Exergy pinch analysis of the primary oil distillation unit

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Abstract. The article is devoted to the issue of thermodynamic optimization of an oil refinery. Optimization is carried out by the exergy method of thermodynamic analysis, which allows you to take into account the quantitative as well as qualitative characteristics of thermal processes. The research uses the principles and rules of pinch analysis. Thus, the article discusses the task of optimizing oil refining processes using the pinch analysis method using exergy. The objective of the article is to increase energy efficiency by reducing exergy losses in technological processes of oil refining. The results of the study allow us to determine exergetic losses and propose measures to reduce them.

Improving the energy efficiency of technical systems is an urgent problem in the modern world, since all types of fuel are becoming more expensive [1]. At the moment, enough methods of energy efficiency analysis are known: energy, entropy and exergy. Each of these methods has its advantages and disadvantages.

To determine the effectiveness of technical systems, it is most rational to use a method that combines the use of the first and second laws of thermodynamics [2].

The method that includes both principles of thermodynamics is called thermodynamic. This method has two varieties: the exergy method (exergy flow method), the entropy method (exergy loss subtraction method).

Exergy makes it possible to assess the qualitative side of energy, i.e., the potential of energy resources.

Pinch analysis is a method of thermodynamic optimization that allows you to reduce the energy consumption of a process by calculating reasonable amounts of energy consumption and approaching them by optimizing heat transfer between processes. Using pinch technology, it is possible to select equipment and energy sources [3, 4, 5].

Pinch analysis uses enthalpy as the main research tool. Enthalpy does not take into account the heat potential. In this article, a pinch analysis of the installation using exergy (instead of enthalpy) is carried out, which can evaluate the heat flux potential and shows the dependence of the heat flux energy on the ambient temperature.

If the change in enthalpy $\Delta H$ occurs at a constant temperature $T$, then the change in exergy $\Delta Ex$ is defined as:

$$\Delta Ex = \Delta H \cdot \left(1 - \frac{T_0}{T}\right)$$

(1)
where \( T_0 \) – ambient temperature.

If the flow temperature is not constant, then the change in exergy is determined by the formula:

\[
\Delta Ex = \Delta H \cdot \left( 1 - \frac{T_0}{\Delta T_{LM}} \right)
\]

(2)

Where \( \Delta T_{LM} \) – logarithmic temperature difference.

Also, to determine exergy, the formula (3) could be used. This formula allows one to determine the exergy without calculating the enthalpy [6].

\[
\Delta Ex = c_p \cdot m \cdot \left[ T_1 - T_2 - T_0 \cdot \ln \frac{T_1}{T_2} \right]
\]

(3)

where \( C_p \) — specific heat of a flow substance at constant pressure, J/(kg·K); \( M \) — mass flow rate, kg/s; \( T \) — temperature, K; \( T_0 \) — ambient temperature, K.

In the exergy method, the optimization of the heat energy system involves the search for the maximum value of the exergy objective function, or the minimization of the reduced costs per unit exergy of the obtained product [7, 8]. The loss of exergy in this case is determined as the sum of the losses of private exergy flows in individual elements of the system. In a pinch analysis, exergy losses are determined in two ways:

- summation of the exergy losses of individual system flows,
- summation of exergy losses in temperature ranges [3].

A classic pinch analysis of a primary oil distillation unit was carried out in a scientific article [9]: heat fluxes were determined, composite curves were displayed on a T-H diagram, a grid diagram was developed with the placement of heat exchangers, and a process flow diagram of the setup was completed.

This article demonstrates the calculation of exergy losses in a primary oil distillation unit using a classical (enthalpy) pinch analysis. The data in article [9] are used.

Description of the ELOU-AT installation - 750 thousand tons of oil per year.

The primary oil refining unit is designed for oil refining. The installation combines the blocks of oil preparation for processing (ELOU), primary oil distillation (AT). The installation consists of: distillation column; furnaces for heating oil; heat exchange series, which is necessary for heating crude oil due to the heat of the waste product fractions; terminal air cooling apparatus (ABO); ELOU block; pumping equipment [9].

At the installation, primary distillation of oil is carried out to obtain diesel fractions and fuel oil. The stream data are presented in table 1.

**Table 1.** Stream data for the installation of the primary distillation of oil.

|                  | Initial temperature, \( ^\circ C \) | Final temperature, \( ^\circ C \) | Mass flow, kg/s | Enthalpy, MW |
|------------------|--------------------------------------|----------------------------------|-----------------|-------------|
| Oil              | 20                                   | 360                              | 48,6            | -46,26      |
| Fuel oil         | 350                                   | 85                               | 25,2            | 13,35       |
| Diesel fraction  | 260                                   | 45                               | 10,9            | 4,68        |
| Circulation irrigation | 260                               | 135                              | 34              | 15,89       |
We will calculate this installation only for summer operation. $\Delta T_{\text{min}}$ is determined and equal to 13 °C.

It should be noted that for calculating exergy all temperatures are translated on the Kelvin scale, but for clarity, in tables and graphs, temperatures are presented in degrees Celsius.

1. Determination of exergy changes using streaming data.

The calculation of the exergy of each stream is performed according to the formula (2).

**Calculation example of Cold Flow 1 (oil):**

$$\Delta E_{\text{Ex}} = -42.26 \left( 1 - \frac{293}{441.387} \right) = -15.554 \text{MW}$$

The other heat flows are calculated similarly.

Next, we consider the external sources of energy.

The missing energy (14 MW), which is necessary for heating oil to 360 °C, is supplied from an external heat source, i.e. from the P-401 furnace, as shown in figure 1. From the technical passport of the furnace we find the change in the temperature of the flue gases 660 °C – 138 °C.

![Figure 1](image)

**Figure 1.** Placement of heat exchangers using classical pinch analysis (flow chart).

The amount of exergy that the furnace gives is determined by the formula (1):

$$\Delta E_{\text{Ex, furnace}} = 14 \left( 1 - \frac{293}{636.14} \right) = 7.558 \text{MW}$$

Fuel oil flow needs to be re-cooled. An air cooler is used for this purpose. The air temperature of the refrigerator is taken equal to the ambient temperature. We calculate the amount of air exergy according to the formula (1):

$$\Delta E_{\text{Ex, air}} = 1.1 \left( 1 - \frac{293}{293} \right) = 0 \text{MW}.$$  

The calculation results are presented in table 2.

| Exergy, MW |
|------------|
| Oil Cold flow 1 | -15,554 |
| Fuel oil Hot flow 2 | 5,175 |
Consequently, the installation loses 4.504 MW of exergy.

2. Determination of changes in exergy using compound curves. Similar calculations are performed using the temperature ranges of the composite curves as in figure 2. We divide the composite curves into temperature intervals, at each interval we determine the exergy of the hot composite curve and the cold composite curve. The results are presented in table 3.

Exergy losses are also 4.504 MW.

So, using the traditional exergy method, the total exergy loss in the system can be determined, calculating the losses on each individual device and then summing them up. The result is the same, but for this it is necessary to have a ready-made project for the heat and power system of the enterprise, and pinch analysis allows you to determine the loss of exergy for the optimal technological scheme of the enterprise before the project is completed.

![Figure 2](image)

**Figure 2.** Display of composite curves in a T-H diagram.

| Temperature intervals, °C | Exergy of hot composite curve, MW | Exergy of cold composite curve, MW |
|---------------------------|----------------------------------|-----------------------------------|
| Oven                      | 7,558                            | -                                 |
| 360-350                   | -                                | -0.725                            |
| 350-260                   | 2,232                            | -6.026                            |
| 260-247                   | 1,149                            | -0.784                            |
| 247-135                   | 8,159                            | -5.569                            |
Thus, it is advisable to determine the exergy loss by pinch analysis. But the traditional pinch analysis does not offer suggestions for reducing exergy losses. Further in the article, optimization of the primary oil distillation unit by exergy pinch analysis is proposed. For this, in the graphs, instead of a change in enthalpy, a change in exergy is used.

3. Exergy pinch analysis
Flow exergy has already been calculated and is presented in table 2.

Next, hot and cold flows in the exergy-temperature coordinate system are depicted, as presented in figure 3-4.

Next, one need to convert the composite curves using the pinch analysis method, as shown in figure 5.
Figure 5. Transformed heat stream in the exergy-temperature coordinate system.

Compound curves are reduced to a minimum temperature $\Delta T_{\text{min}} = 13 \, ^\circ C$.

The theory of pinch analysis states that composite curves have a section whose projection onto the enthalpy axis is not overlapped by the projection of the second curve. That is, a cold composite requires an external heat source, and a hot composite curve requires additional external cooling.

Exergetic pinch analysis data are presented in table 4.

| Component                      | Exergy, MW |
|--------------------------------|------------|
| Oil Cold flow 1                | -15,554    |
| Fuel oil Hot flow 2            | 5,175      |
| Diesel fraction Hot flow 3     | 1,388      |
| Circulation irrigation Hot flow 4 | 5,937   |
| Oven External hot heat source  | 4,1        |
| Air (fridge) External cold heat source | -1,1  |

**Table 4.** Exergy changes with streaming data.

This method allows using almost all of the exergy in the system.

So, having analyzed the graph of composite curves (figure 5), one can determine the features of thermal processes in the installation:

- The cold composite curve needs an external heat source that produces 4.1 MW of exergy. Moreover, the project presented in figure 1 requires an external heat source of 7.558 MW exergy, and does not use 4,503 MW (loss of exergy in the installation). Thus, it is possible to formulate recommendations on the source of heat: use a less powerful furnace or make structural changes to it.
- The hot composite curve loses low-grade heat with an exergy of 1.1 MW. To increase the efficiency of the installation, one can use this heat for technological needs.

**Conclusion**

In this article, the exergy losses of the primary oil distillation unit are calculated by the pinch analysis method. The exergy loss is 4,503 MW. But the traditional pinch analysis does not offer suggestions for reducing exergy losses.
After conducting an exergy pinch analysis of the primary oil distillation unit, the article proposes measures to optimize the project. This analysis allowed us to reduce exergetic losses without bringing together the composite curves (without decreasing $\Delta T_{\text{min}}$).

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