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Feasible Ratio Determination of the Thermal Oil Equipment Waste-Heat Recovery

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Abstract. The applicability of the thermal oil equipment flue gases thermal energy recovery relates to heating the air amount required for the fuel burning, and technical and economic feasibility. The paper objective is to define the regenerative system air heating temperature optimal value and to study the temperature impact on the heat power unit efficiency. The problem solution is air heating temperature optimal value calculation algorithm. The methods of the complex heat exchange mathematical modelling, optimization problem numerical solution, non-linear programming, and feasibility study were used in the research carried out. The study results of the temperature influence of heating the air required for fuel combustion on the thermal oil equipment technical and economic efficiency are presented.

Keywords: thermal oil equipment, regenerator, air, costs, efficiency

1. Introduction

In oil and gas industry, thermal oil equipment including the diathermic oil as a heat transfer fluid and fuel burned in the combustion chamber as an energy carrier is used as the heat supply systems high temperature boiler units. The uniqueness of this method is to obtain the high heating temperature of the heat transfer fluid (up to $+350^{-0}$ C) at the low pressure (up to 5 bar) [1]. This criterion reduces the equipment cost and increases the reliability when operating. The use of diathermic oil in boilers has a number of advantages compared to hot water boilers: heating to high temperatures at low pressures; water treatment plant is not required; free of metal erosion and corrosion; possibility of operating in the full automatic mode.

The fuel combustion in the thermal oil equipment chamber is enhanced due to the complete fuel combustion at the minimum air excess with a possible waste-heat recovery ratio.

2. Problem statement

The main task of the equipment under study is to utilise the flue gases thermal energy efficient recovery (heat recovery feasible ratio) with minimum investments. The possibility of solving this problem will reduce the fuel and energy resources costs. The use of the exhaust gases heat after the heat processing units when heating the air in regenerative devices is the main activity to improve their efficiency [2-6]. However, this results in the devices construction costs increasing, therefore it is appropriate to detect the optimal temperature of heating the air used for the fuel combustion.

3. Theory

The thermal oil unit Lavart 500 DMH produced by CJSC "OmZIT" (figure 1) [7] comprising the heat regenerator: 1 is the burner, 2 is the housing of the thermal oil unit 3 is the outer coil, 4 is the inner coil 5 is the housing insulation, 6 is the slot joining the flue gases discharge pipe, 7 is the explosive

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valve, 8 is the inspection window. Heat exchange surfaces form the concentric spiral consisting of rings made of several seamless alloy tubes. The first ring-shaped spiral forms the basis of the boiler furnace space. The second ring-shaped spiral forms a flow channel for flue gases. Coils are in a leak-tight chamber forming the thermal oil equipment body.

The maximum power of the thermal oil equipment is 0.5 MW when burning the natural gas at the low heating value of 35.9 MJ/m³, the fuel consumption is 0.016 m³/s, the efficiency is 86.4%, the air supply temperature for gas combustion is 50 $^{\circ}$ C, the flue gases temperature is 337 $^{\circ}$ C.



Figure 1. The longitudinal section of the thermal oil equipment Lavart 500 DMH.

The heat regenerator is installed to heat the air behind the thermal oil unit through the exhaust pipe (figure 2): δ is the wall thickness of the regeneration heat exchange, m; d_r is the regenerator inner diameter, m; l_r is the regeneration main heat exchange length, m; d_p is the inner diameter of the discharge pipe, m; t_{a1}, t_{a2} are the air temperatures at the inlet and outlet of the regenerator, ⁰C; t_{g1}, t_{g2} are the gases temperatures at the inlet and outlet of the regenerator, ⁰C.



Figure 2. Heat energy regenerator.

The combustion air optimum temperature can be defined on the assumption of the minimum capital investments and operating costs for the flue gases heat recovery and fuel combustion [8]:

$$\frac{\mathrm{dI}}{\mathrm{dt}_a} = A_f \frac{\mathrm{dB}}{\mathrm{dt}_a} + C_r \frac{\mathrm{dF}}{\mathrm{dt}_a} = 0 \tag{1}$$

$$A_f = C_f \tau \tag{2}$$

$$B = \frac{Q_{us.} + Q_{br} + Q_{rad.} + Q_{ac.}}{Q_{v}(1 - R_{o}) + S_{st}t_{st} - V(C t_{v} + R_{v}) + VC_{o}(t_{o} - \delta t_{v})}$$
(3)

$$A_f = I_r(\mathbf{D}_r + \mathbf{O}) + \mathbf{N}_{d.u.} \left[ZC_{d.u.}(\mathbf{D}_r + \mathbf{O}) + C_e \tau \right]$$
(4)

$$\mathbf{F} = \frac{\mathbf{B}\eta_a \mathbf{V}_a (\mathbf{H}_{a2} \mathbf{t}_{a2} - \mathbf{H}_{a1} \mathbf{t}_{a1})}{\mathbf{I}\varepsilon_{At} \upsilon}$$
(5)

where I is the total capital investments for the regenerator and burnt fuel, RUB/year; t_a is the air temperature in the thermal oil heating unit burner ⁰C; A_f, B are the fuel annual cost and consumption $(RUB/m^3) \cdot (s/year), m^3/s; C_r$ is the cost of 1 m² of the regenerator heating surface, RUB/(m²·year); F is the regenerator heating surface, m²; C_f is the cost of 1 m³ of the natural fuel, RUB/m³; τ is the operating time of the thermal oil equipment over a year, s/year; Qusf. is the useful thermal energy output by the thermal oil equipment, W; Q_{br} is the thermal conductivity heat losses through the unit brickwork into the environment, W; Q_{rad.} is the radiation heat losses through the open inspection window W; Qac. is the accumulation heat losses by the brickwork when taking the thermal oil equipment out of the cold condition, W; Q_1 is the low heating value of natural gas, J/m³; R_2 is the losses rate of the combustion mechanical incompleteness; S_{f1}, t_{f1} are the average heat capacity and the fuel temperature J/(m³ K), ⁰C; V_g is the flue gases amount per unit of the fuel quantity, m³/m³; t_g, H_g are the temperature and heat capacity of the thermal oil unit flue gases, ${}^{0}C$, J/(m³·K); R₁ is the unburned CO heat in flue gases, J/m^3 ; V_a is the air amount required for the fuel quantity unit combustion, m^3/m^3 ; H_{a2} is the air heat capacity at the regenerator outlet, $J/(m^3 \cdot K)$ ⁰C; δt_a is the air temperature drop on the way from the regenerator to the unit burner due to the heat loss into the environment, °C; I_r is the capital investments for the construction of 1 m² of the regenerator heating surface, RUB/m²; D_r is the investments discounting rate 1/year; O is the depreciation rate, 1/year; $N_{d.u.}$ is the power required for maintenance of 1 m^2 of the regenerator heating surface, W/m²; Z is the safety factor of the exhaust and draught units supply and consumption, and the power capacity; Cd.u. is the exhaust and draught units cost, RUB/W; C_e is the electricity cost, RUB/(W·s); η_a is the coefficient taking into account the regenerator air losses; H_{a1} is the air heat capacity at the regenerator inlet, J/(m³·K), ⁰C; K is the heat transfer coefficient, W/(m²·K); $\varepsilon_{\Delta t}$ is the correction factor under the complex heat exchange scheme; v is the average temperature difference.

The thermal oil equipment differential equation (1) solution has the following form:

$$at_a^2 + bt_a + d = 0 \tag{6}$$

$$\mathbf{a} = C_r \eta_a H_{a2}^{\ 2} \mathbf{V}_a \mathbf{W} - I \varepsilon_{\Lambda t} H_{a2} A_f \mathbf{W}^2 \tag{7}$$

$$\mathbf{b} = 2(\mathbf{I}\boldsymbol{\varepsilon}_{\Delta t}A_f \mathbf{U} - C_r \boldsymbol{\eta}_a H_{a1} \mathbf{t}_{a1} \mathbf{V}_a) \mathbf{H}_{a2} \mathbf{W}$$
(8)

$$\mathbf{d} = C_r \eta_a \left[H_{a2} \mathbf{E} \mathbf{U} + H_{a1} \mathbf{t}_{a1} (\mathbf{H}_{a2} \mathbf{V}_a \mathbf{U} - \mathbf{W} \mathbf{E}) \right] - \mathbf{K} \varepsilon_{\Delta t} H_{a2} A_f \mathbf{U}^2$$
(9)

$$U = (D\frac{H_{g1}}{H_{g2}} + G)t_{g1} + (\frac{V_a \eta_a H_{a1}}{V_g \eta_g H_{g2}(1 + \Theta)} - 1)Dt_{a1}$$
(10)

$$W = \frac{DV_a \eta_a H_{a2}}{V_e \eta_e H_{e2} (1+\Theta)} + G$$
⁽¹¹⁾

$$E = \mathbf{Q}_{l}(1 - \mathbf{R}_{2}) + S_{\mathrm{fl}}\mathbf{t}_{\mathrm{fl}} - \mathbf{V}_{g}H_{g}\mathbf{t}_{g} - \mathbf{V}_{g}\mathbf{R} - \mathbf{V}_{a}H_{a2}\delta\mathbf{t}_{a}$$
(12)

$$\mathbf{t}_{g1} = \frac{H_g \mathbf{t}_g + \Theta \mathbf{H}_{a1} \mathbf{t}_{a1}}{(1+\Theta) \mathbf{H}_{g1}} - \delta \mathbf{t}_g \tag{13}$$

$$\mathbf{t}_{g2} = \frac{H_{g1}}{H_{g2}} \mathbf{t}_{g1} - \frac{\mathbf{V}_a \eta_a (\mathbf{H}_{a2} \mathbf{t}_{a2} - H_{a1} \mathbf{t}_{a1})}{\mathbf{V}_g \eta_g H_{g2} (1 + \Theta)}$$
(14)

where D and G are the coefficients depending on the ratio $(t_{g2}-t_{a1})/(t_{g1}-t_{a2})$; H_{g1} , H_{g2} are the gases heat capacities at the regenerator inlet and outlet, $J/(m^3 \cdot K)$; η_g is the coefficient taking into account the heat

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losses through the regenerator enclosing walls into the environment; δt_g is the exhaust gases temperature decrease on the way to the regenerator; Θ is the coefficient taking into consideration the exhaust gases dilution in air on the way to the regenerator.

4. Experimental results

The numerical study the air temperature t_a heating, revealed: the total capital investments and operating costs of the regenerator and burned fuel are reduced (figure 3); the fuel consumption decreases (figure 4); the regenerator heating surface increases (figure 4); the thermal oil equipment efficiency improves η (figure 5).



Figure 3. The dependence of I on t_a .



Figure 4. A and F dependence on t_a .



Figure 5. The dependences of η on t_a .

5. Results discussion

The experiments results (at the calculated optimum temperature of air heating $t_{a.opt}$ =226 ⁰C) made it possible to obtain the following: the fuel consumption and discounted costs are reduced to 15% and 10% correspondingly during the thermal oil equipment operation, thereby increasing the efficiency up to 10%. The air heating optimum temperature is not high, which makes it possible to use inexpensive materials in manufacturing and operating the heat regenerator.

6. Conclusions

Air heating and its optimal value calculation in the regenerator according to the proposed algorithm provides the increase in the technical and economic effect of the thermal oil equipment operation, taking into account the investments and operating costs minimization. The presented algorithm determines the air heating optimal temperature considering the thermal oil equipment operating conditions depending on the regenerator and its design cost, the burned fuel type. The numerical studies results verify the algorithm feasibility when designing the boiler units in oil and gas industry.

7. References

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