Comparative exergy analysis of the processes of heating reserve liquid fuel using various coolants at thermal power plants

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Abstract. In this paper the technologies for heating reserve liquid fuel at a thermal power plant are proposed. Provision is made to implement a transition from fuel oil to another reserve fuel that does not require high-temperature heating at thermal power plants. A comparative analysis of the traditional scheme of heating reserve fuel with industrial steam and other coolants was carried out. The analysis was carried out using the exergy method, which allows taking into account different types of power. Exergy flows, exergy losses and exergy coefficient of efficiency are calculated for traditional and proposed technologies of reserve fuel heating.

1. Introduction
To ensure uninterrupted fuel supply at all thermal power plants (TPPs), there are reserve fuel facilities, most frequently fuel oil facilities, which require significant consumption of fuel-and-power resources for operation [1]. Traditionally, at TPPs, the reserve fuel oil is heated up to 80–110°C with steam for process needs. This scheme has become widely used in the domestic heat power industry, since its main advantage is high reliability, which allows heating fuel to the desired temperatures, regardless of any external factors. However, this technique also has significant disadvantages associated with the use of over-heated steam with a pressure of 1.3–1.5 MPa, which requires substantial fuel consumption by boilers at TPPs, and with the loss of contaminated condensate resulting from the operation of fuel oil heaters [2]. Over recent years, many oil refineries face the enhancement of a technological process of oil refining, as a result of which the production of fuel oil becomes economically unviable. In view of the above, provision is made, at TPPs, to implement a transition from fuel oil to another reserve fuel that does not require high-temperature heating, for example, to the home heating oil (HHO). For the HHO heating to 25–30°C, it is proposed to use low-potential flows of steam and reversed network water [3].

2. Method of exergy analysis for the heating processes
Since remote stationary heaters present the most energy-consuming element of the liquid fuel heating scheme, this paper presents the results of a comparative exergy analysis of the heating techniques for two types of reserve liquid fuel: fuel oil and the HHO – using various coolants, at TPPs.

The method of exergy analysis is disclosed in [4–6]; the use of this method makes it possible to determine relative impact on the process efficiency with respect to various stages of power consumption, to identify the elements associated with greatest power losses as well as to determine the exergy efficiency.
The sum of all exergy flows entering the system $\Sigma E'$, W, is

$$\Sigma E' = \Sigma E'_i + \Sigma E'_{q} + \Sigma L'_j$$  \hspace{1cm} (2)

The sum of all exergy flows leaving the system $\Sigma E''$, W, is

$$\Sigma E'' = \Sigma E''_q + \Sigma E''_{s} + \Sigma L''_j$$  \hspace{1cm} (3)

$\Sigma E'$, $\Sigma E''$ – the exergy of substance flows entering and leaving the system, W; $\Sigma E'_i$, $\Sigma E''_q$ – the exergy of heat fluxes entering and leaving the system, W; $\Sigma L'_j$, $\Sigma L''_j$ – work, supplied to the system with incoming substance flows and removed with outgoing substance flows, W.

3. Application of exergy method for the analysis processes of heating reserve liquid fuel at thermal power plants

Let us calculate the exergy efficiency for the traditional scheme of heating the reserve fuel – M100 fuel oil – with steam for process needs from the ITT-80-130/13 turbines. Thermodynamic analysis was performed using the following source data: steam temperature at the heat exchanger inlet is $T_{p.s.}= 510$ K, steam pressure at the heat exchanger inlet is $p_{p.s.} = 1.6 \cdot 10^6$ Pa, the temperature of condensed steam at the heat exchanger outlet is $T_{p.e.}= 475$ K, the degree of steam dryness at the heat exchanger inlet is $x_0 = 1$, the degree of steam dryness at the heat exchanger outlet is $x_0 = 0$; steam consumption is $G_s = 10$ kg/s, the temperature of fuel oil at the heat exchanger inlet is $T_{M1} = 343$ K, the temperature of fuel oil at the heat exchanger outlet is $T_{M2} = 403$ K, fuel oil consumption is $G_m = 169.57$ kg/s, pressure created by pumps is $\Delta p_p = 0.28 \cdot 10^6$ Pa, pump efficiency is $\eta_p = 0.75$.

The flow of exergy $E'_{p.s.}$, W, supplied with steam per time unit, is determined by the expression

$$E'_{p.s.} = G_s \left[ h_{p.s.} - h_{p.o.} - T_0 (s_{p.s.} - s_{p.o.}) \right],$$  \hspace{1cm} (4)

$h_{p.s.}$ and $s_{p.s.}$ are the enthalpy and entropy of steam at the heat exchanger inlet with the parameters $T_{p.s.}$, $p_{p.s.}$, J/kg and J/(kg·K); $h_{p.o.}$ and $s_{p.o.}$ are the enthalpy and entropy of steam at $T_0$ and $p_0$ for the climatic conditions of the Ulyanovsk region, J/kg and J/(kg·K).

The flow of exergy $E'_{f.s.}$, W, supplied to the heat exchanger with fuel per time unit, is calculated using the equation

$$E'_{f.s.} = G_m \left[ c_{p1}(T_{M1} - T_0) - T_0 c_{p1} \ln(T_{M1}/T_0) \right],$$  \hspace{1cm} (5)

c_{p1} is the average heat capacity of fuel at a temperature of $T_{av1} = 0.5(T_{M1} + T_0)$, J/(kg·K).

Heat is not supplied to the heat exchanger from the outside, otherwise than with substance flows, therefore $\Sigma E'_q = 0$.

Work $L'$, W, supplied to the system with flows due to the power of pumping units, is determined from the equation

$$L' = \frac{G_m \Delta p_p}{\eta_p \rho_{av1}},$$  \hspace{1cm} (6)

$\rho_{av1}$ is the average density of fuel at a temperature of $T_{av1}$, kg/m$^3$.

As a result, the sum of exergy flows at the heat exchanger inlet, determined from the equation (2), is $\Sigma E' = 18.119$ MW.
Then, the sum of the exergy flows at the heat exchanger outlet $\Sigma E''$ is calculated. The flow of exergy $E_{p,s}^*$, W, removed from the heater with steam-and-condensate mixture per time unit, is determined from the equation

$$E_{p,s}^* = G_s \left[ h_{p,e} - h_{p,o,e} - T_0 (s_{p,e} - s_{p,o}) \right],$$

(7)

$h_{p,e}, s_{p,e}$ are the enthalpy and entropy of steam-and-condensate mixture at the heat exchanger outlet, $h_{p,e} = 858.61 \cdot 10^3$ J/kg, $s_{p,e} = 2.344 \cdot 10^3$ J/(kg·K) at $T_{p,e} = 475$ K, $p_{p,e} = 1.6$ MPa, $x_b = 0$.

The flow of exergy $E_{f,s}^*$, W, removed from the heat exchanger with fuel per time unit, is calculated using the equation

$$E_{f,s}^* = G_f \left[ c_{p,2} \left( T_{M2} - T_0 \right) - T_0 c_{p,2} \ln \left( T_{M2} / T_0 \right) \right],$$

(8)

c_{p,2} is the average heat capacity of fuel oil at a temperature of $T_{av,2} = 0.5(T_{M2} + T_0)$, J/(kg·K).

Since useful heat and work are not removed from the system, we take $\Sigma E_q'' = 0$ and $\Sigma L'' = 0$.

As a result, the sum of exergy flows at the outlet of the system, determined from the equation (3), is $\Sigma E'' = 15.133$ MW.

An exergy diagram for the scheme of fuel oil heating in a heater, with steam for process needs from a turbine, is presented in figure 1.

![Exergy Diagram](image)

**Figure 1.** The exergy diagram for the process of fuel oil heating with steam for process needs from the PT-80-130/13 turbine.

The exergy efficiency of reserve fuel oil heating with steam for process needs from a turbine, determined from the equation (1), is $\eta_{ex1} = 0.835$.

Based on the similar methodology using the equations (1) – (8), let us calculate the exergy efficiency for the scheme of the HHO heating with steam of the 5th regenerative bleed-off from the T-100/120-130 turbine. Specific feature of the HHO use resides in the fact that there is no need for high-temperature heating, therefore, it is possible to significantly reduce the temperature to 30ºC as well as the heated coolant consumption to 58.33 kg/s, and this will be sufficient to maintain an average temperature of 20–25ºC in the fuel tank, wherein an acceptable viscosity of the HHO is ensured.

Thermodynamic analysis of the second scheme involves the following source data: steam temperature and steam pressure at the heat exchanger inlet are $T_{p,s} = 406$ K and $p_{p,s} = 0.25 \cdot 10^6$ Pa, the temperature of condensed steam at the heat exchanger outlet is $T_{p,e} = 406$ K, the degree of steam dryness at the heat exchanger inlet and outlet is $x_a = 1$ and $x_b = 0$, steam consumption is $G_s = 0.9$ kg/s,
the temperature of the HHO at the heat exchanger inlet is \( T_{HHO1} = 283 \text{ K} \), the temperature of the HHO at the heat exchanger outlet is \( T_{HHO2} = 303 \text{ K} \), the HHO consumption is \( G_{HHO} = 58.33 \text{ kg/s} \); additional pressure created by pumps is \( \Delta p_p = 0.28 \cdot 10^6 \text{ Pa} \); pump efficiency is \( \eta_p = 0.75 \).

The flow of exergy \( E'_{p.s.} \), W, supplied with steam per time unit, is determined by the equation (4) \( E'_{p.s.} = 0.951 \text{ MW} \). The flow of exergy \( E'_{HHO1} \), W, supplied to the heat exchanger with the HHO per time unit, is determined by the equation (5) \( E'_{HHO1} = 0.282 \text{ MW} \). Heat is not supplied to the heat exchanger from the outside, otherwise than with substance flows, therefore \( \Sigma E'_q = 0 \). Work \( L' \), W, supplied to the system with flows due to the power of pumping units, determined from the equation (6), is \( L' = 0.023 \text{ MW} \). The sum of exergy flows at the heat exchanger inlet, determined from the equation (2), is \( \Sigma E' = 1.256 \text{ MW} \).

The flow of exergy \( E'^*_{p.s.} \), W, removed from the heat exchanger with condensed steam per time unit, calculated using the equation (7), is \( E'^*_{p.s.} = 0.169 \text{ MW} \). The flow of exergy \( E'^*_{HHO2} = 0.655 \text{ MW} \), removed from the heat exchanger with the HHO per time unit, can be derived from the equation (8). Since useful heat and work are not removed from the system, we take \( \Sigma E''_q = 0 \) and \( \Sigma L'' = 0 \). Then, using the equation (3), it is possible to determine the sum of exergy flows at the heat exchanger outlet, and we get \( \Sigma E'' = 0.824 \text{ MW} \). The calculation results are presented in figure 2 in the form of an exergy diagram. The exergy efficiency for the scheme of the HHO heating with steam of the 5th regenerative bleed-off from the T-100/120-130 turbine, calculated using the equation (1), is \( \eta_{ex2} = 0.656 \).

The exergy diagram for the process of the HHO heating with steam of the 5th regenerative bleed-off from the T-100/120-130 turbine.

Based on the similar methodology using the equations (1)–(8), let us calculate the exergy efficiency for the scheme of the HHO heating with reversed network water in a water-fuel heat exchanger.

Thermodynamic analysis involves the following source data: the temperature of heating water at the heat exchanger inlet is \( T_{p.s.} = 323 \text{ K} \), the temperature of heating water at the heat exchanger outlet is \( T_{p.e.} = 308 \text{ K} \); heating water consumption is \( G_s = 31.28 \text{ kg/s} \); the temperature of the HHO at the heat exchanger inlet is \( T_{HHO1} = 283 \text{ K} \), the temperature of the HHO at the heat exchanger outlet is \( T_{HHO2} = 303 \text{ K} \), the HHO consumption is \( G_{HHO} = 58.33 \text{ kg/s} \); additional pressure created by pumps is \( \Delta p_p = 0.28 \cdot 10^6 \text{ Pa} \); pump efficiency is \( \eta_p = 0.75 \).

By substituting the source data in the equations (2)–(8), it is possible to determine the sum of exergy flows at the heat exchanger inlet and outlet, and we get \( \Sigma E' = 2.835 \text{ MW} \) at the inlet and \( \Sigma E'' = 2.735 \text{ MW} \) at the outlet.
Figure 3 presents the exergy diagram for the process of the HHO heating with reversed network water having a temperature of $t_{w.r.} = 50^\circ C$, with the values of exergy flows specified.

**Figure 3.** The exergy diagram for the process of the HHO heating with reversed network water in a water-fuel heat exchanger.

As a result, the exergy efficiency of the scheme for the HHO heating with the flow of reversed network water, calculated using the equation (1), is $\eta_{ex3} = 0.965$.

Since the temperature of network water is not constant, it varies in accordance with the heating system temperature curve, the dependence of the exergy efficiency on the temperature of reversed network water is determined for the scheme with a water-fuel heater, and the calculation results are presented in figure 4.

**Figure 4.** The dependence of the exergy efficiency of the scheme for the HHO heating in a water-fuel heater on the temperature of reversed network water.

As is seen from the diagram, with an increase in the temperature of heating water from 50°C to 70°C, a slight decrease in the value of exergy efficiency is observed, however, even at $t_{w.r.} = 70^\circ C$ $\eta_{ex3} = 0.944$, which is greater than the values of exergy efficiency of the other two schemes. This fact
proves that the process of the HHO heating with reversed network water has thermodynamic advantages and greater energy efficiency.

4. Conclusion

- To reduce thermal energy consumption for the needs of the reserve fuel facilities, at TPPs, provision is made to implement a transition to another types of reserve fuel, for example, to the HHO, as well as to change the traditional scheme of its heating using low-potential coolants, such as reversed network water and steam of the 5th regenerative bleed-off from extraction turbines.
- The comparative exergy analysis of the processes of heating reserve liquid fuel at TPPs using various coolants has been performed. The exergy efficiency for the traditional scheme of fuel oil heating with steam for process needs made $\eta_{ex1} = 0.835$, for the scheme of the HHO heating with steam of the 5th regenerative bleed-off from the T-100/120-130 turbine made $\eta_{ex2} = 0.656$, and for the scheme of the HHO heating with reversed network water made $\eta_{ex3} = 0.965$, which witnesses in favor of the fact that the latter scheme has thermodynamic advantages and greater energy efficiency.
- For the scheme of the HHO heating in a water-fuel heater, the dependence of the exergy efficiency on the temperature of reversed network water has been obtained.

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