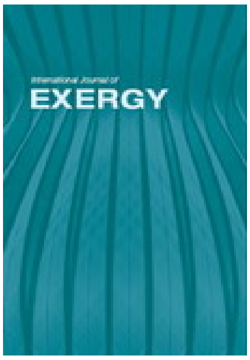

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The use of pinch analysis technology to assess the energy efficiency of oil refining technologies

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Abstract: Exergy pinch-analysis of the heat exchange system of the furnace of the primary oil refining unit is carried out. Composite curves are created using a mathematical model, and then the optimal structure of the heat exchange with minimal exergy losses is constructed. Exergy pinch analysis allows revealing the magnitude and location of exergy losses. In the heat exchange system of the furnace exergy loss is 9 MW. It is possible to increase the efficiency of the furnace by 18.5%. An additional heat exchanger connecting it to the oil stream is introduced for rational use of residual exergy.

Keywords: exergy; exergoeconomic; pinch analysis; exergy pinch analysis; heat exchanger system; primary distillation of oil.

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Biographical notes: Ekaterina Yushkova completed her Postgraduate studies in the specialty 'Industrial Heat Power Engineering' of St. Petersburg Mining University in 2020. Her research covers a number of different areas of thermodynamics and heat transfer, mainly focusing on exergy analysis, pinch analysis and their combination.

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1 Introduction

Today, improving energy efficiency is an urgent task (Muraveinikov et al., 2019). Energy efficient technologies can reduce the consumption of natural resources and decrease environmental damage (Malarev et al., 2021; Tsvetkov et al., 2020). Many scientists are creating energy efficient technologies (Kopteva et al., 2021; Morenov et al., 2020; Sobota et al., 2019; Tsvetkov, 2021).

There are many different methods for assessing energy efficiency (Shabalov et al., 2021; Boguslavskii and Fitsak, 2017). The current areas of research are enthalpy, exergy, exergoeconomic and exergoecological analysis. Exergy analysis is a powerful tool for measuring power quality, thereby helping to make complex thermodynamic systems more efficient.

The oil refining industry is energy intensive (Bazhin and Titov, 2017; Nedosekin et al., 2019; Ponomarenko et al., 2020). Oil refineries have a large amount of heat flows, with large potentials for thermal energy. One of the effective methods for optimising heat flows is pinch analysis.

Pinch analysis makes it possible to represent a large number of heat flows, in the form of a hot composite curve (heat generating flows) and a cold composite curve (heat demanding flows). Pinch analysis optimises the heat exchange system by bringing the composite curves to the minimum temperature difference. The optimised heat exchange system has maximum flow recovery and minimum external energy costs. Then structural optimisation is carried out using a special algorithm.

Many refineries use this method with the help of special software (Aspenn Energy Analysis). However, the pinch analysis is based on the enthalpy approach. In order to give a more objective and complete assessment of various types of energy, one should resort to the exergy approach, which takes into account another important characteristic of energy – its quality.

Zhang et al. (2018) investigates a blast furnace. The paper proposes energy efficiency improvements through heat recovery and mixture preheating. The blast furnace has the highest exergy loss.

Bejan and Tsatsaronis (2021) and Bandyopadhyay et al. (2019) conducted studies using exergy and pinch analysis.

Aspelund et al. (2007) represent an extended pinch analysis and design procedure utilising pressure based exergy. This methodology combines the search for the minimum external energy carriers (pinch analysis) with the minimisation of irreversibility (exergy analysis). This method uses ten heuristic rules for the design. The improvement is achieved by maximising the use of pressure changes in the flows. The object of the research is low-temperature processes.

Marmolejo-Correa and Gundersen (2015) present different classifications of exergy. The study presents a combination of two methods: exergy and pinch analysis, hot and cold composite curves are constructed in the enthalpy-temperature and exergy-temperature planes. The detected excess of exergy is equal to the destruction of exergy due to thermodynamic irreversibility. The object of the research is low-temperature processes.

Goodarzvand-Chegini and GhasemiKafrudi (2017) use pinch analysis and exergy analysis in their research. Exergy analysis determines the possibilities for increasing energy recovery. The object of the research is the process of hydrocracking.

Mehdizadeh-Fard et al. (2021) states that it is possible to conduct an exergy analysis of a heat exchanger system using pinch analysis. The advantage is that you can evaluate the system as a whole, rather than considering each heat exchanger individually.

Thus, the exergy pinch analysis shows which exergy losses can be reduced. The research on reducing exergy loss is presented below.

Sheikholeslami et al. (2020) presents measures to improve the efficiency of heat exchangers. The exergy loss is inversely proportional to the increase in the pump power. To reduce exergy losses, it is necessary to decrease the Renolds number.

The system can be exergically and energetically optimised by minimising avoidable exergy degradation.

Manjunath and Kaushik (2014) confirm that the second law and constructive theory can be used together to improve the performance of heat exchangers. Exergy analysis has the potential to pinpoint where energy degradation occurs in a process, and also provides an alternative way to evaluate and compare processes (Doohan et al., 2016).

There are different variations on the use of both pinch analysis and exergy analysis. The object of the research is low-temperature processes in many cases, and systems with a large number of heat exchangers are also the object of the research. The novelty of this study is the analysis of the furnace of the primary oil distillation unit with the help of exergy pinch analysis. The furnace heats the petroleum before the distillation column. In this study, all stages of exergy pinch analysis are presented: heat flows are determined, composite curves are plotted, exergy losses are found, and the optimal furnace heat exchange system is constructed. A mathematical model is presented that makes it possible to construct composite curves for hot and cold flows, taking into account exergy losses.

2 Procedure for exergy pinch analysis

2.1 Parametric optimisation by exergy pinch analysis

The first stage of the exergy pinch analysis is the construction of composite curves and their convergence to the minimum temperature difference. The optimisation criterion is to minimise exergy losses (Lebedev and Yushkova, 2020). This is represented by formula (1):

$$\sum \Delta Ex \to \min \tag{1}$$

where $\sum \Delta Ex$ is the sum of exergy losses in the system.

To fulfil the optimisation criterion, it is necessary that the difference between the exergy of hot and cold flows tends to minimum. Many heating exchange systems require external costs: additional heating or cooling. External costs are the financial burden of the enterprise. Taking into consideration mentioned above, in order to optimise the heat exchange system, in addition to convergence of the compound curves to ΔTmin, the following formula should be used (2):

$$\begin{aligned}
&\sum \Delta Ex = |ex_h| - |ex_c| + |Ex_{UH}| - |Ex_{UC}|, \\
&|ex_h| - |ex_c| \to \min, \\
&\sum Ex_{UH} \to \min, \\
&\sum Ex_{UC} \to \min,
\end{aligned} \tag{2}$$

where ex_h is the exergy of the hot composite curve, ex_c is the exergy of a cold composite curve, Ex_{UH} is the exergy of external hot energy carriers, Ex_{UC} is the exergy of external cold energy carriers.

For a standard pinch analysis (using enthalpy), various mathematical models for constructing composite curves have been developed (Agapov, 2011). A mathematical model for exergy pinch analysis is presented below. Input data for the model are formed as four matrices. The first matrix includes input data for hot flows [formula (3)]; the second matrix contains input data for cold flows [formula (4)]. One line describes one heat flow. The number of hot flows is denoted by *n*, the number of cold flows by *m*. The two matrices have five columns. The first column is the initial temperatures of the flows, the second column is the final temperatures, the third column is the ambient temperature, the fourth column is the natural logarithms of the ratio of initial temperature to final temperature, and the fifth column is the heat capacity flow rate (CP kW/°C). This is the product of the flow rate (m) in kg/s and the specific heat capacity (Cp kJ/kg°C). $CP = m \times Cp$. Temperatures are presented in Kelvin. The initial and final heat flow temperatures from the source data matrices (3) and (4) are divided into temperature intervals in matrices (5) and (6), taking into account the temperature rise.

$$Ex_H = \begin{vmatrix}
T_{h.in.1} & T_{h.f.1} & T_{0.h.1} & \ln\dfrac{T_{h.in.1}}{T_{h.f.1}} & CP_{h.1} \\
T_{h.in.2} & T_{h.f.2} & T_{0.h.2} & \ln\dfrac{T_{h.in.2}}{T_{h.f.2}} & CP_{h.2} \\
\cdots & \cdots & \cdots & \cdots & \cdots \\
T_{h.in.n-1} & T_{h.f.n-1} & T_{0.h.n-1} & \ln\dfrac{T_{h.in.n-1}}{T_{h.f.n\text{-}1}} & CP_{h.n-1} \\
T_{h.in.n} & T_{h.f.n} & T_{0.h.n} & \ln\dfrac{T_{h.in.n}}{T_{h.f.n}} & CP_{h.n}
\end{vmatrix}. \tag{3}$$

$$Ex_C = \begin{vmatrix}
T_{c.in.1} & T_{c.f.1} & T_{0.c.1} & \ln\dfrac{T_{c.in.1}}{T_{c.f.1}} & CP_{c.1} \\
T_{c.in.2} & T_{c.f.2} & T_{0.c.2} & \ln\dfrac{T_{c.in.2}}{T_{c.f.2}} & CP_{c.2} \\
\cdots & \cdots & \cdots & \cdots & \cdots \\
T_{c.in.m-1} & T_{c.f.m-1} & T_{0.c.m-1} & \ln\dfrac{T_{cin.m-1}}{T_{c.f.m\text{-}1}} & CP_{c.m-1} \\
T_{c.in.m} & T_{c.f.m} & T_{0.c.m} & \ln\dfrac{T_{c.in.m}}{T_{c.f.m}} & CP_{c.m}
\end{vmatrix}. \tag{4}$$

$$T_H = \begin{vmatrix} T_{h1} \\ T_{h2} \\ \dots \\ T_{hk-1} \\ T_{hk} \end{vmatrix}. \tag{5}$$

$$T_C = \begin{vmatrix} T_{c1} \\ T_{c2} \\ \dots \\ T_{ck-1} \\ T_{ck} \end{vmatrix}. \tag{6}$$

The functional dependences that form the composite curve of hot flows have the form (7):

For the first temperature range:

$$ex_h = \left(T_{h2} - T_{h1} - T_o \ln \frac{T_{h2}}{T_{h1}} \right) \sum_{i=1}^{n} CP_{hi} \Big|_{T_{h1}}^{T_{h2}}, T_{h1} < T_{h2};$$

For the first and second temperature ranges:

$$ex_h = \left(T_{h2} - T_{h1} - T_o \ln \frac{T_{h2}}{T_{h1}} \right) \sum_{i=1}^{n} CP_{hi} \Big|_{T_{h1}}^{T_{h2}} + \left(T_{h3} - T_{h2} - T_o \ln \frac{T_{h3}}{T_{h2}} \right) \sum_{i=1}^{n} CP_{hi} \Big|_{T_{h2}}^{T_{h3}}, T_{h1} < T_{h2} < T_{h3};$$

For $(k-1)^{\text{th}}$ temperature intervals:

$$ex_h = \sum_{j=1}^{j=k-1} \left[\left(T_{hj} - T_{h(j-1)} - T_o \ln \frac{T_{hj}}{T_{h(j-1)}} \right) \sum_{i=1}^{n} CP_{hi} \Big|_{T_{h(j-1)}}^{T_{hj}} \right]$$
$$+ \left(T_{hk} - T_{h(k-1)} - T_o \ln \frac{T_{hk}}{T_{h(k-1)}} \right) \sum_{i=1}^{n} CP_{hi} \Big|_{T_{h(k\text{-}1)}}^{T_{hk}}, T_{h(k\text{-}2)} < T_{h(k-1)} < T_{hk};$$

For k^{th} temperature intervals:

$$ex_h = \sum_{j=1}^{j=k} \left[\left(T_{hj} - T_{h(j-1)} - T_o \ln \frac{T_{hj}}{T_{h(j-1)}} \right) \sum_{i=1}^{n} CP_{hi} \Big|_{T_{h(j\text{-}1)}}^{T_{hj}} \right], T_{h(k-1)} < T_{hk}. \tag{7}$$

The functional dependencies that form the composite cold flows have the form (8):

For the first temperature range:

$$ex_c = \left(T_{c2} - T_{c1} - T_o \ln \frac{T_{c2}}{T_{c1}} \right) \sum_{i=1}^{n} CP_{ci} \Big|_{T_{c1}}^{T_{c2}}, T_{c1} < T_{c2};$$

For the first and second temperature ranges:

$$ex_c = \left(T_{c2} - T_{c1} - T_o \ln\frac{T_{c2}}{T_{c1}}\right)\sum_{i=1}^{n} CP_{ci}\Big|_{T_{c1}}^{T_{c2}} + \left(T_{c3} - T_{c2} - T_o \ln\frac{T_{c3}}{T_{c2}}\right)\sum_{i=1}^{n} CP_{ci}\Big|_{T_{c2}}^{T_{c3}}, T_{c1} < T_{c2} < T_{c3};$$

For $(k-1)^{\text{th}}$ temperature intervals:

$$ex_c = \sum_{j=1}^{j=k-1}\left[\left(T_{cj} - T_{c(j-1)} - T_o \ln\frac{T_{cj}}{T_{c(j-1)}}\right)\sum_{i=1}^{n} CP_{ci}\Big|_{T_{c(j-1)}}^{T_{cj}}\right] + \left(T_{ck} - T_{c(k-1)} - T_o \ln\frac{T_{ck}}{T_{c(k-1)}}\right)\sum_{i=1}^{n} CP_{ci}\Big|_{T_{c(k-1)}}^{T_{ck}}, T_{c(k-2)} < T_{c(k-1)} < T;$$

For k^{th} temperature intervals:

$$ex_c = \sum_{j=1}^{j=k}\left[\left(T_{cj} - T_{c(j-1)} - T_o \ln\frac{T_{cj}}{T_{c(j-1)}}\right)\sum_{i=1}^{n} CP_{ci}\Big|_{T_{c(j-1)}}^{T_{cj}}\right], T_{c(k-1)} < T_{ck}. \quad (8)$$

Functional dependencies (7 and 8) are composite curves that sequentially sum up exergy at each temperature interval.

This mathematical model is used for flows without phase transitions.

Thermomechanical exergy includes exergy based on temperature Ex^T and pressure Ex^P (Marmolejo-Correa and Gundersen, 2015).

The model is applicable for systems where pressure changes can be neglected, i.e., it is possible to use only Ex^T. In the process of optimisation, there is a necessity for the process of convergence of the composite curves relative to the abscissa axis to ΔTmin, taking into account the optimisation criterion represented by formulas (1) and (2). The temperature head must not be less than the minimum value (Smith et al., 2000): minimum value of ΔTmin for shell-and-tube heat exchangers is 10°C; minimum value of ΔTmin for plate heat exchangers is 5°C; minimum value of ΔTmin for plate-fin heat exchangers is 1°C–2°C. If the temperature difference is reduced, the heat exchange area will increase, which is not economically viable.

By approaching the composite curves to ΔTmin, we increase heat recovery and bring the need for external energy carriers to a minimum.

Table 1 Initial data for the heat exchange system from the example

	Initial temperature, °C	*Final temperature, °C*	*Initial temperature, K*	*Final temperature, K*	*The heat capacity flow rate (CP)*	*Exergy, W*
Hot stream 1	120	100	393	373	14	65.7476
Hot stream 2	140	90	413	363	10	121.899
Cold stream 1	60	100	333	373	7	–47.343
Cold stream 2	90	110	363	383	40	–171.43

We will give an example of constructing composite curves using the exergy pinch analysis method for a better understanding of the operation of the mathematical model. The initial data of the system are presented in Table 1. The system includes two cold and two hot streams.

To begin with, we present the initial stream data in matrices for hot and cold flows, respectively:

$$Ex_H = \begin{vmatrix} 393 & 373 & 293 & \ln\frac{393}{373} & 14 \\ 413 & 363 & 293 & \ln\frac{413}{363} & 10 \end{vmatrix};$$

$$Ex_C = \begin{vmatrix} 333 & 373 & 293 & \ln\frac{333}{373} & 7 \\ 363 & 383 & 293 & \ln\frac{363}{383} & 40 \end{vmatrix}.$$

Then we arrange the initial and final temperatures of the flows, taking into account the increase for hot and cold flows:

$$T_H = \begin{vmatrix} 363 \\ 373 \\ 393 \\ 413 \end{vmatrix};$$

$$T_C = \begin{vmatrix} 333 \\ 363 \\ 373 \\ 383 \end{vmatrix}.$$

These matrices allow the flows to be divided into temperature intervals. The first temperature interval for hot streams is from 363 K to 373 K (from 90°C to 100°C). To construct a hot composite curve, we use expression (7). Exergy at the first temperature interval is:

$$ex_h = \left(363 - 373 - 293\ln\frac{363}{373}\right)\cdot 10 = 20.37\ W,$$

Exergy in the first and second temperature intervals is:

$$ex_h = \left(363 - 373 - 293\ln\frac{363}{373}\right)\cdot 10 + \left(363 - 373 - 293\ln\frac{363}{373}\right)\cdot(10+14) = 133\ W.$$

As a result, the total exergy over three intervals is equal to (This is the fourth point to plot the hot curve):

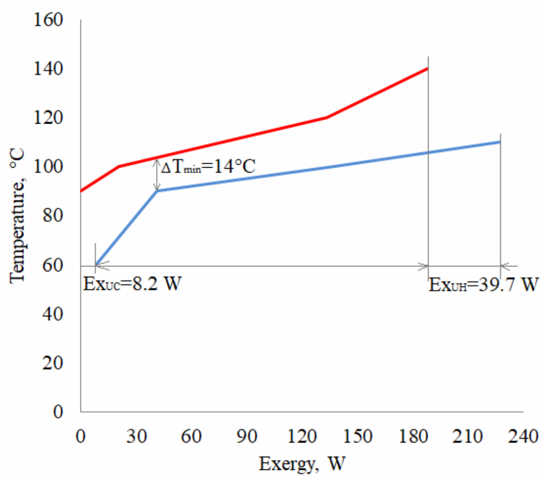
$$ex_h = \left(363 - 373 - 293\ln\frac{363}{373}\right)\cdot 10 + \left(393 - 373 - 293\ln\frac{393}{373}\right)\cdot(10+14)$$
$$+\left(413 - 393 - 293\ln\frac{413}{393}\right)\cdot 10 = 187.64\ W.$$

The points for building a hot composite curve are:

- 363 K (90°C) – 0 W
- 373 K (100°C) – 20.37 W
- 393 K (120°C) – 133 W
- 413 K (140°C) – 187.64 W

Thus, we combine two hot steams into one and build a curve in the axes temperature – exergy.

Figure 1 Approximate composite curves up to Δ*T*min = 14°C (see online version for colours)



The cold composite curve is calculated similarly.

Exergy at the first temperature interval is:

$$ex_c = \left(363 - 333 - 293\ln\frac{363}{333}\right)\cdot 7 = 33\ W,$$

Exergy in the first and second temperature intervals is:

$$ex_c = \left(363 - 333 - 293\ln\frac{363}{333}\right)\cdot 7 + \left(373 - 363 - 293\ln\frac{373}{363}\right)\cdot(40+7) = 128.84\ W.$$

As a result, the total exergy over three intervals is equal to:

$$ex_c = \left(363 - 333 - 293\ln\frac{363}{333}\right)\cdot 7 + \left(373 - 363 - 293\ln\frac{373}{363}\right)\cdot(40+7)$$
$$+\left(383 - 373 - 293\ln\frac{383}{373}\right)\cdot 40 = 218.77\,W;$$

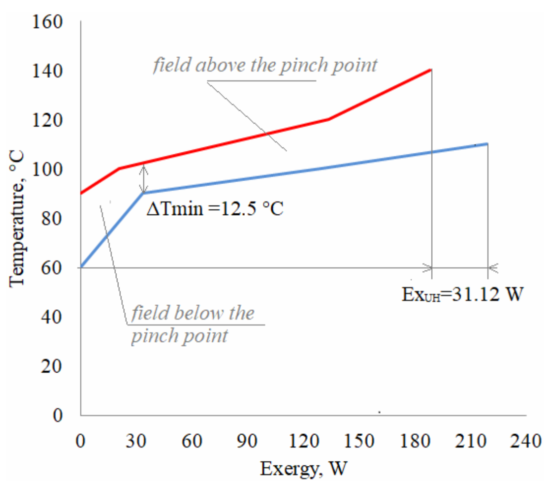
The functions $ex_h(T)$ and $ex_c(T)$ are depicted on the temperature-exergy plane. Then the procedure of convergence of composite curves is performed, in this example up to ΔTmin = 14°C (Figure 1). In this case, we are using external energy to heat up the residuals of cold streams from 105.7°C to 110°C Ex_{UH} = 39.7 W, and we use external energy to cool the hot stream from 95°C to 90°C Ex_{UC} = 8.2 W.

We can improve the system by reducing the temperature difference of the system to 12.5°C (Figure 2). In this case, we do not need external cold energy carriers Ex_{UC} = 0 W, and hot external energy carriers have been decreased to Ex_{UH} = 31.12 W.

Marmolejo-Correa and Gundersen (2015) say that Ex_{UH} is a deficit of exergy, which is not enough to heat cold streams. But above the pinch point, the required exergy is the sum of Ex_{UH} and exergy destruction: $\Delta Ex_{requirement,min} = \Delta Ex_{deficit,min} + \Delta Ex_{destruction,min}$.

Therefore, the required exergy will be higher than 31.12 W per destruction exergy.

Figure 2 Approximate composite curves up to ΔTmin = 12.5°C (see online version for colours)



2.2 *Structural optimisation by exergy pinch analysis*

The last step in the exergy pinch analysis is the construction of a heat exchanger system. When designing heat exchanger systems, a set of traditional pinch analysis rules is used, but exergy balances are used instead of enthalpy balances (Smith et al., 2000):

1 The flows are divided into two types: heat flows above the pinch point and heat flows below the pinch point.

2 The design of connections starts from the pinch point.

3 To build a connection between heat exchangers, the following rules must be followed:

- it is possible to build a heat exchanger above the pinch point if CP hot is $\leqslant$ CP cold
- it is possible to build a heat exchanger below the pinch point if CP hot is $\geqslant$ CP cold.

where CP is the heat capacity flow rate.

4 The flows that have met their exergy requirements are marked with a check mark. Thus, you can clearly see which streams still need exergy.

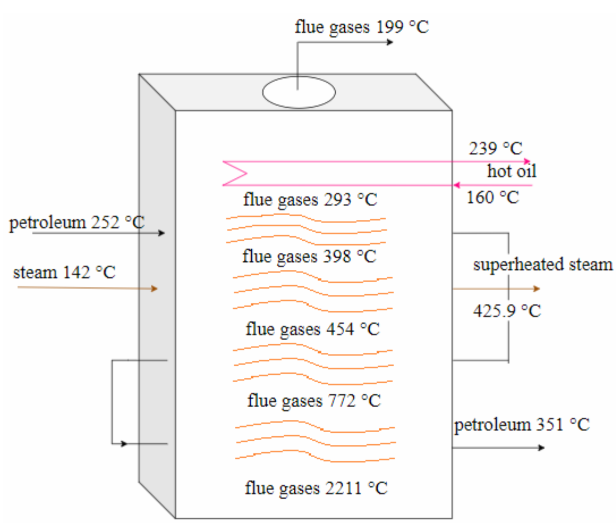
5 Heat exchange connections are built until all exergy of the system is exhausted

3 Improving the energy efficiency of the heat exchange system of the furnace for heating oil before the distillation column

The object of the research is the source of thermal energy of the primary oil distillation unit – a furnace for heating oil before the distillation column. The analysis was carried out by two methods – traditional (enthalpy) pinch analysis and exergy pinch analysis. It is necessary for comparison of the two methods.

A traditional (enthalpy) pinch-analysis of the source of thermal energy of the primary oil refining unit (furnace) has been carried out. To analyse the heat exchange system of the furnace, heat flows were determined. The flows in the furnace are distributed as follows: hot streams – flue gases that give off their heat, cold flows – steam, petroleum, oil. The heat flows of the furnace are shown in the diagram (Figure 3).

Figure 3 Scheme of the furnace (see online version for colours)



The first method for analysis is traditional pinch analysis.

The constructed composite curves of the furnace heat flows are shown in Figure 4. The curves are reduced to ΔTmin = 56°C. As the enthalpy method shows, the hot heat flows of the furnace almost completely give up their energy to the cold flows. Therefore, the system is optimal.

Figure 4 Converted heat flows of the furnace in the 'enthalpy-temperature' coordinate system (see online version for colours)

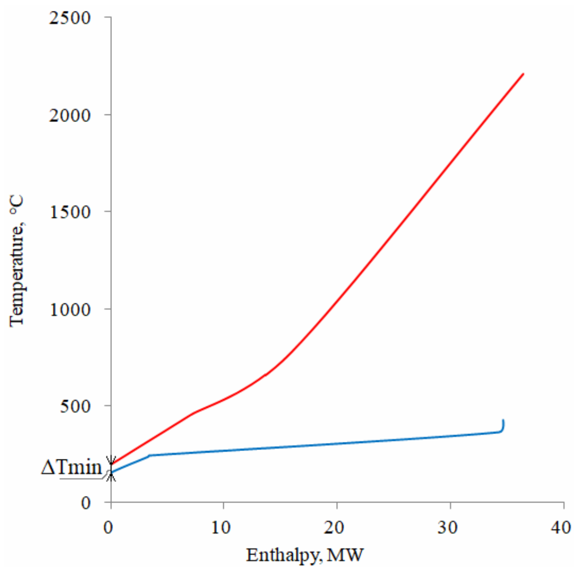
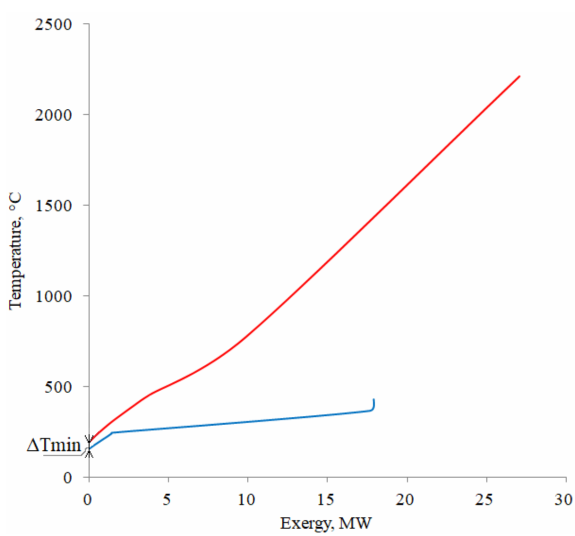


Figure 5 Converted heat flows of the furnace in the 'exergy-temperature' coordinate system (see online version for colours)



The second method for analysis is exergetic pinch analysis.

The specific heat capacity of flue gases depends on the temperature. In this solution, we use a simplified model for the preliminary calculation and take the heat capacity flow rate of flue gases constant.

Parametric optimisation of the furnace heat exchange system was carried out using a mathematical model (the model is described in paragraph 2.1 of this article). The initial data of heat flows are represented by two matrices:

$$Ex_{Hot} = \begin{vmatrix} 2{,}484 & 1{,}045 & 273 & \ln\dfrac{2{,}484}{1{,}045} & 27.6 & \textit{Flue gases in the radiant section of the furnace} \\ 1{,}045 & 727 & 273 & \ln\dfrac{1{,}045}{727} & 27.6 & \textit{Flue gases in the second convection part of the furnace} \\ 727 & 671 & 273 & \ln\dfrac{727}{671} & 27.6 & \textit{Flue gases in the superheater of the furnace} \\ 671 & 566 & 273 & \ln\dfrac{671}{566} & 27.6 & \textit{Flue gases in the first convection part of the furnace} \\ 566 & 472 & 273 & \ln\dfrac{566}{472} & 27.6 & \textit{Flue gase heating oil} \end{vmatrix}$$

$$Ex_{Hot} = \begin{vmatrix} 415 & 698 & 273 & \ln\dfrac{415}{698} & 6.1 & \textit{Steam} \\ 516 & 637 & 273 & \ln\dfrac{1{,}045}{727} & 251 & \textit{Petroleum} \\ 433 & 512 & 273 & \ln\dfrac{727}{671} & 34.5 & \textit{Oil} \end{vmatrix}$$

It should be noted that in the mathematical model exergy is calculated by the formula:

$$Ex = CP \cdot \left[T_1 - T_2 - T_0 \cdot \ln\frac{T_1}{T_2} \right], \tag{9}$$

where T_1 is the initial temperature of the flow (K); T_2 is the final temperature of the flow (K); T_0 is the ambient temperature (K).

In the radiant section of the furnace, the heat is transferred mainly by radiation. Therefore, the change in exergy in the radiant part of the furnace is calculated by formula (10):

$$\Delta Ex = Q_L \left(1 - T_0 \frac{\ln\dfrac{T_1}{T_2}}{T_1 - T_2} \right), \tag{10}$$

where Q_L is the heat transferred in the radiant part of the furnace.

The transformed composite curves by the exergy pinch method are shown in Figure 5. The composite curves are reduced to ΔTmin. The pinch point lies in the far left area of the graph. The exergy pinch analysis shows the need to reduce losses in the radiant section of the furnace (Figure 5 – the upper section of the hot joint curve).

These losses are a consequence of the irreversibility (Marmolejo-Correa and Gundersen, 2015). By reducing the irreversibility, this high-potential energy can be used.

Three main sources of irreversibility in heat exchangers are well known (Mehdizadeh-Fard et al., 2021):

- heat transfer from the hot to the cold flow

- pressure loss due to friction between fluids and walls
- emission of thermal energy into the environment.

All three positions can happen at the same time. However, the heat dissipated to the environment is usually small compared to the total heat exchanged between fluids in heat exchangers, so it is often neglected.

Next, the structural optimisation of the heat exchange system is carried out. The exergy pinch analysis will reduce exergy losses to minimum, thereby increasing the energy efficiency of the total primary distillation unit.

Let us describe in detail the process of structural optimisation by exergy pinch analysis.

The project should use the algorithm presented in paragraph 2.2 of this article. The hot and cold furnace streams are shown in Figure 6(a). The pinch point is on the left side of the graph; therefore, all heat flows are above the pinch point.

The heat exchange system already exists, so we will start designing from existing heat exchangers. Gradually, we will determine the place where there is unused exergy and add a heat exchanger connection.

The designing begins from the pinch line. The first heat exchanger is built between hot stream 5 and cold stream 3. We check the condition that the CP of the hot stream must be less than the CP of the cold stream. This condition must necessarily be observed near the pinch point.

Hot stream 5 has CP of 27.6 MW/°C, and is cooled from 293°C to 199°C, releasing 1.226 MW of heat. Cold stream 3 is heated from 160°C to 239°C and with a CP of 34.5 MW/°C and requires 1.14 MW. CPh < CPc (27.6 < 34.5) – the condition is fulfilled. Now it is necessary to find out how much exergy is involved in this heat exchanger. The cold stream requires 1.14 MW of exergy, the hot stream can provide 1.226 MW. The cold stream fully satisfies its requirements, so we put a tick over it – this stream is not necessary anymore. Let us denote how much exergy is involved in the first heat exchanger (1.14 MW). The remaining exergy in hot stream 5 is 1.226 – 1.14 = 0.086 MW [Figure 6(b)].

The second heat exchanger is built between cold stream 2 and hot stream 4. The condition is checked: CPh < CPc (27.6 < 251.4) – the condition is met; the heat exchange process is possible. Hot stream 4 is ticked (exergy requirements are met). We denote how much exergy is involved in this heat exchanger (1.615 MW) [Figure 6(c)]. Cold flow 2 still needs exergy 15.85 – 1.615 = 14.235 MW, therefore, it is possible to form a second heat exchange connection.

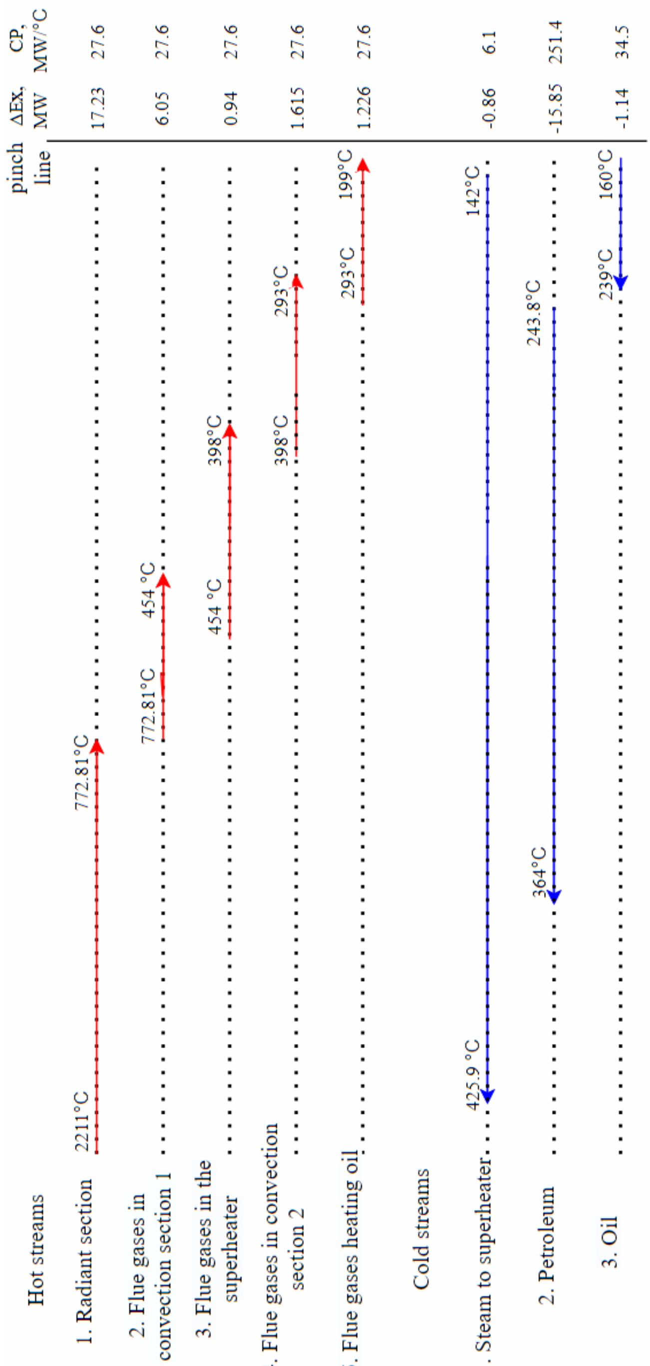
We determine to what temperature cold stream 2 will be heated by hot stream 4, using the formula (9).

We substitute the known data of cold flow 2 into the formula (CP = 25.14 MW/°C, T_1 = 516.8 K (243.8°C) exergy used to heat the flow is 1.615 MW):

$$-1.615 = 251.4 \cdot \left[516.8 - T_2 - 293 \cdot \ln \frac{516.8}{T_2} \right].$$

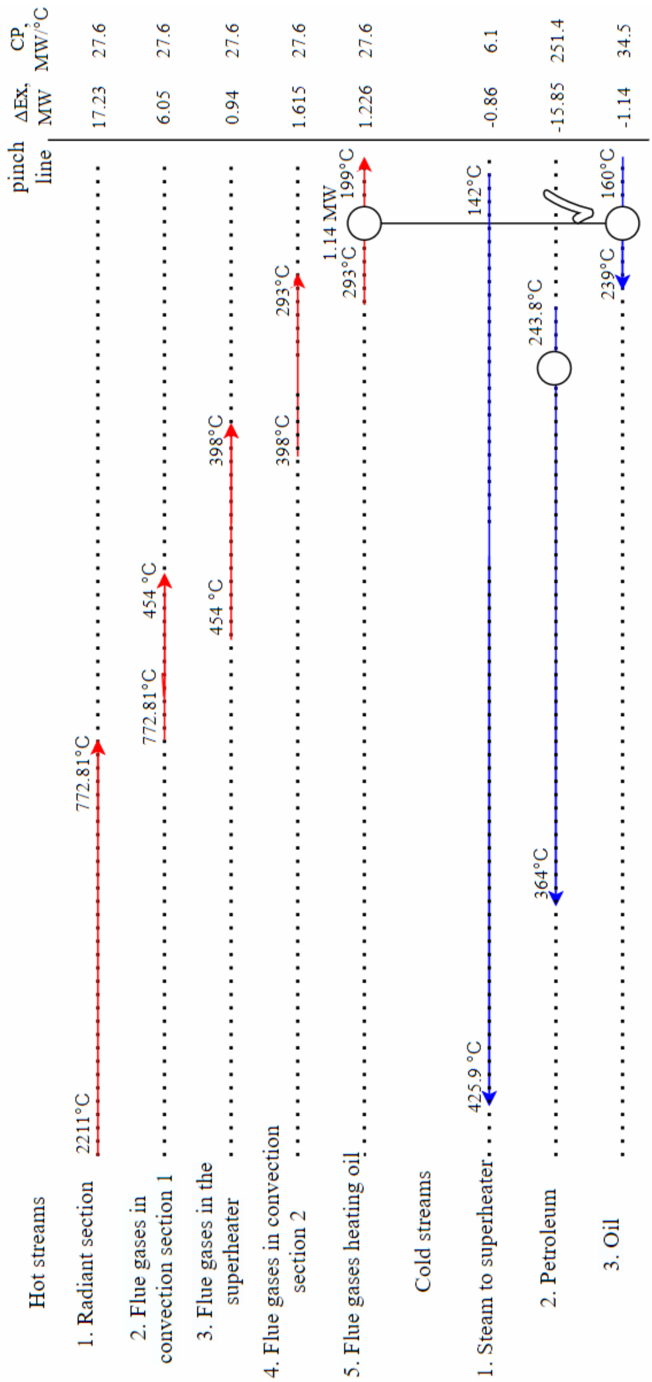
The result is an equation with one unknown. After solving this equation, T_2 is equal to 530.3 K (257.3°C).

Figure 6 (a) Hot and cold streams before building heat exchangers (b) Construction of the first heat exchanger (c) Construction of the second heat exchanger (d) The final heat exchanger system after optimisation (see online version for colours)



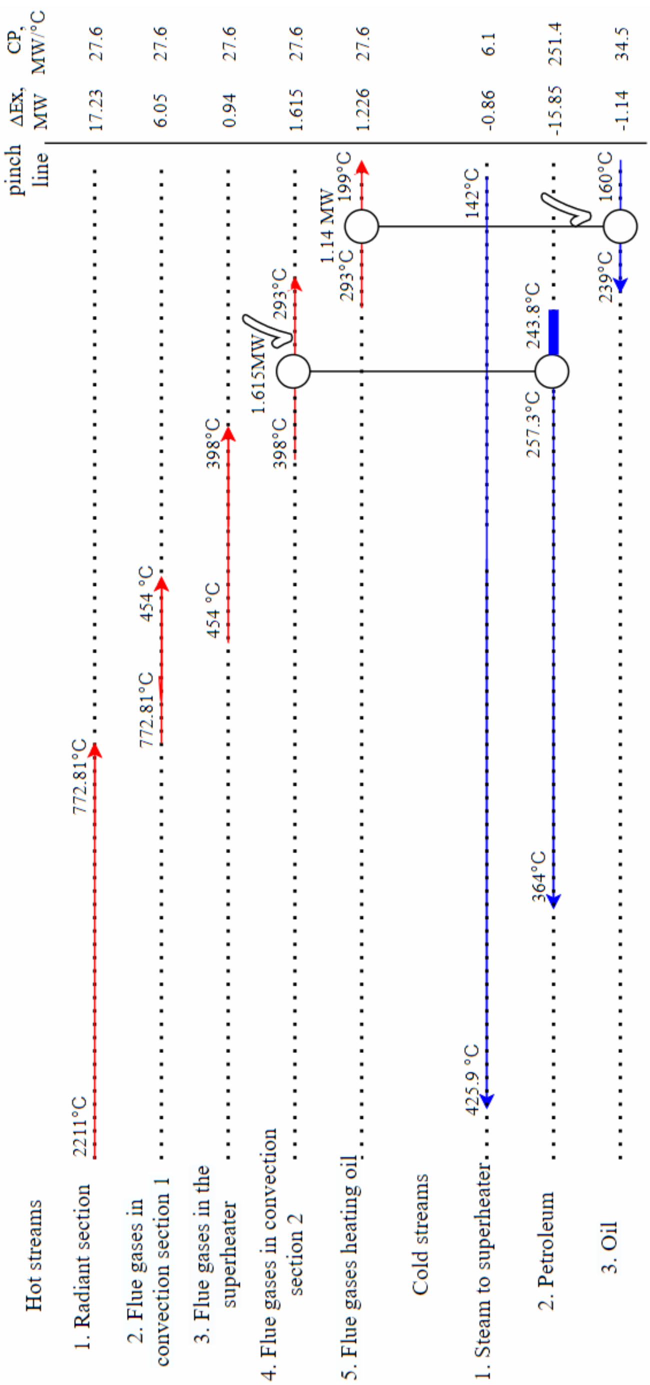
(a)

Figure 6 (a) Hot and cold streams before building heat exchangers (b) Construction of the first heat exchanger (c) Construction of the second heat exchanger (d) The final heat exchanger system after optimisation (continued) (see online version for colours)



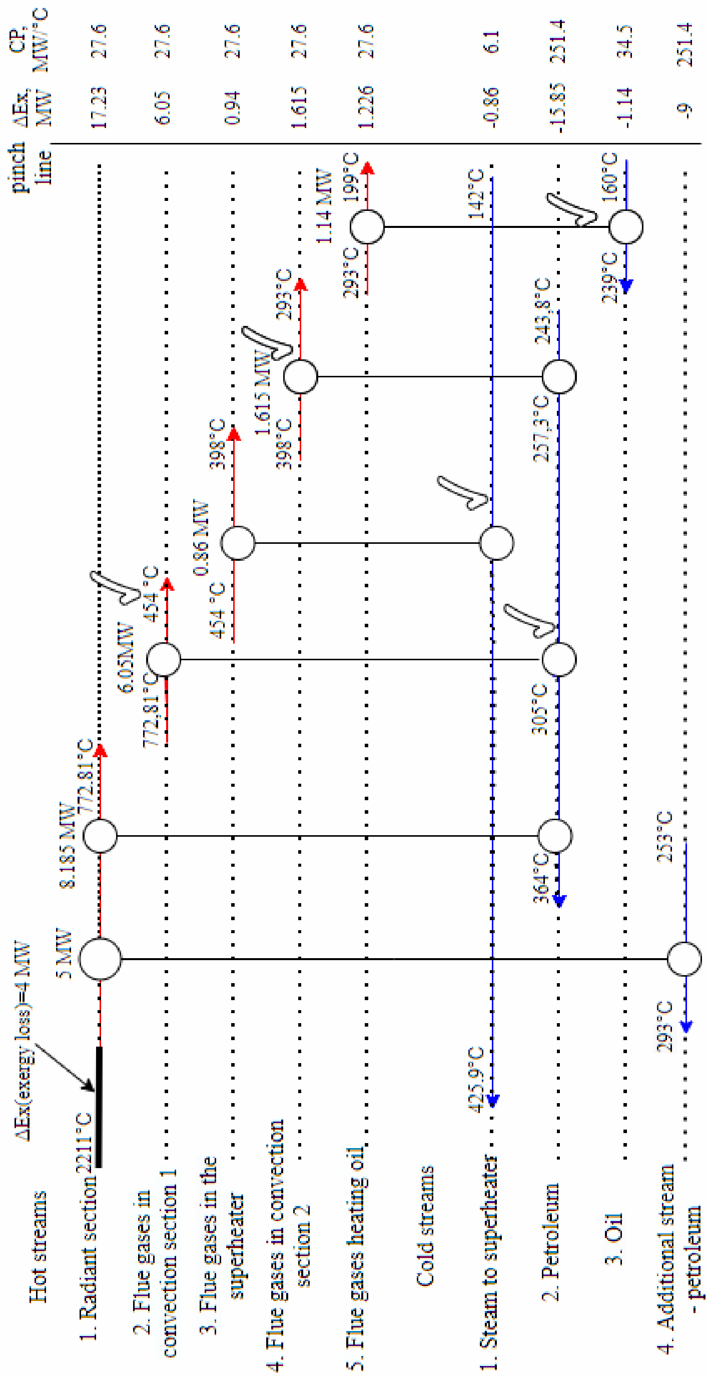
(b)

Figure 6 (a) Hot and cold streams before building heat exchangers (b) Construction of the first heat exchanger (c) Construction of the second heat exchanger (d) The final heat exchanger system after optimisation (continued) (see online version for colours)



(c)

Figure 6 (a) Hot and cold streams before building heat exchangers (b) Construction of the first heat exchanger (c) Construction of the second heat exchanger (d) The final heat exchanger system after optimisation (continued) (see online version for colours)



(d)

Hot stream 2 gives all its exergy (*Ex* = 6.05 MW) to cold stream 2, heating it from 257.3°C to 305°C. The conditions are met CPh < CPc (27.6 < 251.4). But the cold stream requires another 8.185 MW of exergy. We use hot stream 1. Conditions are met CPh < CPc (27.6 < 251.4). To heat a cold stream to the final temperature of 364°C from 305°C, 8.185 MW of exergy is needed. We denote the amount of exergy on the heat exchange connection. We design the existing connection of the steam reheater (hot stream 3 and cold stream 1).

Thus, hot stream 1 has an exergy of 17.23 MW, it has spent 8.185 MW, 9 MW has remained.

We propose to use this exergy and introduce an additional oil stream, thereby reducing the load from the other furnace. The additional oil steam will be heated from 253°C to 293°C.

The final heat exchanger system after optimisation is shown in Figure 6(d).

The study revealed an exergy loss of 9 MW in the radiant part of the furnace. These external energy losses are due to many factors, including typically inefficient or outdated equipment and processes, inadequate heat recovery, and poor integration of heat sources and sinks (Goodarzvand-Chegini and GhasemiKafrudi, 2017). In this case, we can reduce the exergy loss from 9 MW to 4 MW. That is, 5 MW of exergy in the radiant section of the furnace will be used to heat the additional flow. To use this exergy, an additional oil stream has been introduced. The oil from the refining column is heated by two furnaces. Prior to optimisation, this stream was heated in a second furnace. Now this oil stream is heated from 253°C to 293°C in the radiant part of the first furnace. This solution reduces the load on the second furnace.

A summary of the optimisation of the results is presented in Table 2. After optimisation with the help of exergy pinch analysis, we increased the efficiency of the furnace by 18.5%.

Table 2 The summary table of the results of furnace optimisation

	Before the introduction of additional stream	*After the introduction of an additional stream*
$\sum E_{rel}, MW$	27	27
$\sum E_{rec}, MW$	17	22
$\eta = \frac{\sum E_{rec}}{\sum E_{rel}}$	0.629	0.815

where ΣE_{rec} is the flow exergy received, ΣE_{rel} is the flow exergy released.

4 Conclusions

A constructive-parametric optimisation of the heat exchange system of the furnace of the primary oil refining unit was carried out to assess and improve the energy efficiency of an oil refinery. The results of the study using the traditional pinch method showed that the furnace does not require optimisation. However, the results of the exergy analysis showed that the furnace has exergy losses. In the furnace heat exchange system, the exergy loss is 9 MW. It is possible to increase the efficiency of the furnace from 62.9% to 81.5%. An additional oil stream has been introduced for reaching this goal. The method of exergy pinch analysis makes it possible to formulate and substantiate specific design measures to improve the energy efficiency of the furnace. Exergy pinch analysis can identify the unused exergy and determine in which part the losses occur. Thus, exergy analysis allows us to take a different look at assessing the energy efficiency of process plants.

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