as a function of the air temperature, the calculated equation is obtained:

\[
\frac{dZ_r}{dt_a} = C_r \frac{dF_r}{dt_a} + C_r \frac{dH_r}{dt_a} = 0
\]  

(1)

where \( Z_r \) is the comparative efficiency of the minimal discounted costs investments, RUB/year; \( C_r, F_r \) are the annual cost and fuel consumption, (RUB/m²)(c/year), m³/s; \( C_r \) is the cost per 1 m² of the recuperator heating surface, RUB/(m²•year); \( H_r \) is the recuperator heating surface, m²; \( t_a \) is the recuperator output air temperature, °C.

The equation (1) solution has the following form:

\[
a t_{a_2}^2 + b t_{a_2} + d = 0
\]

(2)

\[
a = C_r \eta_a C_{a_2}^2 V_a W - K \epsilon_{a_1} C_{a_2} C_f W^2
\]

(3)

\[
b = 2(K \epsilon_{a_1} C_f U - C_r \eta_a C_{a_1} t_{a_1} V_a) C_{a_2} W
\]

(4)

\[
d = C_r \eta_a [C_{a_2} E + C_{a_1} t_{a_1} (C_{a_1} V_a U - W E)] - K \epsilon_{a_1} C_{a_2} C_f U^2
\]

(5)

\[
U = (A \frac{C_{a_1}}{C_{g_2}} + B)t_{g_1} + (\frac{V_a \eta_a C_{a_1}}{m V_g \eta_g C_{g_2} (1 + \Theta)} - 1)A t_{a_1}
\]

(6)

\[
W = \frac{A V_a \eta_a C_{a_2}}{m V_g \eta_g C_{g_2} (1 + \Theta)} + B
\]

(7)

\[
E = Q_i (1 - R_g) + C_i \eta_i - V_g C_{g_1} t_{g_1} - \delta V_g C_{a_2} \delta t_a
\]

(8)

\[
t_{g_1} = \frac{C_{a_2} t_{a_2} + \Theta C_{a_1} t_{a_1} - \delta t_g}{(1 + \Theta) C_{g_1}}
\]

(9)

\[
t_{g_2} = \frac{C_{g_1}}{C_{g_2}} t_{g_1} - \frac{V_a \eta_a (C_{a_2} t_{a_2} - C_{a_1} t_{a_1})}{m V_g \eta_g C_{g_2} (1 + \Theta)}
\]

(10)
4. Experimental results

The influence numerical studies of the air heating temperature $t_{a2}$ required for the fuel combustion revealed the following [7]: the radiant tube $F_r$ total costs (figure 4) and fuel consumption are reduced (figure 5); the recuperator heating surface $H_r$ is increased (figure 5).
5. Results discussion
The experimental results show that the fuel consumption is reduced to 36% and discounted costs are decreased to 20%. The air heating temperature is not high $t_{\text{opt},a}=430^\circ\text{C}$ which makes possible to use the existing materials of the recuperator.

6. Conclusions
The air heating, calculating and choosing the recuperator air temperature optimal value leads to improving the technical and economic efficiency of the thermal plant taking into account the costs minimization. The developed algorithm makes it possible to define the air heating optimal temperature taking into consideration the thermal plant operating conditions changes depending on the recuperator design and cost, the fuel cost and type.

7. References

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