Exergy pinch analysis of a furnace in a primary oil refining unit

Vladimir Lebedev*, Ekaterina Yushkova and Ivan Churkin

Saint-Petersburg Mining University, 2, 21st Line, St Petersburg 199106, Russia

Abstract. The article considers the issue of thermodynamic optimization of heat power equipment. The solution to this problem allows one to increase the energy efficiency of heat systems by reducing the energy resources consumption. The article compares the traditional (enthalpy) pinch method and the exergy pinch method. The exergy method of thermodynamic analysis allows one to take into account both quantitative and qualitative characteristics of thermal processes. A furnace that heats oil in the ELOU AT-6 primary oil refining unit was selected as an object of the study. The results obtained using the traditional pinch method showed that the furnace does not require optimization. However, the exergy analysis showed that the furnace has exergy losses. The method of exergy pinch analysis allows us to formulate and justify specific design measures aimed at increasing the furnace energy efficiency. Using the exergy pinch analysis, one can identify the unused exergy and determine the part in which the loss occurs.

1 Introduction

Currently, a fully developed approach is used to assess the energy efficiency of technical systems. This approach is based on the well-known energy, entropy and exergy methods of thermodynamic analysis. Each of these methods has well-known advantages, disadvantages, and limitations.

The energy (enthalpy) method of assessing energy efficiency was used at the early stages of the engineering and technology development. However, technologies are not remaining static and new methods should be developed. Although this method is still used in housing and communal services and industrial power engineering. In addition, the enthalpy method does not show the true value of various types of energy and energy resources [1-3].

The exergy approach allows one to get a more complete and objective assessment of various energy types. This method takes into account the energy quality and its ability to transform under the conditions of the studied object functioning [4-6].

When solving the problems of increasing the energy efficiency of technical systems, the issues of thermodynamic optimization of processes occurring in the elements of heat power equipment and in the heat power systems themselves are considered on a first-priority basis. One of the most effective methods for parametric optimization of heat energy processes is the pinch analysis or the method of thermal processes integration [7-9]. One of the main limitations of this method is its orientation toward the enthalpy approach to analysis and optimization of heat flows in the system under consideration. Thus, it becomes necessary to develop a method for thermodynamic analysis and improvement of technical systems, that would combine the advantages of the exergy method and the method of structural and parametric optimization of thermal processes based on pinch analysis.

In the pinch analysis theory, all heat flows can be divided into two groups. The first group includes flows that require cooling. They are called “hot flows”. Since the enthalpy of hot flows decreases when the flow is cooled, these flows will be characterized by a vector directed from right to left in temperature-enthalpy coordinates. The second group includes flows that require heating before onward work with them. They are called “cold streams” [7].

The change in flow enthalpy for various initial and final temperatures is expressed by the formula:

$$H = c_p \cdot m \cdot (T_1 - T_2),$$

where $c_p$ is the specific heat capacity of flow material at a constant pressure, $J/(kg\cdot K)$; $m$ is the mass consumption of the flow material, kg/s; $T_1$ is the final flow temperature, $T_2$ is the initial flow temperature, K; $H$ is the heat content of the flow, W.

Exergy at various initial and final temperatures is determined by the formula (2) [10, 11]:

$$E = c_p \cdot m \cdot \left[ T_1 - T_2 - T_0 \cdot \ln \frac{T_1}{T_2} \right],$$

where $c_p$ is the specific heat capacity of flow material at a constant pressure, $J/(kg\cdot K)$; $m$ is the mass consumption of the flow material, kg/s; $T_1$ is the final flow temperature, $T_2$ is the initial flow temperature, K; $T_0$ is the ambient air temperature, K.

One of the Russian oil refineries uses a furnace to heat oil at the ELOU AT-6 unit. The T-1B furnace is a

* Corresponding author: lebedev_va@spmi.ru

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vertical box-type furnace with high heating intensity. Each furnace has a section for heating the product, a section for superheated steam and a section for heating “hot oil” (coolant).

2 Conventional pinch analysis of the furnace

At the first stage of pinch analysis the heat flow of the furnace is determined. Here the analysis is carried out on the example of T-1B furnace. The T-1A and T-1B furnaces are identical, therefore, the calculations will be similar.

Calculation of the radiant section.

The lower calorific value of fuel is determined by the equation of Mendeleev:

\[ Q_{\text{low}} = \frac{42215.504}{p} \text{ kJ kg} \]

The hourly fuel consumption is:

\[ B = 0.863 \text{ kg/s} \]

The amount of gases produced when burning of 1 kg fuel is:

\[ m_{\text{CO}_2} = 0.03667 \cdot C = 0.03667 \cdot 85 = 3.117 \text{ kg / kg} \]

\[ m_{\text{H}_2\text{O}} = 0.09 \cdot H + 0.01 \cdot W + W_f = 0.09 \cdot 13 + 0.01 \cdot 0 + 0 = 1.17 \text{ kg / kg} \]

\[ m_{\text{O}_2} = L_0 \cdot (\alpha - 1) \cdot 0.232 = 14.26 \cdot (1.25 - 1) \cdot 0.232 = 0.8271 \text{ kg / kg} \]

\[ m_{\text{N}_2} = \alpha \cdot L_0 \cdot 0.768 = 1.25 \cdot 14.26 \cdot 0.768 = 13.6896 \text{ kg / kg} \]

\[ m_{\text{SO}_2} = 0.02 \cdot S = 0.02 \cdot 1 = 0.02 \text{ kg / kg} \]

The temperature of combustion products leaving the burner is:

\[ T_p = 1045.81 \text{ K} \]

The heat content of combustion products at a temperature of \( T_p = 1045.81 \text{ K} \) is determined by the formula (3):

\[ I = (T_p - 273) \cdot \left( m_{\text{CO}_2} \cdot C_{\text{CO}_2} + m_{\text{H}_2\text{O}} \cdot C_{\text{H}_2\text{O}} + m_{\text{O}_2} \cdot C_{\text{O}_2} + m_{\text{N}_2} \cdot C_{\text{N}_2} + m_{\text{SO}_2} \cdot C_{\text{SO}_2} \right) = (1045.81 - 273) \cdot (3.117 \cdot 1.06825 + 1.17 \cdot 2.0514 + 0.8271 \cdot 1.0071 + 13.6896 \cdot 1.07915 + 0.02 \cdot 0.7534) = 16638 \text{ kJ / kg} \]

The amount of heat transmitted to the product in a radiant section is calculated using the following expression:

\[ Q_p = \left( Q_{\text{low}} \cdot \eta_h - q_{\text{hot}} \right) \cdot B \]  

\[ H_{\text{hot1}} = Q = (42215.504 \cdot 0.96 - 16638.2) \cdot 0.863 = 20.615 \cdot 10^4 \text{ kJ / s} \]

Calculation of the convection chamber.

Oil passes through the convection chamber two times. In order to determine the amount of hot flow heat that are used for oil heating, the formula (1) is used:

\[ H_{\text{hot2}} = Q = 1.2 \cdot \frac{\text{kJ}}{\text{kg} \cdot ^\circ \text{C}} \cdot 23 \cdot \frac{\text{kg}}{\text{s}} \cdot (772.8^\circ \text{C} - 45^\circ \text{C}) = 8799 \frac{\text{kJ}}{\text{s}} = 8.79 \text{ MW} \]

\[ H_{\text{hot4}} = 1.2 \cdot \frac{\text{kJ}}{\text{kg} \cdot ^\circ \text{C}} \cdot 23 \cdot \frac{\text{kg}}{\text{s}} \cdot (398^\circ \text{C} - 293^\circ \text{C}) = 2898 \frac{\text{kJ}}{\text{s}} = 2.898 \text{ MW} \]

In the steam superheater hot flows are also calculated using the formula (1):

\[ H_{\text{hot5}} = 1.2 \cdot \frac{\text{kJ}}{\text{kg} \cdot ^\circ \text{C}} \cdot 23 \cdot \frac{\text{kg}}{\text{s}} \cdot (454^\circ \text{C} - 398^\circ \text{C}) = 1545 \frac{\text{kJ}}{\text{s}} = 1.545 \text{ MW} \]

Before entering the chimney, the exhaust gases heat the oil, which is the coolant in the air heater:

\[ H_{\text{hot5}} = 1.2 \cdot \frac{\text{kJ}}{\text{kg} \cdot ^\circ \text{C}} \cdot 23 \cdot \frac{\text{kg}}{\text{s}} \cdot (293^\circ \text{C} - 199^\circ \text{C}) = 2594 \frac{\text{kJ}}{\text{s}} = 2.594 \text{ MW} \]

Cold flows are calculated in a similar way using the formula (1).

The heat flow data of the T-1B furnace are presented in Table 1.

After calculating the enthalpy, it is necessary to plot the composite curves, which are presented in Figure 1.
The analysis shows that it is impractical to synthesize new heat flows, since after minimum converging of temperatures, the amount of recovery heat is 34.5 MW. Thus, the enthalpy method shows that the furnace hot heat flows almost completely give their heat to cold flows.

### 3 Exergy pinch analysis of the furnace

Heat flows in the furnace are already known.

The flow exergy is calculated by formula (2). The calculation data are presented in Table 2.

Further, it is necessary to convert the composite curves using the pinch analysis (Figure 2).

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### Table 1. Enthalpy of heat flows of the T-1B furnace.

| Flow                      | Initial temperature, °C | Final temperature, °C | Mass consumption kg/s | Mass heat capacity, kJ/kg·°С | Enthalpy, MW |
|---------------------------|-------------------------|-----------------------|------------------------|-------------------------------|--------------|
| Hot flow 1 Radiant section | 2211                    | 772.81                |                        |                               | 20.620       |
| Hot flow 2 Exhaust gases in convection section 1 | 772.81                   | 454                   | 23                     | 1.2                           | 8.799        |
| Hot flow 3 Exhaust gases in superheater | 454                      | 398                   | 23                     | 1.2                           | 1.545        |
| Cold flow 1 Steam in superheater | 142.67                   | 425.99                | 0.78                   | 7.84                          | -1.729       |
| Hot flow 4 Exhaust gases in convection section 2 | 398                      | 293                   | 23                     | 1.2                           | 2.898        |
| Cold flow 2 Petroleum | 243.8                    | 364                   | 119.6                  | 2.1                           | -30.189      |
| Hot flow 5 Exhaust gases heating oil | 293                      | 199                   | 23                     | 1.2                           | 2.59         |
| Cold flow 3 Oil | 160                      | 239                   | 15                     | 2.3                           | -2.72        |
2) It is possible to transfer exergy between processes (recovery) in the amount of 17.86 MW of exergy. The exergy method also determines the need to take into account fuel exergy. The main share of fuel exergy is its chemical exergy, as in practice fuel with parameters equal to ambient parameters are used. The chemical exergy was calculated for a number of gaseous and liquid organic substances by Z. Rant [12].

For a gaseous fuel, a molecule of which contains more than one carbon atom:

\[ e_0 = 0.95 \cdot Q_h \]  
(5)

Further we calculate the fuel exergy for the selected boiler according to formula (3). The considered fuel is mazut with higher calorific value of \( Q_h = 44.98 \text{ MJ} \), the consumption is 0.863 kg/s.

\[ E_{\text{fuel}} = 0.95 \cdot 44.98 \cdot 0.863 = 36.87 \text{ MW} \]

The furnace received 36.87 MW of fuel exergy, but the hot streams lost 27 MW of exergy. Consequently, the loss of fuel exergy is 27%. This makes it necessary to find ways to reduce exergy losses.

The ELOU AT-6 unit uses two furnaces to heat oil before the column 2. The presented analysis was performed for the T-1B furnace. The T-1A furnace and the T-1B furnace are similar to each other. It is impractical to analyze the T-1A furnace, since the flow data from the T-1B furnace differ slightly.

### 4 Conclusions

Conventional pinch analysis does not offer suggestions for reducing exergy losses. Exergy pinch analysis shows that the furnace loses high potential energy of 9.21 MW exergy. To optimize the furnace, it is necessary to reduce losses in the radiant section of the furnace (the upper section of the hot composite curve of Figure 2). Using the exergy pinch analysis, one can identify unused exergy and determine in which part the loss occurs.

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### Table 2. Exergy of heat flows of the T-1B furnace.

| Flow                                | Initial temperature, °C | Final temperature, °C | Exergy, MW |
|-------------------------------------|-------------------------|-----------------------|------------|
| Hot flow 1 Radiant section          | 2211                    | 772.81                | 17.23      |
| Hot flow 2 Exhaust gases in convection section 1 | 772.81                | 454                   | 5.97       |
| Hot flow 3 Exhaust gases in super heater | 454                   | 398                   | 0.89       |
| Cold flow 1 Steam in super heater   | 142.67                  | 425.99                | -0.87      |
| Hot flow 4 Exhaust gases in convection section 2 | 398                   | 293                   | 1.38       |
| Cold flow 2 Petroleum               | 243.8                   | 364                   | -15.85     |
| Hot flow 5 Exhaust gases heating oil | 293                   | 199                   | 1.5        |
| Cold flow 3 Oil                     | 160                     | 239                   | -1.13      |
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