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# Determination of Energy Efficiency Features of Oil Refinery Units and Their Complexes

Leonid M. Ulyev*, Maxim V. Kanischev, Roman E. Chibisov

RusEnergoProect LLC, Dep. Science and Engineering, Volokolamsk highway 2, 125080, Moscow, Russia
leonid.ulyev@gmail.com

The index of the process energy efficiency has been introduced to assess the energy efficiency of oil refinery units and their complexes. The index is calculated as the ratio of the payload difference of the hot utilities of the operational unit and the reference unit to the payload of the operational unit. As a reference unit, the examined unit is selected with a thermal energy recuperation system, which has a specified value of driving force for vertical heat transfer. This value of the minimum temperature difference of the heat transfer carrier in the heat-exchange equipment is selected using the best available technologies in heat transfer. Additionally, the energy efficiency index is calculated taking into account the elimination of heat losses to the environment. A simplified method for estimating heat losses from heated surfaces of oil refinery equipment has been developed for this purpose. It is shown that to determine the energy efficiency of a unit complex, it is possible to use the temperature Total Site profile. Indices of energy efficiency for crude oil unit, catalytic reforming with preliminary hydrotreating for the production of stable catalysis unit and hydrotreating of diesel fuel and kerosene unit, as well as their complex, are determined. Indices for economically optimal integration of these processes are decided. The introduced index of the energy efficiency potential of the process is an absolute value indicating the grade of the process perfection. The introduced index can be used to compare the energy efficiency of both individual units and plants.

## 1. Introduction

In developed countries, a significant part of the primary energy resources in the industry is used for heating raw materials for processing and at the same time cooling products for their further use. In EU countries, 73 % of all consumed energy in industry is used for heating, and this is a quarter of all consumed energy (Mistry and Misener, 2016). It means that these processes are also responsible for a significant part of $CO_2$ emissions. At the same time, most of the energy required for industrial processes is eventually released back into the environment as heat (Element Energy Limited, 2014). The problem of heat loss is typical for all industrialized countries. US industry uses $2.77\times10^{19}$ J/y, from them $1.41\times10^{19}$ J/y (about 51 %) of heat is rejected (LLNL Flow Charts, 2019). Reducing the specific energy consumption in industrial enterprises will lead to significant useful results, such as sustainable development of society, clean environment, and increase of the competitiveness of advanced enterprises. It is unlikely to be possible to abandon existing processes, so it is necessary to develop a reasonable strategy for investing in their modernisation.

In the work of Feng et al. (2011) the boundaries of energy saving at two petrochemical production complexes for the production of aniline and the aromatic hydrocarbons production are determined. Individual process integration was performed for the first complex. For the second one, individual thermal integration was supplemented by interprocess integration. The performed case studies showed the percentage of achievement of the calculated energy saving values. It would be reasonable to indicate the existing and achieved degrees of energy perfection of processes at the complexes.

A procedure for optimising industrial complexes taking into account individual and Total Site integrations was presented in the paper of Nemet et al. (2016). Li et al. (2018) showed that inter-unit integration is more profitable than individual integration. However, the values for comparing the energy efficiency of existing industrial plants and their complexes were not presented in these studies.

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In the paper of Varbanov et al. (2018), the authors developed the concept of investment planning for the retrofit of heat exchange systems based on the NPV (net present value). The authors work of Ke et al. (2013) used system methods to compare the energy efficiency for cement industry. In the paper of Sardarmehni et al. (2017), process integration methods were used to assess the energy efficiency of power use in chemical plants. In the work of Yang et al. (2016) modeling methods were used to select a reference installation with specific energy consumption that compared the specific energy consumption of the process under consideration.

It is clear that not all industrial units operate with the same energy efficiency, so in order to select priority areas of modernisation, it is necessary to create a method for evaluating the energy efficiency of industrial units, which would show simultaneously both the improvement of the process under consideration and the potential for reducing specific energy consumption.

In the paper of Kanischev et al. (2018), the authors propose an indicator for determining the energy efficiency index of oil refineries that is calculated based on a Pinch Methodology (Klemeš et al., 2018):

$$\varepsilon_{ef} = \frac{Q_{H\min(real)} - Q_{H\min(bench)}}{Q_{H\min(real)}} \tag{1}$$

where $Q_{H\min(real)}$ is the payload for the hot utilities of the process at the moment; $Q_{H\min(bench)}$ is the payload for the hot utilities of the reference unit.

As a reference unit, it is proposed to choose a unit with the current production process, but with a minimum temperature difference on heat exchangers, which can be achieved under the condition of vertical heat exchange (Smith et al., 2000) in an integrated heat exchange system using the best available technologies in the field of heat exchange. When performing Pinch retrofit projects for more than fifty different oil-refining processes, it was found that the incomplete recuperation temperature on modern heat exchange equipment could reach 10 °C. It is clear that the lower the value of $\varepsilon_{ef}$ is, the more energy efficient the refinery is. When $\varepsilon_{ef} \rightarrow 1$, the energy efficiency of the installation is reduced.

This paper analyses the energy efficiency of the LK-6Us production complex, which consists of three oil-processing units: the CDU-6 - (U-1), the Catalytic Reforming Unit with Preliminary Hydrotreatment - (U-2), and the Diesel Fuel and Kerosene Hydrotreatment Unit - (U-3).

## 2. Characteristics of the process

The CDU (U-1) is the head unit of the combined industrial complex LK–6Us. The unit includes a section for electric desalting and dehydrating of crude oil, a section for atmospheric distillation of desalted oil and stabilisation of straight-run gasoline. The nominal capacity of the unit at the time of the survey was 7 Mt/y for refined oil. The heat exchange network of the unit involves 28 process streams (Kanischev et al., 2019b).

The catalytic reforming unit with preliminary hydrotreating for the production of stable catalyzate (U-2) of the LK-6Us complex processes 1,150 kt of raw materials per year. The raw material is a fraction of 85-100 °C, allocated at the CDU. In this heat exchange system, 5 cold and 10 hot process streams are involved (Kanischev et al., 2019c). The hydrotreating unit (U-3) of the combined LK-6Us complex includes two processes. One of them is hydrotreating diesel fuel from sulfur compounds and dewaxing that increase the cold flow of diesel fuel. The capacity of this process is 2 Mt/y for processed raw materials. The second process is designed for hydrotreating kerosene from sulfur compounds, and its nominal capacity is 600 kt/y for processed raw materials. 17 process streams participate in the heat exchange system of this section (Meshalkin et al., 2019).

## 3. Determination of the energy efficiency index of the LK-6Us units

In the paper of Kanischev et al. (2019b) by constructing a Composite Curves for CDU (U-1) the main energy characteristics of the process are defined: useful load for the hot utilities ($Q_{H\min(real)}$), cool utilities ($Q_{C\min(real)}$), capacity of heat energy recuperation – $Q_{REC(real)}$, heat capacity that must be supplied to the cold process streams $\Delta H_{hot}$ and taken from the hot process streams – $\Delta H_{cold}$ (projections of the corresponding Composite Curves on the abscissa axis). These units are described in Table 1. In the work of Kanischev et al. (2019c), these values are defined for the process of (U-2), and in the paper of Meshalkin et al. (2019) – for the process of (U-3). These values are also shown in Table 1.

Using the construction of Composite Curves for $\Delta T_{\min}$ = 10 °C, the main energy characteristics for the reference process units are determined (Table 2): the useful loads on hot ($Q_{H\min(bench)}$), cold ($Q_{C\min(bench)}$) utilities, and the capacity of heat energy recuperation $Q_{REC(bench)}$. It is clear that the values of $\Delta H_{hot}$ and $\Delta H_{cold}$ are constants for processes. Summing up presented values, we obtain energy values for the entire complex of LK-6Us without interprocess heat integration.

*Table 1: Main energy indicators of the existing processes.*

| Units | $Q_{H\min(real)}$, MW | $Q_{C\min(real)}$, MW | $Q_{REC(real)}$, MW | $\Delta H_{hot}$, MW | $\Delta H_{cold}$, MW |
|---|---|---|---|---|---|
| U-1 | 128.8 | 86.5 | 124.2 | 210.7 | 253.0 |
| U-2 | 22.3 | 42.7 | 78.3 | 121.0 | 100.6 |
| U-3 | 46.2 | 48.3 | 97.6 | 145.9 | 144.4 |
| $\sum$ | 197.3 | 177.5 | 300.1 | 477.5 | 498.0 |

*Table 2: Main energy indicators of reference units.*

| Units | $Q_{H\min(bench)}$, MW | $Q_{C\min(bench)}$, MW | $Q_{REC(bench)}$, MW |
|---|---|---|---|
| U-1 | 83.2 | 43.1 | 167.8 |
| U-2 | 8.2 | 28.6 | 92.5 |
| U-3 | 21.7 | 23.8 | 122.1 |
| $\sum$ | 113.1 | 95.5 | 382.4 |

The energy efficiency index of CDU-6 (U-1) was determined with the help of Eq(1) – $\varepsilon_{ef}$ = 0.39. The energy efficiency index of a Catalytic Reforming Unit with Pre-hydrotreating (U-2) – $\varepsilon_{ef}$ = 0.63 and the energy efficiency index for a Diesel Fuel and Kerosene Hydrotreating Unit (U-3) – $\varepsilon_{ef}$ = 0.53 were determined analogous. The resulting energy efficiency indices were determined without taking into account heat losses to the environment. To better account of the potential for improving the energy efficiency of oil refining units, let us assume that the reference units eliminate the loss of heat energy from heated surfaces. The estimation of heat loss capacity at oil refineries is performed using data from Table 3, which is obtained as a result of survey, modeling and statistical processing of data obtained from more than fifty oil refineries.

*Table 3: The value of heat capacity losses from various types of non-isolated equipment at the refinery*

| Equipment | $Q_{Losses}$, kW |
|---|---|
| Open sections of pipes, m | 1.3 |
| Valve | 3.0 |
| Heat exchanger flange and pipe | 1.2 |
| Heat exchanger cover | 2.9 |
| Open parts of the heat exchanger shell | 8.0 |
| Pump (hot) | 3.0 |
| Furnace | 900.0 |

The total heat losses from the unit equipment to the environment are estimated, including losses from the insulating surfaces of furnaces – $Q_{HLossesSF}$ and losses from transfer pipes and the heat exchange network of the unit – $Q_{HLosses}$ (Table 4).

*Table 4: Capacity of heat losses to the environment.*

| Process Unit | $Q_{Hlosses}$, MW | $Q_{HLossesSF}$, MW | Total, MW |
|---|---|---|---|
| U–1 | 4.2 | 4.0 | 8.2 |
| U–2 | 2.7 | 2.7 | 5.4 |
| U–3 | 1.4 | 1.4 | 2.8 |
| $\sum$ | 8.3 | 8.1 | 16.4 |

The possibility of furnace energy efficient retrofit for oil refineries is usually not considered when evaluating energy efficiency. Therefore, we will consider the possibility of reducing the specific energy consumption only by eliminating heat losses from the heated surfaces of the heat exchange system and transfer pipes. In this case, the energy efficiency index is determined by the expression Eq(2):

$$\varepsilon_{efL} = \frac{Q_{H\min(real)} - \left(Q_{H\min(bench)} - Q_{HLosses}\right)}{Q_{H\min(real)}}. \quad (2)$$

By calculating the energy efficiency index, taking into account the elimination of heat losses from heated and not thermally insulated surfaces, we obtain a slightly greater potential for increasing energy efficiency (Table 5).

*Table 5: Energy efficiency indices of the surveyed refineries.*

| Process Unit | $\varepsilon_{ef}$ | $\varepsilon_{efL}$ |
|---|---|---|
| U–1 | 0.35 | 0.39 |
| U–2 | 0.63 | 0.75 |
| U–3 | 0.53 | 0.56 |

## 4. Determination of the energy efficiency index of the combined industrial complex LK-6Us

When determining the energy efficiency indices, the main energy characteristics of the units were also found: payloads for hot – $Q_{H\min(real)}$, cold utilities – $Q_{C\min(real)}$, heat recovery capacity – $Q_{REC(real)}$, heat power that must be brought to the cold process streams of $\Delta H_{hot}$ and diverted from the hot process streams $\Delta H_{cold}$ of the described units (Table 2). Summing up these indicators for all units included in the complex, we find the energy characteristics of the entire complex as a whole.
Using (1), we obtain the energy efficiency index of the combined LK-6Us complex ignoring the elimination of heat losses to the environment $\varepsilon_{efTS}$ = 0.43.
If we take into account the elimination of heat losses to the environment, then the net capacity of hot utilities on the reference complex of units will be $Q_{H\min(bench)} \approx 113.1-8.3 = 104.8$ MW, and cold utilities will not change much. Note that these values are obtained for a complex without inter-process integration. The energy efficiency index, taking into account the elimination of heat losses in the heat exchange system of the complex, will be equal – $\varepsilon_{efTSL}$ = 0.47.
With the help of stream data obtained for units of combined LK-6Us complex and the Pinch-SELOOP software package (Kanischev et al., 2019a) the Grand Composite Curves (GCC) of units included in the combined complex (Figure 1) were constructed. GCC shows the possibility of distributed localization of utilities and the areas where heat energy is recovered, the so-called "Pockets" of recuperation (Smith et al., 2000). By cutting off the pockets and summing up the loads in the temperature intervals that divide the temperature axis of the GCC kink coordinates, we obtain the temperature profile of the combined LK–6Us complex (Figure 2), which shows the requirements for placing utilities for the entire set of reference units.
The temperature profile of the complex of reference plants shows the total payload for the hot and cold utilities $Q_{Htotal}$ and $Q_{Ctotal}$. These values correspond to the values from Table 3 for the complex without inter-process integration.

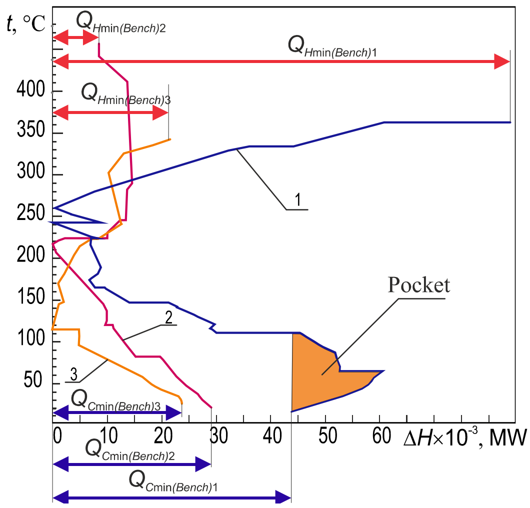


*Figure 1: Grand Composite Curve. 1 – for unit U-1; 2 – for unit U-2; 3 – for unit U-3.*

All units are part of one territorial complex – the combined production complex LK-6Us and they are located on the same industrial site and it is possible to carry out thermal integration without intermediate heat carriers.
To do this, the temperature profile of the hot streams must move to the right until it touches the profile of cold streams (Figure 2). We will see the amount by which the payload of hot and cold utilities can be reduced by performing interprocess integration. This value in our case is $\Delta Q_{H\min} = \Delta Q_{C\min}$ = 11.44 MW. This is possible because at the point of contact of the temperature profiles, the temperature difference between the cold and hot streams is $\Delta T_{\min}$ = 10°C, as GCC units were built with a shift of the temperatures of cold streams by

$\Delta T_{min}/2$ up and hot streams down (Smith et al., 2000), and $\Delta T_{min}$ for all reference plants is the same and equal to 10°C. Therefore, during interprocess integration, the useful power of hot utilities necessary for carrying out processes on a complex of reference plants will be reduced to $Q_{Htotalbench}$ = 101.65 MW, and of cold utilities to $Q_{Ctotalbench}$ = 84.07 MW.
The obtained values allow us to calculate the energy efficiency index of the LK-6Us combined complex in the case when heat losses to the environment is not taken into account:

$$\varepsilon_{efB} = \frac{197.3 - 101.65}{197.3} = 0.49 .$$

When allowance for heat losses to the environment, the energy efficiency index will be equal to

$$\varepsilon_{efBL} = \frac{197.3 - (101.65 - 8.25)}{197.3} = 0.53 .$$

We write the results obtained in the table of energy efficiency indices of the combined complex LK-6Us (Table 6).

*Table 6: Energy efficiency indices of the combined complex LK-6Us.*

| LK-6Us | $\varepsilon_{efB}$ | $\varepsilon_{efBL}$ |
|---|---|---|
| Without of the interprocess integration | 0.43 | 0.49 |
| With of the interprocess integration | 0.47 | 0.53 |

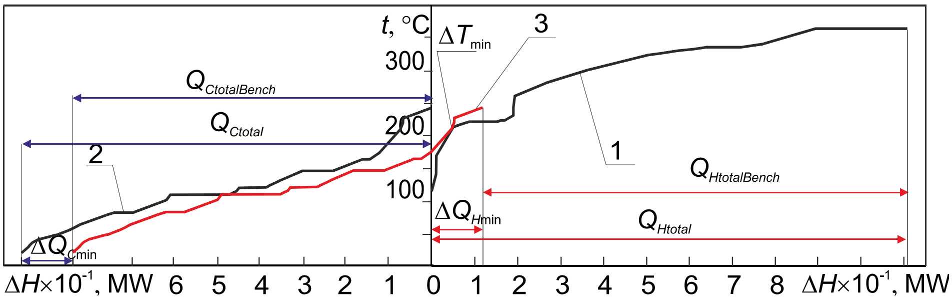


*Figure 2: The temperature profile for combine production complex LK-6Us. 1 – for cold technological streams; 2 – for hot technological streams; 3 – for hot technological streams with the interprocess integration.*

Note that the value of the energy efficiency index can be considered as the value of the energy-saving potential of oil refineries. This means that the maximum amount by which the payload for hot utilities of the LK-6Us combined complex can be reduced is 53 % of the current consumption of hot utilities, or 103.9 MW. The value of cold utilities can be reduced by 177.5-84.07 = 93.43 MW.
Taking into account the cost of hot and cold utilities 120 $ and 10 $ for 1 kW a year respectively, we will get energy-saving potential in monetary terms, which is equal to ~ 13.4 million USA dollars a year.
The monetary values of the energy saving potential for individual integrations are calculated similarly. For U-1 – 6 M$, for U-2 – 2.1 for U-3 – 3.4, i.e. with additional interprocess integration, profit increases by 1.4 M$ per year. The obtained values of energy efficiency indices help the company management to choose plants to analyze the possibility of their modernization. It should be noted that the results presented in the article were obtained based on data that were collected according to the developed methodology without going to the enterprise. To complete the work, it was enough to indicate the regulatory numbers of the sensors from which it is necessary to obtain data. The next step is the synthesis of reconstruction projects of selected process units in consideration of specific technical, technological and economic constraints (Ulyev et al., 2018) and the calculation of NPV and IRR (internal rate of return), based on which the conclusions are drawn about the need for investment (Kanischev, et al., 2018). All ideas presented in the article by the authors are implemented in a commercial package (Ulyev et al., 2019).

## 5. Conclusion

In this paper, based on pinch analysis methods, a comparative method for determining the energy efficiency of oil refining industry units and their complexes is proposed. For this purpose, the main characteristics of reference units are determined and algorithms for determining comparative indexes are proposed, which show the potential for increasing of the unit energy efficiency and their complexes. To determine the energy efficiency indices, taking into account the heat capacity losses into the environment from a unit of the corresponding equipment was determined too. Energy efficiency indexes are absolute characteristics that show the degree of energy perfection of processes. The developed method is used to determine the energy efficiency index of crude oil unit without a vacuum block, a catalytic reforming unit with pre-hydrotreating, and diesel fuel and kerosene hydrotreating unit for sulfur compounds included in the LK-6Us production complex. Thermal integration of units and the Total Site integration of the combined LK-6Us complex show the possibility of reducing energy consumption by 53 %.

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