CHEMICAL ENGINEERING TRANSACTIONS
VOL. 70, 2018
A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš

ISBN 978-88-95608-67-9; **ISSN** 2283-9216
DOI: 10.3303/CET1870253

Energy Efficiency Retrofit of Two-Flow Heat Exchanger System

Leonid M. Ulyev[a,*], Maxim V. Kanishev[a], Mikhail A. Vasilyev[a], Abbass Maatouk[b]

[a]RusEnergoProekt LLC, Volokolamsk Avenue 2, 125080, Moscow, Russian Federation
[b]National Technical University “Kharkiv Polytechnic Institute”, 2 Kirpichova St., 61002, Kharkiv, Ukraine
leonid.ulyev@gmail.com

This paper presents the retrofit of the two-flow heat-exchange system with utility paths in order to optimize the heat recuperation capacity under the technical limitation conditions. Analytical dependences of heat load of the existing heat exchangers and utilities on the surface area of the new heat exchanger are obtained. The work shows that the determination of technological parameters for existing heat exchangers during the retrofit of the heat exchange system is an important task because they affect the cost of retrofit. For case study, two streams problem for heat transfer in heat network at the crude and gas separation units is considered in this paper. The existing system has three heat exchangers. The temperature measurements were fulfilled for all heat exchangers and the heat loads for heat exchangers and utility were calculated. The installation of one heat exchanger at the cool side of the system is proposed in retrofit. The dependences of the temperature changes for the hot and cold process stream from the value of the additional surface were obtained for each heat exchanger. Utility capacity and capacity recovery of thermal energy in the system is also analyzed.

1. Introduction

The article deals with the optimal placement of a new heat exchange surface for dual-flow heat exchange network with retrofit of the refinery network. It was determined that 13 % of all incoming oil to the plant is used for oil refining as fuel practically at all Russian plants. This ratio is observed in almost all oil refineries. In Russia, about 320 Mt of crude oil are processed, and, consequently, 41.5 Mt of crude oil are spent on its processing, and at the price of 65 USD per barrel, the cost of energy spent on processing of oil in Russia is ~19 billion USD. It is possible to reduce fuel consumption by an amount of 3 % to 50 % using the methods of processes integration at the surveyed plants (Smith, 2016), depending on the technological conditions and technical restrictions. Previously in the work of Linnhoff and Flower (1978) constructive methods for generation of energy optimal networks were proposed. Various optimality criteria were considered by Flower and Linnhoff (1978). Hihdmarch and Linnhoff (1983) proposed a method for designing integrated heat exchanger networks for chemical-technological systems. Tjoe and Linnhoff (1986) developed a method for determining the target values of additional surface area of heat exchange and utility loads in the design of thermal networks. Papoulias and Grossmann (1983) proposes a method of optimization of thermal networks by means of mixed integer linear programming, and Duran and Grossmann (1986) uses methods of nonlinear programming. Wan Alwi and Manan (2010) have developed a new graphic method for utility targeting and network design for maximum energy recuperation.

Most of these works have dealt with grassroots design, but recently, much attention has been paid to thermal integration in heat exchange systems of operating enterprises. In (Reisen et al., 1995) the path method for the retrofit of heat exchange networks was proposed. In the paper (Liu and Luo, 2013) a hybrid genetic algorithm was presented to obtain optimal heat exchange systems with full use of existing heat exchangers and their structures. In Bonhivers et al. (2017a) the bridge analysis method, which is based on energy transfer diagrams and changes in heat transfer of the heat network necessary to reduce energy consumption, which are called "bridges", is published. In Bonhivers et al. (2017b), its graphical interpretation is given. In the paper (Osman at al., 2016) the authors propose to increase the heat recovery capacity in the heat exchange system by changing the temperature of technological flows without a significant change in the topology of the heat exchange system.

Please cite this article as: Ulyev L.M., Kanischev M.V., Vasilyev M.A., Maatouk A., 2018, Energy efficiency retrofit of two-flow heat exchanger system , Chemical Engineering Transactions, 70, 1513-1518 DOI:10.3303/CET1870253

In Akpomiemie and Smith (2015), a methodology is proposed that combines heuristic rules and optimization strategy with the analysis of utility paths for the retrofit of heat exchange networks without changing their topology and without increasing the surface area of heat exchange. In the paper by Nemet et al. (2017) the importance of risk assessment in the safe synthesis of heat exchanger networks is noted.

It should be mentioned that technical, technological and economic constraints could only be partially taken into account in programming techniques, and in pinch analysis techniques can also be used as heuristics. As a rule, in industry during the retrofit of heat exchange systems it is required to use the minimum possible number of new devices, even by reducing the economic benefit. But if it is possible to make an energy-efficient retrofit project only by re-linking the existing heat exchangers, when it is implemented, in the heat exchange system there will be a redistribution of temperatures on the devices and their thermal loads. If these parameters go beyond the passport values, it is necessary to carry out industrial safety expert examination for the system heat exchangers to avoid the risk of accidents, since heat exchangers are equipment operating under pressure. As a result, it would seem that without an investment event, the rebinding of heat exchangers turns into an event with high costs and a payback period, since the cost of carrying out the industrial safety expert examination of one heat exchanger is 4-5 k USD. Therefore, when carrying out energy-efficient retrofit projects, it is necessary to monitor the technological parameters of existing and new devices.

2. Method

In this paper, efficiency improvement and optimization of two-flow heat exchange systems with utilities are considered. Two-stream heat exchange systems in which raw materials in front of a reactor or separation system are heated by waste products are found in almost all chemical processes. For example, they are found in basic chemistry processes (Tovazhnyansky et al., 2010), production of benzene (Tovazhnyansky et al., 2011), crude oil refining (Ulyev et al., 2013), secondary oil refining processes (Ulyev et al., 2014), processes of coke making (Ulyev and Vasilyev, 2015), petrochemical processes (Kapustenko et al., 2015) and in the processes of gas separation (Ulyev et al., 2016).

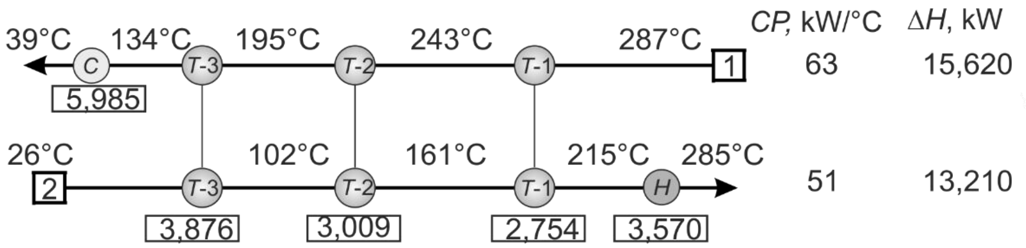


Figure 1: Grid diagram of the existing two-stream heat exchange problem

One of the heat transfer subsystems on the recycling oil unit is presented in Figure 1. It consists of three series-connected heat exchangers *T*-1, *T*-2 and *T*-3, one heater (hot utility) *H*, and one refrigerator (cold utility) *C*. The inlet temperature of the hot process stream is equal to t^h_S =287 °C, the outlet one is equal to t^h_T = 39°C. The inlet temperature of cool process stream is equal to t^c_S =26 °C, and the outlet temperature is equal to t^c_T= 285°C. The capacity of the hot utility is the value $Q_{H\text{min}}$=3,617 kW, the cold utility is equal to $Q_{C\text{min}}$=6,032 kW, the recuperation capacity of heat energy is Q_{REC}=9,592 kW. Stream heat capacity of the hot process flow is equal to CP_h = 63 kW/°C g, cold CP_c = 51 kW/°C. When carrying out the retrofit project of the heat network, the thermophysical properties of heat carriers were considered constant, heat losses in the heat exchange system were absent, and heat exchange surfaces *S* and heat transfer coefficients *K* to be fixed and given in Table 1.

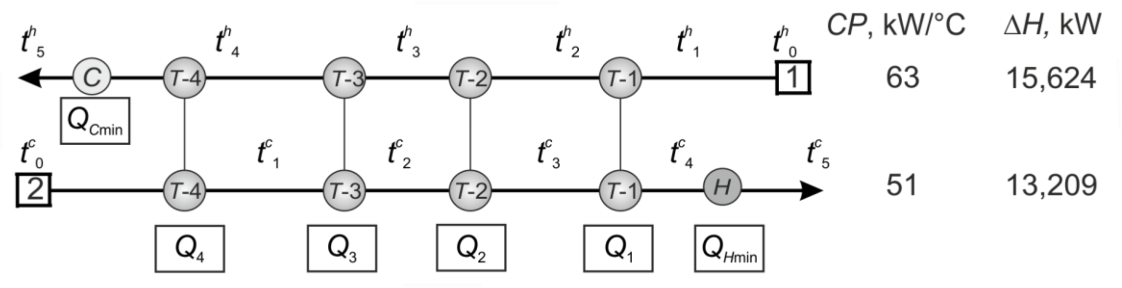
The load on the cooling of the hot stream is $\Delta H_h = CP_H \times (t^h_S - t^h_T)$ = 15,620 kW, and the heating of the cold stream is $\Delta H_C = CP_C \times (t^c_S - t^c_T)$ = 13,210 kW, which is greater than the recuperation capacity. In this case, to reduce the value of utilities, it is necessary to increase the heat recuperation capacity in the system, and for this, it is necessary to increase the surface area of the heat exchange, since the parameters of the existing heat exchangers are fixed.

The passport data of the pumping equipment and the existing pressure drops allow to install additional heat exchange equipment in the considered heat exchange system. The analysis of the equipment location on the unit has shown that it is possible to install an additional heat exchanger only on the cold edge of the heat exchange system as shown in Figure 2. Let us consider how the temperatures on the heat exchangers will change depending on the heat load of the new *T*-4 heat exchanger. For this purpose, the thermal balances will be write down for each heat exchanger, assuming that there are *N* devices in the system:

Table 1: Characteristics of heat exchangers

HE	t^h_{in}, °C	t^h_{out}, °C	CP_h, kW/°C	t^c_{In}, °C	t^c_{out}, °C	CP_c, kW/°C	S, m^2	K, kW/m^{2}°C
T-1	287	243	63	161	215	51	214	0.17
T-2	243	195	63	102	161	51	214	0.16
T-3	195	134	63	26	102	51	214	0.18

Figure 2: Grid diagram of a two-flow heat exchange system with four heat exchangers



$$CP_c(t^c_{N-i} - t^c_{N-i-1}) = CP_h(t^h_i - t^h_{i+1}),\ i = 0\ldots N\text{-}1, \tag{1}$$

where t^h_0 - is the initial temperature of the hot stream, in our case, equal to 287 °C, t^c_0 – is the initial temperature of the cold stream, in our case, equal to 26 °C.

On the other hand, the load on the heat exchanger is defined as:

$$Q_i = S_i \Delta T_{\ln i} K_i,\ i{=}0\ldots N\text{-}1, \tag{2}$$

and then for the *i*-th heat exchanger can be recorded:

$$S_i K_i \frac{\left(t^h_i - t^h_{i+1}\right) - \left(t^c_{N-1} - t^c_{N-i-1}\right)}{\ln\frac{t^h_i - t^c_{N-1}}{t^h_{i+1} - t^c_{N-i-1}}} = CP_h(t^h_i - t^h_{i+1}), i = 0 \ldots N - 1\,. \tag{3}$$

Taking into account Eq(1), the ratio for the temperature difference is obtained:

$$t^h_i - t^c_{N-1} = \left(t^h_{i+1} - t^c_{N-i-1}\right)e^{A_i},\ i{=}0\ldots N\text{-}1, \tag{4}$$

where $A_i = \frac{S_i K_i}{CP_h}\left(1 - \frac{CP_h}{CP_c}\right)$.

Considering that *N*=4, i.e. in heat exchange system there are 4 heat exchangers, and making consecutive substitutions in the system of equations Eq(4), the temperature of the cold flow at the outlet from the first heat exchanger is found:

$$t^c_4 = t^h_0 - \left(t^h_4 - t^c_0\right)E, \tag{5}$$

where $E = e^{A_1}e^{A_2}e^{A_3}e^{A_4}$.

Using the expression for the heat balance of the entire system of heat transfer

$$(t^c_4 - t^c_0)CP_c = \left(t^h_0 - t^h_4\right)CP_h, \tag{6}$$

the temperature of the hot stream at the outlet of the 4th heat exchanger is found:

$$t^h_4 = \frac{t^h_0\left(1 - \frac{CP_h}{CP_c}\right) + t^c_0(E-1)}{E - \frac{CP_h}{CP_c}}. \tag{7}$$

Next, the temperature difference between heat carriers on the cold side of the heat exchange system is determined:

$$\Delta t_m = t^h_4 - t^c_0 = \left(t^h_0 - t^c_0\right)\frac{CP_c - CP_h}{ECP_c - CP_h}. \tag{8}$$

From the system of equations Eq(1), the heat carrier temperatures at the inlet to the heat exchangers and the heat carrier temperatures at the outlet of the heat exchangers is determined:

$$t_1^c = b + d\Delta t_m e^{A_4}, \tag{9}$$

$$t_2^c = b + d\Delta t_m e^{A_4} e^{A_3}, \tag{10}$$

$$t_3^c = b + d\Delta t_m e^{A_4} e^{A_3} e^{A_2}, \tag{11}$$

$$t_4^c = b + d\Delta t_m e^{A_4} e^{A_3} e^{A_2} e^{A_1}, \tag{12}$$

$$t_1^h = b + g\Delta t_m e^{A_4} e^{A_3} e^{A_2}, \tag{13}$$

$$t_2^h = b + g\Delta t_m e^{A_4} e^{A_3}, \tag{14}$$

$$t_3^h = b + g\Delta t_m e^{A_4}, \tag{15}$$

where $b = \frac{CP_C t_0^c - CP_H t_4^h}{CP_C - CP_H}$, $d = \frac{CP_h}{CP_c - CP_h}$, $g = \frac{CP_c}{CP_c - CP_h}$.
After the temperatures calculating, the capacities of hot and cold utilities are determined:

$$Q_{C\min} = CP_h\left(t_4^h - t_5^h\right), \tag{16}$$

$$Q_{H\min} = CP_c\left(t_5^c - t_4^c\right). \tag{17}$$

Using the found coolant temperatures at the inlet and outlet of the heat exchangers shown in Figure 3, the heat exchanger loads are calculated:

$$Q_i = CP_c\left(t_{N+1-i}^c - t_{N-i}^c\right) = CP_h\left(t_{i-1}^h - t_i^h\right). \tag{18}$$

In this case, for technological reasons, only shell-and-tube heat exchangers can be used for reconstruction. The cost of installing one section of the shell-and-tube heat exchanger will be determined as (Smith, 2016):

$$CosT = A + B(S)^c, \tag{19}$$

where A - is the cost of installing one section of the heat exchanger, B - is the equivalent of the cost of 1 m^2 of the heat exchange surface area, c – is an indicator of the nonlinear dependence of the cost, reflecting the possibility of placing the heat exchange surface of different sizes in one casing. In this case, the values of these parameters are A = 40,000 USD; B = 1,000 USD; c = 0.97.
The maximum surface area of the heat exchange for one section of the selected manufacturer is $S_{\max}$ = 250 m^2. Taking into account the value of the maximum heat exchange surface of one section, the expression Eq (18) for one heat exchange placement will take the form of:

$$CosT_m = A\left\lceil \frac{S}{S_{\max}} \right\rceil + B(S)^c, \tag{20}$$

where $\lceil x \rceil$ - Iverson's ceiling function returning the smallest integer greater than or equal to x (Graham, 1994).
The cost of hot utilities in the installation includes the cost of own gas, natural gas from the city highway, the cost of liquid fuel consisting of a mixture of fuel oil, gas oil and diesel fuels. The final cost of hot utility is the value that is equal to C_H = 120 USD for 1 kW a year. The cost of cold utilities includes the cost of the fresh cooling water, cost of electricity, feed-pump drives, fan motors of air coolers, and it is equal to C_C = 25 USD per year.
The present value of the installed equipment is determined by the expression (Smith, 2016):

$$C_d = CosT_m \frac{i(i+1)^n}{(i+1)^n - 1}, \tag{21}$$

where i - is the annual discount rate, n - is the number of years.
The reduced cost of energy in the heat exchange system under consideration is determined by the ratio:

$$CE = Q_{H\min} C_H + Q_{C\min} C_C. \tag{22}$$

3. Results and discussion

When the area of the heat exchange surface of the new heat exchanger increases, its thermal load will increase as shown in Figure 3a, and the heat load of existing heat exchangers will decrease, although the total heat recuperation capacity will only increase. As a result, the capacity of hot and cold utilities decreases with the increase in the heat exchange surface of the fourth apparatus as shown in Figure 3b. Reducing the heat load of existing devices is mainly due to the increase in the heat exchange surface of the fourth unit. With decrease in loading on the existing devices, there is the decrease in difference of temperatures of heat carriers on them, and decrease in temperature of heat carriers in devices as shown in Figure 4.

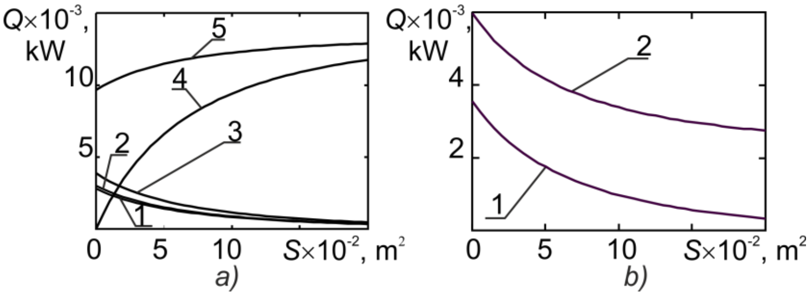


Figure 3: The capacity of thermal energy. a) for recuperation: 1 - on the first heat exchanger; 2 - on the second heat exchanger; 3 - on the third; 4 – on the fourth; 5 - the total heat recovery capacity in the new heat exchange system. b) for utilities consumed by the process: 1-cold; 2 - hot

The greatest difference of temperatures between heat carriers, since some size of its surface, will be observed on the new heat exchanger. As a result, all coolant temperatures on the hot side of the new heat exchanger will tend to their boundary values on the hot side, and the temperature of the hot coolant on the cold side of the new apparatus to the target value.

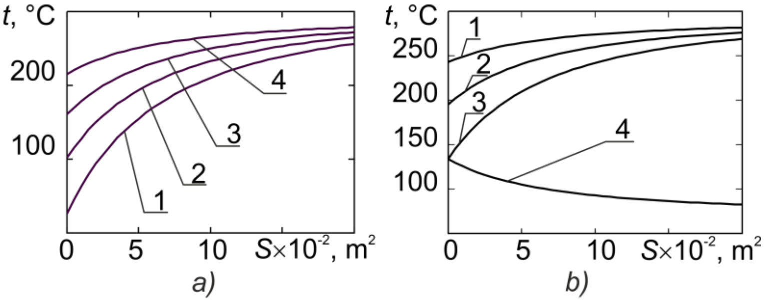


Figure 4: Change of temperature of the heat carriers. a) – cold:1- inlet temperature in the fourth heat exchanger; 2- in the 3rd; 3 - in the 2nd; 4 - in the 1st; b) - hot. In depending on the size of the heat exchange surface area of the new heat exchanger. 1 - Outlet temperature of the first heat exchanger, 2 - from 2nd, 3 - from 3rd, 4 - from 4th

In order to determine the required area of the heat exchange surface of the new heat exchanger, the discounted values of capex and energy depending on its heat exchange surface will be constructed as shown in Figure 5. The increase in the surface leads to the monotonous increase in its cost and increase in the cost of heat

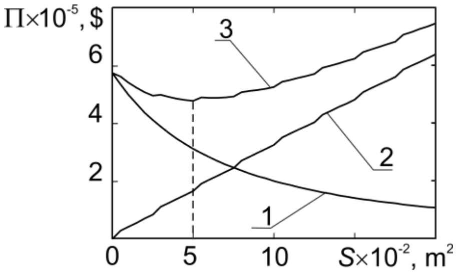


Figure 5: Discounted cost values. 1- the annual cost of energy; 2 - the reduced capital costs; 3 - the total present value of the re-construction project

exchange sections, but the cost of energy due to the increase in the heat recovery capacity monotonically decreases. As a result, the total present value of the renovation project will be a non-monotonic function. The minimum value will correspond to the minimum present costs for the retrofit project of heat exchange system, and the value of the new heat exchange surface area will be optimal for the retrofit project. In our case, the optimal value is the heat exchange surface area of 500 m^2.

4. Conclusions

The theoretical analysis of heat transfer processes for two-stream systems with the presence of hot and cold utilities is carried out. It is shown that the total discounted cost of the heat network retrofit is a nonmonotonic function of the additional heat exchange surface. In this case, the minimum annual cost is observed when installing 500 m^2 additional heat exchange surface, which corresponds to the heat exchanger, which consists of two sections. It should be noted that the developed method could be used to optimize two-stream heat network with utilities in all industries.

References

Akpomiemie M.O., Smith R., 2015, Retrofit of heat exchanger without topology modifications and additional heat transfer area, Applied Energy, 159, 381–390.

Bonhivers J.-C., Srinivasan B., Stuart P.R., 2017a, New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 1 – Concepts, Applied Thermal Engineering, 119, 659–669.

Bonhivers J.-C., Alva-Argaez A., Srinivasan B., Stuart P.R., 2017b, New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 2 – Stepwise and graphical approach, Applied Thermal Engineering, 119, 670–688.

Duran M.A., Grossmann I.E., 1986, Simultaneous optimization and heat integration of chemical processes, AIChE J, 32, 123–138.

Flower J.R., Linnhoff B., 1978, Synthesis of heat exchanger networks – 2. Evolutionary generation of networks with various criteria of optimality, AIChE J, 24, 642–654.

Graham R.L., Knuth D.E., Patashik O., 1994, Concrete Mathematics. A Foundation for Computer Science, Second Edition, Addison-Wesley, Amsterdam.

Kapustenko P.O., Ulyev L.M., Ilchenko M.V., Arsenyeva O.P., 2015, Integration Processes of Benzene-toluene-xylen Fractionation, Hydrogenation, Hydrodesulphurization and Hydrothermoprocessing Installation of Benzene Unit, Chemical Engineering Transactions, 45, 235–240.

Linnhoff B, Flower J.R., 1978, Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks, AIChE J, 24, 633–642.

Linnhoff B., Hihdmarsh E., 1983, The Pinch Design Method for Heat Exchanger Networks, Chemical Engineering Science, 38, 745–763.

Liu X.-W., Luo X., Ma H., 2013, Studies on the retrofit of heat exchanger network based on the hybrid genetic algorithm, Applied Thermal Engineering, 61, 785–790.

Nemet A., Klemeš J.J., Moon I., Kravanja Z., 2017, Synthesis of safer heat exchanger networks, Chemical Engineering Transactions, 56, 1885–1890.

Osman A., Abdul Mutalib M.I., Shigidi I., 2016, Heat recovery enhancement in HENs using a combinatorial approach of paths combination and process streams' temperature flexibility, South African Journal of Chemical Engineering, 21, 37–48.

Papoulias S.A., Grossmann I.E., 1983, A structural optimization approach in process synthesis — III. Total processing systems, Computers and Chemical Engineering, 7, 723–734.

Reisen van J.L.B., Grievink J., Polley G.T., Verheijen P.J.T., 1995, The placement of 2-strem and multi-stream heat-exchangers in an existing network through path-analysis, Comput. Chem. Eng, 19, 143–148.

Smith R, 2016, Chemical Process Design and Integration, 2nd Edition, Wiley & Sons Ltd, Chichester, UK.

Tovazhnyansky L., Kapustenko P., Ulyev L., Boldyryev S., 2011, Heat integration improvement for benzene hydrocarbons extraction from coke-oven gas, Chemical Engineering Transaction, 25, 153–158.

Tovazhnyansky L., Kapustenko P., Ulyev L., Boldyryev S., Arsenyeva O., 2010, Process integration of sodium hypophosphite production, Applied Thermal Engineering, 30, 2306–2314.

Ulyev L.M., Kapustenko P.A., Melnykovskaya L.A., Nechyporenko D.D., 2013, The Precise Definition of the Payload Tube Furnaces for Units of Primary Oil Reforming, Chemical Engineering Transaction, 35, 247–252.

Ulyev L.M., Kapustenko P.O., Nechiporenko D.D., 2014, The Choice of the Optimal Retrofit Method for Sections of the Catalytic Reforming Unit, Chemical Engineering Transactions, 39,169–174.

Ulyev L.M., Vasilyev M.A., 2015, Heat and Power Integration of Processes for the Refinement of Coking Products, Theoretical Foundation of Chemical Engineering, 49, 676–687.

Ulyev L., Vasilyev M., Maatouk A., Duic N., Khusanov A., 2016, Total Site Integration of Light Hydrocarbons Separation Process, Chemical Engineering Transaction, 52, 1–6.

Wan Alwi S.R., Manan Z.A., 2010, STEP – A new graphic tool for simultaneous targeting and design of a heat exchanger network, Chemical Engineering Journal, 162, 106–121.