CONSTRUCTION OF A MATHEMATICAL MODEL OF THE10E02 CONDENSER HEAT EXCHANGER FOR HEATING OIL AND GAS CONDENSATE RAW MATERIALS

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Abstract: *Ensuring energy efficiency and energy conservation is one of the most important factors for the successful implementation of the economic and social reforms being carried out in our country. The intensification of the problem associated with the constant increase in the cost of energy carriers leads to finding ways to reduce consumption costs and efficient use of energy resources. Finding the optimal modes of production and consumption of energy, organizing its accounting. When solving a set of technical measures to increase the efficiency of the atmospheric oil distillation unit of the Bukhara Oil Refinery, a system of mathematical equations has been developed. It allows determining the optimal technological cost of oil and gas condensate of raw materials, while reducing the existing heat transfer surface of heat exchange equipment in production and reducing the consumption of heat and electricity. Based on thermal, technical, and economic calculations, it is shown that the proposed method helps to reduce the consumption of energy costs.*

Keywords: *Optimization, modernization, shell-and-tube heat exchanger, condenser, energy efficiency, naphtha, fuel fraction, rectification, distillation.*

Introduction. In recent years, an acute deficiency of gasoline and other types of petroleum products has regularly occurred in Uzbekistan. Due to the insignificant deposits of oil in our country, the supply of oil is carried out mainly from Russia by rail, which increases its cost. One of the republic's oil refineries is the Bukhara Oil Refinery. Since 2019, a project has been launched at the Bukhara Oil Refinery to modernize and reconstruct existing production lines with the installation of additional equipment aimed at improving the quality of products. The plant, founded in 1997, is technologically updated for the first time in 22 years. The modernization project is aimed at increasing the processing depth of the existing refinery capacities up to 95%, the yield of light oil products from 77% to 91%, and the production of oil products that meet the requirements of the Euro-5 standard. After the completion of these works, the refinery will be able to annually process 2.5 million tons of oil and gas condensate, due to which the production of 1.2 million tons of Euro-5 gasoline, 200 thousand tons of jet fuel, 750 thousand tons of diesel fuel and 30 thousand tons of fuel oil. Oil refineries (OR), whose production task is to provide hydrocarbon fuel to various sectors of the economy are consumers of a significant amount of fuel and energy resources for their own needs.

In typical oil refining processes, feed streams are heated, usually for physical separation (rectification) or for endothermic reactions (catalytic reforming). Despite the fact that heat exchange between streams is widely used to heat the raw materials of plants, as a rule, additional heat is required.

In particular, the most costly, in terms of the use of energy as a fuel, steam or electricity, processes at refineries are:

- heating of crude oil or raw materials for technological installations;

ISSN 2277-3630 (online), Published by International journal of Social Sciences & Interdisciplinary Research., under Volume: 14 Issue: 11 in November-2025
https://www.gejournal.net/index.php/IJSSIR

- obtaining the steam for the mechanical drive of turbines to power the main compressors and some large pumps, heating processes and power steam-jet vacuum ejectors;

- heating reboilers; - movement of flows, with the help of electric motors of pumps, etc. [2].

In modern conditions, the economic success of an enterprise, profitability and competitiveness depends on how effectively the chain of energy intensity → energy efficiency → technical development → modernization of the enterprise is implemented [3].

The reduction of these losses is possible due to heat recovery through the extraction and use of heat lost through the walls of technological equipment, energy dissipated into the environment, with cooling water or air, through heat exchange between product flows and the use of low-grade waste heat [3].

Therefore, with the most rational use of heat exchangers, pumps, compressors, etc., as well as the heat of waste oil fractions, it is possible significantly reduce the consumption of heat and electricity. It is proved that the degree of intensification of the process of heating raw materials with hydrocarbon coolants ranges from 10.4 to 45.9%, depending on their phase state and process parameters. It is also very significant that the use hydrocarbon vapors, the technological efficiency of the oil refinery increases by 2.47%, and the uniform distribution oil flow through the heat exchange tubes under the influence of the centrifugal force field increases the efficiency of the apparatus by 18.7% [4].

In this regard, it is necessary to implement organizational, legal, technical, technological, economic and other measures aimed at reducing the volume of energy resources used while maintaining the corresponding beneficial effect from their use (including the volume of production, work performed, services rendered).

Research methods and techniques. Heat exchange equipment makes up a significant part of technological equipment in the chemical, petrochemical, oil refining and food industries, thermal power engineering, construction, metallurgy, and many other sectors of the national economy.

The development of the economy of the Republic of Uzbekistan requires the use of modern methods of analysis and calculation of heat exchange equipment in the oil refining industry, in which the technological parameters of the process play a significant role. With large investments in the technological process, reducing costs even by a fraction of a percent due to the use of optimally sized devices provides significant cost savings for the enterprise.

In this work, a method for solving and calculating the optimization problem of recuperative heat exchangers operating at an oil refinery is proposed (OR) for heating the oil and gas condensate mixture of an atmospheric distillation plant, by determining the heat transfer surface, hydraulic calculation of the resistance of the tubular apparatus and the technological cost of the heated oil and gas condensate feedstock.

The plant under consideration includes the following blocks: apparatus for the first stage of preheating, apparatus for the second stage of heating, distillation column, preliminary fractionation column, raw material heating furnaces, and apparatus for the third stage of heating and pumping equipment [10].

Modernization of the calculation is to optimize the size and mode of operation of the heat exchange equipment of the block for the first stage of preheating of raw materials. This direction has significant prospects, as it allows, with the help of small capital investments and in a short time, to achieve a significant reduction in energy costs per unit of production.

The most widespread are tubular heat exchangers, which account for about 50% of the production cycle. It is known that on a national scale, a large amount of metals is spent on tubular heat exchange devices.

ISSN 2277-3630 (online), Published by International journal of Social Sciences & Interdisciplinary Research., under Volume: 14 Issue: 11 in November-2025
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Therefore, the aim of the study is to create, with the help of mathematical modeling, the most efficient and compact heat exchangers. They, in turn, provide significant savings in fuel, metal, as well as savings in labor costs [5].

A mathematical model is a system of mathematical description equations that reflects the essence of the phenomena occurring in the simulation object, which, using a certain algorithm makes it possible to predict the behavior of the object when the input and control parameters change.

Mathematical modeling of heat exchange equipment is based on the laws of conservation of mass, impulse and energy of transported oil. It is more expedient to use a less "modern", but simpler model that reflects only the individual, main features of the original.

Taking into account the performance of the heat exchanger G and the limitation on the technological parameters of raw materials and the heating coolant, the optimality criterion in general can be expressed in the form of dependencies [4].

$$R = f(G, K_c, K_z, E_z) \qquad (1)$$

K_c - technological indicators of raw materials; K_z and E_z - specific capital and operating expenses for the implementation of the process, referred to one year of the standard payback period Tn. The incoming economic values Kz and Ez give universality to this criterion and allow it to be used to optimize any design of apparatus, regardless of their purpose and features.

When identifying the optimal boundaries of the technological mode of heating oil feedstock with the heat of fuel fractions in the vapor and liquid phases, it is advisable to choose the technological cost of the heated feedstock C_T as an optimality criterion. The composition of the technological cost of production traditionally includes the costs of raw materials, subsidiary materials, heat carriers, heat and electricity, salaries of maintenance personnel and other expenses [4, 5].

$$C_{\text{тех}} = C_о G_о + C_т G_т + C_э(N_н+N_д) + A_а F_т + A_{кн} F_{кн} + A_н(N_н+N_д) \qquad (2)$$

where $C_o, C_{T,}$ and C_e, are respectively the cost of raw materials, heating coolant and electricity; G_o and $G_т$ are raw material and heat carrier productivity; $N_н$ and $N_д$ - pump power for pumping oil and fraction distillates; $F_т$ and F_{kn} - heat transfer surface of heat exchangers and condensers; A_a and A_n - depreciation deductions for technological devices and pumps.

Oil during heating is not exposed to technological processing. Therefore, the cost of crude oil ***Co*** depends on its quality and does not depend on the mode of operation of heat exchange equipment. It should also be taken into account that the flows of distillates of fuel fractions and the distillation residue leaving the distillation column are subject to cooling to the temperature of their storage in Oil refinery parks [1, 6]. Consequently, in order to improve the thermal efficiency of the refinery, these hot streams are used for successive multi-stage preheating of oil, for further entry into the coil furnace. Therefore, the costs associated with the use of hot streams do not affect the technological cost of heated oil in heat exchangers. In addition, the wages of personnel for the maintenance of the apparatus also do not depend on the intensity of operation of the equipment. Due to the above circumstances, the costs associated with the purchase of oil, coolants and the salary of technical personnel are not included in the expression of the optimality criterion of the process under study (2) [4].

$$C_{\text{тех}} = C_э(N_н+N_д) + A_а F_а + A_{кн} F_{кн} + A_н(N_н+N_д) \qquad (3)$$

As it is known, tubular heat exchangers of three blocks of preliminary heating of raw materials of an oil refinery have different designs and performance [1, 2, 4, 6, 7]. For this reason, in order to identify the optimal composition of the heat exchanger blocks of an oil distillation plant and develop its energy-saving technological scheme, it is advisable to take the specific technological cost of the heated raw material $\boldsymbol{C_s = C_{tex} / G_o}$ as an optimality criterion. In this case, (3) can be expressed as:

$$C_{уд} = 1/\, G_o\, [C_e\,(N_n + N_d) + A_a F_a + A_{kn} F_{kn} + A_n\,(N_n + N_d)] \qquad (4)$$

ISSN 2277-3630 (online), Published by International journal of Social Sciences & Interdisciplinary Research., under Volume: 14 Issue: 11 in November-2025
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A comparative assessment of the impact of the cost item on the technological cost of heated oil is carried out by analyzing the equations for calculating the parameters included in the expression of the objective function of the optimality criterion (4).

Pump capacity N (kWt) for pumping process streams (oil and distillate fractions) through the tubes of heat exchangers can be determined by the well-known expression [8]:

$$N = (G_о \cdot \Delta P)/(1000\,\rho\,\eta_н) \qquad (5)$$

which in the example, $G_о$ - mass flow rate, kg/s; ΔP - hydraulic resistance of the flow pumping path, Pa; ρ - flux density, kg/m^3; $\eta_н$ - efficiency pump.

The value of pressure loss ΔP to overcome the forces of internal friction in the heat exchange tubes of the apparatus is determined by the well-known formula [9]:

$$\Delta P = 0{,}5\,\upsilon^2\rho\,(\lambda L_{общ}/d_{экв}+\sum\varphi_i) \qquad (6)$$

that, $\upsilon = G/(0{,}785 d_{вн}^2\rho)$ - flow velocity in apparatus tubes, m/s; d_{in} – interior diameter of the tubes, m; λ = f(Re) - coefficient of friction, determined depending on the mode of movement of the raw material in the tubes according to the Re number; ; $Re = (\upsilon d_{вн}\rho)/\mu$ - Reynolds number; μ - dynamic coefficient of viscosity of the raw material, Pa*s; L_{tot} = n*l - total length of tubes, m; n - the number of pipes in the apparatus, pcs.; l – effective length of one pipe, m; $\sum\varphi_i$ - total coefficient of local resistance.

Taking into account the performance of heat exchangers in terms of raw materials *Go*, their heat transfer surface Fa is determined by the expression

$$F_a = Q/(K\,\Delta t_{ср}) = G_о\,(c_{вых}\,t_{вых} - c_{вх}\,t_{вх})/(K\,\Delta t_{ср}) \qquad (7)$$

that, $Q = G_о(c_{вых}\,t_{вых} - c_{вх}\,t_{вх})$ - thermal load of the apparatus, W; c_{in} and c_{out} - the heat capacity of the raw material at the temperatures of its inlet to the apparatus $t_{in.}$ and at the outlet of it $t_{ot.t}$, Dj/(kg.ºC); K - heat transfer coefficient in the apparatus, Wt/(m^2 °C); $\Delta t_{average}$ - useful temperature difference, ºC.

The heat capacity of oil feed c (kJ/kg.ºC), taking into account its temperature T and relative density, is determined by the formula [1, 2, and 4]:

$$c_p = 1{,}5072 + \frac{T-223}{100}\times(1{,}7182 - 1{,}5072\rho_4^{20}) \qquad (8)$$

The heat transfer coefficients from the heating coolant to the pipe wall $\propto_1$ and from the wall to the heated liquid $\propto_2$, as well as the heat transfer coefficient K in heat exchangers is calculated according to the refined method [9], by taking into account the operating conditions, using temperature changes in the raw material properties indicators - density ρ, viscosity v, and μ, heat capacity c, thermal conductivity λ, etc.

It should be noted that at present at oil refineries (refinery) depreciation deductions $\boldsymbol{A_a}$ are accepted as a conditionally constant value of the cost of ***Tsa*** devices. In reality, the indicator ***Aa*** is a variable and depends on the intensity of the work of heat exchangers T [4].

$$A_а = (E_н Ц_а)/24T\,F_а = (E_н Ц_а)/24T_н\,[G_о\,(c_{вых}t_{вых} - c_{вх}t_{вх})/K\cdot\Delta t_{ср}] \qquad (9)$$

here $E_n = 0.15$ is the standard coefficient of efficiency of capital investments in the industry; $Ц_a$ -the price of the device, sum.

Similarly, depreciation charges for A_n pumps [4].

$$A_н = (E_н Ц_н)/24\,T_н\;N = (E_н Ц_т)/24\,T_н\,[(G\cdot\Delta P)/(1000\,\rho\,\eta_н)] \qquad (10)$$

that, $Ц_n$ is the cost of the pump, sum.

Restrictions in the area of research of the target function of the optimality criterion are set according to the temperature of the heated raw material at the outlet of the heat exchanger unit t_{res} (t_{out}≤ 220÷240 °C) and the specifics of the coil furnace operation (minimum temperature of raw materials at the furnace inlet t_{min} ≤ 120÷150 °C).

ISSN 2277-3630 (online), Published by International journal of Social Sciences & Interdisciplinary Research., under Volume: 14 Issue: 11 in November-2025
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Research findings. The results of the research based on the analysis of heat transfer occurring inside the heat transfer pipes are presented in the following system of equations.

$$\begin{cases} G\, d(ct)/dl = \alpha_2 \pi d_{in} n\, (t_w - t), & (11) \\ c_p = 1{,}5072 + \dfrac{T-223}{100} \times (1{,}7182 - 1{,}5072\rho_4^{20}) & (12) \\ \rho_4^t = 1000\rho_4^{20} - \dfrac{0{,}58}{\rho_4^{20}}(t-20) - \dfrac{\left|[t - 1200(\rho_4^{20} - 0.68]\right.}{1000} \cdot (t-20); & \end{cases}$$

(13)

here, G is the consumption of hydrocarbon raw materials. It is determined from the material balance of the process, kg/s; T = t + 273.15 - liquid temperature, K; c is the heat capacity of the raw material at temperature t, J/(kg ºC); d_{in} - internal diameter of heat transfer pipes, m; n is the number of pipes in the apparatus, pcs.; α_2- coefficient of heat transfer from the pipe wall to the heated liquid, W/(m^2.ºC); t_w - temperature of the inner surface of the pipe wall, °C; - raw material density at 20 °C, kg/m^3.

Restrictions in the area of research of the objective function of the optimality criterion are set by the temperature of the heated raw material at the block outlet of the heat exchanger t restrictions ($t_{ou\,t}$≤20÷240 ^{0}C) and the specifics of the coil furnace operation (the minimum temperature of the raw material at the furnace inlet t_{min} ≤ 120÷150 ^{0}C).

The temperature of hydrocarbon feedstock heating ***t*** is taken in accordance with the requirements of the technological regulations for the operation of an oil refinery. The temperature of tube wall t_{ct} depends on the temperature of the hot coolant (vapour fractions in liquid or phase states). The value of the heat transfer coefficient from the pipe wall to the heated liquid α2 in the apparatus is determined by a well-known method [6], using experimental data on the physical and thermophysical properties of oil and gas condensate raw materials [7].

Mathematical model of the statics of the process of heating hydrocarbon feedstock in a horizontal tubular apparatus, including changes in the feedstock temperature t along the length of horizontal pipes l (1) and indicators of its physical and thermophysical properties - heat capacity (2) and density (3).

The statics of the heating process in the horizontal shell-and-tube heat exchanging condenser 10E-02 of the oil and gas condensate mixture, consisting of 30% oil and 70% gas condensate (30% H + 70% HA) in the pipe space was studied by the heat of the condensing vapors of the total naphtha fraction leaving the columns preliminary fractionation 10C01 and distillation column 10C02 of the primary distillation unit of the Bukhara Oil Refinery. In primary oil distillation units, hot distillates and distillation residues, as well as oil vapors, are used as heat carriers. The heating of this mixture in 10E-02 is carried out in the first raw material preheating unit, which is a system of 8 heat exchangers connected in series. Heat exchanger 10E-02 has the following design parameters: d = 20/25 mm, length of heat transfer pipes l = 4.8 m, number of pipes n = 580 pcs. In this case, the heat transfer surface of the apparatus is F = 196,7 m^2. The heating of the mixture in the heat exchanger tubes was studied at the following regulated values of the technological parameters of the process: the operational capacity of the apparatus for the mixture G = 105508 kg/h, the density of the mixture at 20 °C is ρ_{20} = 768 kg/m^3, the temperature of the mixture at the inlet to the apparatus tin = 25, 6 °C, at its outlet – t_{out} = 49.1 °C, the condensation temperature of total naphtha vapor in the annular space of the apparatus is tb = 148.7 °C. The specified technological regimes correspond to the parameters of the 1st quarter of 2013 of unit No. 10 of the Bukhara Refinery (BNPZ) [10]. The average value of

ISSN 2277-3630 (online), Published by International journal of Social Sciences & Interdisciplinary Research., under Volume: 14 Issue: 11 in November-2025
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the heat transfer coefficient from the pipe wall to the heated mixture is α_2 = 526.4 W/(m^2·K), heat transfer coefficient K = 259 W/(m^2·K).

Based on the results of the study of the process on a mathematical model, a curve distribution of the temperature of oil and gas condensate mixture t along the length of the heat transfer pipes ***l*** of the heat exchanger was formed for its given technological capacity G (Fig. 1).

It is also known that the factors affecting the speed and temperature of the flow of raw materials, when calculating the hydraulic resistance of heat exchangers, the higher the speed and temperature, the smaller the layer of scale formed on the inner surface of the heat transfer tubes [8].

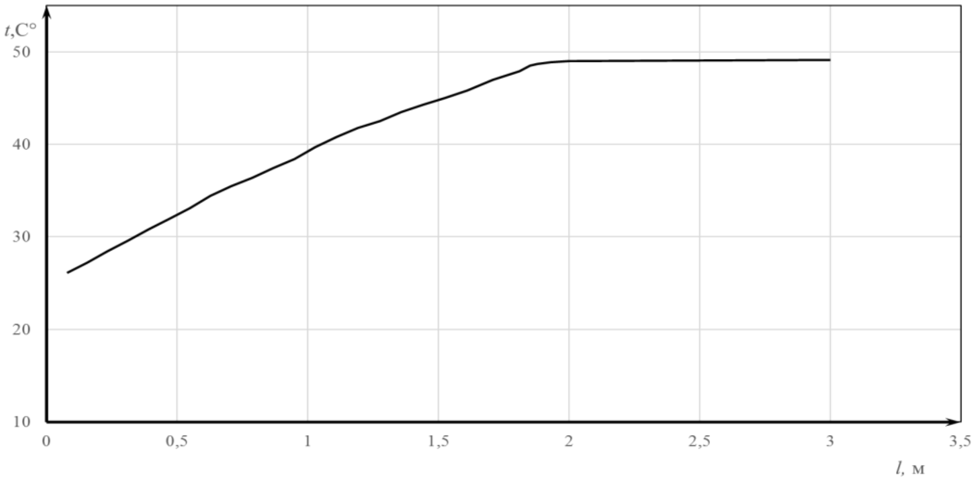

Fig. 1. Temperature distribution of oil and gas condensate mixture t along the length of the pipes *l* of the 10E-02 heat exchanger at its flow rate G = 105508 kg/h and the heat transfer coefficient in the apparatus α_2 = 526.4 W/(m^2 K)

Figure 1 shows how, at a given flow rate, the temperature of the oil and gas condensate mixture t gradually increases with increasing speed up to a pipe section with a length of l = 1.96 m. 2 to 4.8 m).

Analysis of the curve l = f (t) shows that to achieve the required mixture heating temperature at the outlet t_{out} = 49.1°C, a section of the tube bundle with an active length *lact* = 1.9567 m is sufficient, which is 41% of the total length. The main process of heating the mixture takes place in the first half of the tube section (l ≤ 1.97 m), while the rest of the tubes are idle. This circumstance indicates the insufficient use of the thermal power of the apparatus, as well as the possibility of further doubling the flow rate of the heated mixture in the apparatus.

It is proposed, the objective function of the optimality criterion, consisting of a system of equations, to calculate the technological cost of oil feedstock heated by hydrocarbon coolants in a shell- and-tube heat exchanger:

$$\begin{cases} C_{\text{уд}} = 1/G_{\text{о}}\,[C_{\text{э}}N_{\text{н}} + C_{\text{э}}N_{\text{д}} + A_{\text{а}}F_{\text{а}} + A_{\text{н}}N_{\text{н}} + A_{\text{н}}N_{\text{д}}]; \\ N_{\text{н}} = (G_{\text{о}}\,\Delta P)/(1000\rho\eta_{\text{н}}); \\ \Delta P = 0{,}5\,\upsilon^2\rho\,(\lambda L_{\text{общ}}/d_{\text{экв}} + \sum\varphi_{\text{i}}); \\ F_{\text{кн}} = G_{\text{о}}\,(c_{\text{вых}}\,t_{\text{вых}} - c_{\text{вх}}\,t_{\text{вх}})/(K\cdot\Delta t_{\text{ср}}); \\ c_p = 1{,}5072 + \dfrac{T-223}{100}\times(1{,}7182 - 1{,}5072\rho_4^{20}). \\ A_{\text{а}} = (E_{\text{н}}Ц_{\text{а}})/24T_{\text{н}}\,F_{\text{а}}; \\ A_{\text{н}} = (E_{\text{н}}Ц_{\text{н}})/24T_{\text{н}}\,N_{\text{н}}; \end{cases} \quad (14)$$

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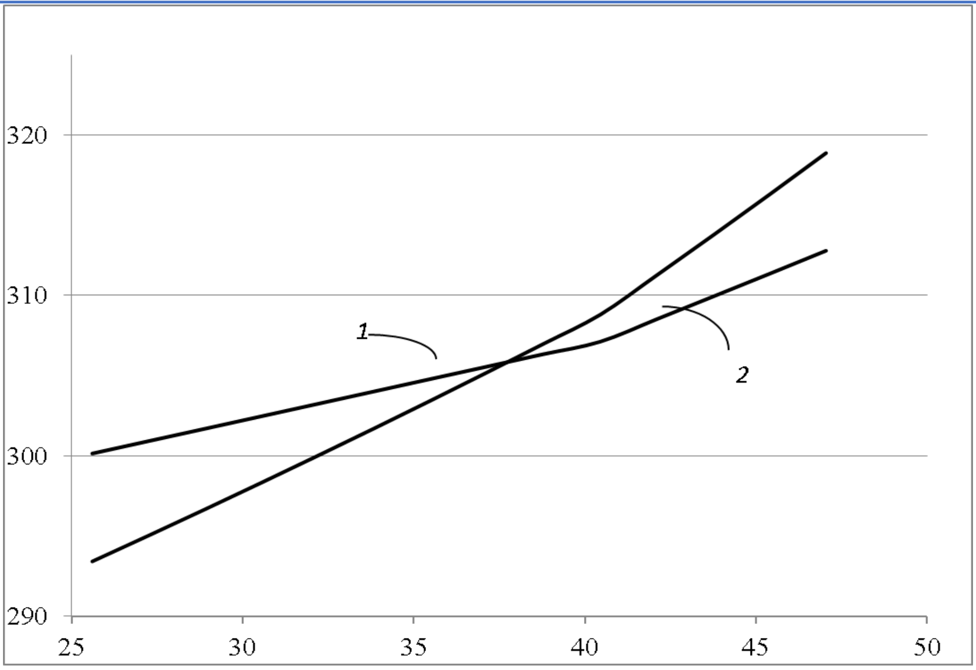

Fig.2. Dependence of the depreciation expenses of the pump (1) and heat exchanger-condenser 10E02 (2) on the temperature of oil and gas condensate mixture

The nature of the changes in the components of the specific technological cost of heating the working mixture (Sud) in the heat exchanger on the temperature of the energy costs for the implementation of the process E = CeNn + AnNn and depreciation deductions for equipment A = AaFa are shown in **Figure 2**. The analysis of the values of these components of the cost of heating the mixture is as follows . To pump the mixture through the tubes of the apparatus in the amount of Go = 105508.3 kg/h, Nн = 15.4 kW of power is required. With the cost of electricity Se = 440.52 soum/kW, in our opinion, the point of intersection of curves 1 and 2, where the value of the heat exchange surface F = 221.9 m^2, E = 305.57 soum/kg, A = 305.21 soum/ kg, Cd = 610.79 soum/kg, and the temperature of the heated mixture at the outlet of the apparatus tout = 37.5 °C, characterize the optimal operating conditions of the 10E-02 heat exchanger at a given raw material capacity Go = 105508.3 kg/h.

Discussion. Efficiency in the production, transmission and use of thermal energy directly depends on the efficiency of heat power and heat technology equipment. The problem of increasing the efficiency and compactness of heat exchangers is mainly solved using new promising methods for intensifying heat transfer in devices and using new schemes for economical modifications. In our opinion, the solution of the system of equations is reduced to identifying the most acceptable operating conditions for the heat exchangers of the oil heating unit, which ensure the optimal technological cost of heating the raw material. Thus, from the calculation of the system of equations, the objective function of the optimality criterion for heating oil and gas condensate raw materials was obtained equal to Ct = 610.8 sum/kg. At the same time, the optimal heat transfer surface F = 222 m^2 was calculated with a length of heat transfer tubes equal to 2 meters. And also, the optimal temperature of the raw oil and gas complex was determined - from 38 °C to 49 °C for an effective operation mode. When analyzing the mathematical model, a direct relationship between the heat transfer coefficient and the length of the heat transfer pipes was revealed, the shorter the pipes, the greater the heat transfer coefficient.

Conclusion. As indicated above from the description, the installation includes a plurality of recuperative heat exchangers and material and thermal recycle flows, which ensures high heat

ISSN 2277-3630 (online), Published by International journal of Social Sciences & Interdisciplinary Research., under Volume: 14 Issue: 11 in November-2025
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integration [11]. Each stream is characterized by a high parametricity equal to 48. Due to the above calculations, as well as the analysis of the kinetic patterns of the technological process, the optimal criteria for heating the oil and gas condensate mixture in the shell-and-tube apparatus - condenser 10E-02 were found, which are the sum of the total energy consumption for electricity to pump the streams (mixture and naphtha distillate), depreciation deductions of the heat exchanger - condenser and pump, optimal dimensions of equipment with an equal amount of heat transferred due to the corresponding speeds of movement of heat exchange media. The proposed method for determining the objective function of the optimality criterion (11) for oil heating will be tested on eight heat exchangers of an atmospheric oil distillation unit (AT), to which oil is supplied after an electric desalination unit (ELOU). After considering possible options, based on the data obtained for all eight heat exchangers, technical and economic indicators for the modernization of the plant, proposals for increasing energy efficiency and norms for the technological mode of operation of the plant as a whole will be drawn up. Not only the yield and quality of the resulting oil fractions, but also the technical and economic indicators of the entire oil refining process depend on the operation of this installation.

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ISSN 2277-3630 (online), Published by International journal of Social Sciences & Interdisciplinary Research., under Volume: 14 Issue: 11 in November-2025
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