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THE HEAT EXCHANGE PROCESS FOR OPTIMIZING PARAMETERS AND INCREASING PRODUCTION EFFICIENCY

Shomansurov Fozilbek
Junior Researcher at the Institute of General and Inorganic Chemistry, Academy of Sciences of the Republic of Uzbekistan. Tashkent, Uzbekistan Email: shomansurovfozilbek@mail.ru
Ismailov Oybek
Doctor of Technical Sciences at the Institute of General and Inorganic Chemistry, Academy of Sciences of the Republic of Uzbekistan. Tashkent, Uzbekistan
Sheraliyeva Ozoda
PhD, Associate Professor at the Department of Technological Machines and Equipment, Tashkent Chemical-Technological Institute, Republic of Uzbekistan, Tashkent

Abstract: This research enables the optimization of the process of heating a hydrocarbon condensate mixture, considering the influence of various parameters on the process cost. By utilizing the target function of optimality criteria, optimal operational parameters for heat exchange equipment at a specific refinery were analytically determined. These parameters help reduce production costs and enhance process efficiency, potentially leading to improved overall economic performance of the enterprise.
Keywords: Optimization, cost, shell and tube heat exchanger, condenser, energy efficiency, oil, fuel fraction, rectification, distillation.

Introduction.

At the Bukhara Oil Refinery in Uzbekistan, the main portion of consumed energy is directed towards heat exchange processes. These processes are implemented through various types and designs of heat exchange equipment [1–5].

Various heat carriers are used for heating, such as hot water or steam. Energy consumption is one of the important factors that significantly influences the design of heat exchangers [6].

Therefore, with the maximally rational use of heat exchangers, pumps, compressors, and also the heat from waste oil fractions, it is possible to significantly reduce the consumption of thermal and electrical energy [7].

As known, the criterion of optimality is a measure of the quantitative assessment of the optimized quality of the object - process or apparatus [8].

Expressing the optimality criterion in the form of economic evaluations, such as productivity, cost of production, profit, profitability, etc., is a common formulation of the optimization problem. Therefore, the main goal of the research is to create a mathematical model with a system of equations for optimizing the sizes and operating modes of heat exchange equipment at the Bukhara Oil Refinery in Uzbekistan. This will allow developing the most efficient and compact heat exchangers, leading to significant fuel and metal savings and reduced labor costs [9].

The paper proposes a method for solving and calculating the optimization problem affecting heat exchangers at the refinery, including determining the heat transfer surface area, hydraulic calculation of tube apparatus resistances, and technological cost of heating oil and gas condensate raw materials.

Methods and Research Techniques.

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The mathematical model of the static process of heating hydrocarbon raw materials in a horizontal tubular apparatus is based on equations describing changes in the temperature of the material along its flow (1) and also takes into account the physical properties of the material, such as heat capacity (2) and density (3). This model allows for the analysis of heating processes and optimization of equipment parameters to increase production efficiency and reduce energy consumption.

$$G\frac{\partial(ct)}{\partial l} = \pi\alpha d_{id} n(t_w - t). \quad (1)$$

G - the flow rate of hydrocarbon raw material, determined by the material balance of the process (kg/s); $_{id}$ - the internal diameter of the heat transfer tubes (m); - the number of tubes in the apparatus (pcs); - the heat transfer coefficient from the tube wall to the heated liquid (W/(m^2°C); $_w$ - the temperature of the internal surface of the tube wall (°C);
To calculate the heat capacity of oil and oil products C (kJ/kg·K), taking into account their temperature T, relative density ρ_{15}^{15}, and chemical composition, the Watson and Nelson equation [10] is used:

$$C_p = \left[1{,}28076 - 0{,}70279 \cdot \rho_{15}^{15} + T\left(0{,}00615 - 0{,}0023\rho_{15}^{15}\right)\right]\left(0{,}055K + 0{,}35\right). \quad (2)$$

Where K is a characteristic factor of the oil product. The characteristic factor K for oil and gas condensate mixtures is calculated using the formula [11]:

$$K_{см} = \frac{K_o \cdot V_o + K_{gc} \cdot V_{gc}}{V_o + V_{gc}}, \quad (2.1)$$

Where K_o and K_{gc} are the characteristic factors of oil and gas condensate, respectively; V_o and V_{gc} are the proportions of oil and gas condensate in the mixtures, expressed in percentages.
For a more accurate calculation of the density of hydrocarbon raw materials over a wide range of temperatures (up to 300°C), the equation of A.K. Manovyan is applied, which guarantees an accuracy of no less than 97% [11]:

$$\rho_4^t = 1000\rho_4^{20} - \frac{0{,}58}{\rho_4^{20}}(t - 20) - \frac{\left[t - 1200\left(\rho_4^{20} - 0{,}68\right)\right]}{1000} \cdot (t - 20). \quad (3)$$

When identifying the optimal boundaries of the technological regime for heating crude oil with fuel fractions in the vapor and liquid phases, it is advisable to select the technological cost of heated raw materials (denoted as $C_т$) as the criterion of optimality. The technological cost of production traditionally includes expenses on raw materials, auxiliary materials, heat carriers, thermal and electrical energy, salaries of service personnel, and other expenses [7,9]:

$$C_т = C_{rm}G_{rm} + C_{hm}G_{hm} + C_e(N_p+N_d) + A_{he}F_{he} + A_p(N_p+N_d), \quad (4)$$

Where C_o, $C_т$, and Ce represent the respective costs of raw materials, heating medium, and electricity; G_{rm} and G_{hm} denote the consumption rates of raw materials and the heating medium; N_p and N_d stand for the power of the pump for transferring oil and distillate fractions; F_{he} represents the heat transfer surface area of the heat exchangers; and A_{he} and A_p are the depreciation charges for technological equipment and pumps.
The expenses on raw materials and the heating medium do not influence the technological cost of heated crude oil in heat exchangers. Due to the aforementioned circumstances, the costs associated with the purchase of crude oil, heating mediums, and salaries of technical personnel are not included in the expression of optimality criterion of the investigated process [7]:

$$C_т = C_e(N_p+N_d) + A_{he}F_{he} + A_p(N_p+N_d), \quad (5)$$

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As it is known, tubular heat exchange apparatuses of three preliminary heating blocks in the oil refining plant have different designs and productivity [7,12,13,14,15]. For identifying the optimal composition of heat exchanger blocks in the oil refining plant and developing its energy-saving technological scheme, it is expedient to adopt the specific technological cost of heated raw material ($C_{stc} = C_t/G_{rm}$) as a criterion of optimality. In this case, (3) can be expressed as:

$$C_{stc} = 1/\, G_{rm}\, [C_e(N_p+N_d) + A_{he} F_{he} + A_p(N_p+N_d)], \qquad (6)$$

A comparative assessment of the impact of cost items on the technological cost of heated oil is conducted by analyzing the equations for calculating parameters included in the expression of the target function of optimality criterion (6). The power of the pump N (kW) for pumping technological flows (oil and distillate fractions) through the tubes of heat exchange apparatus can be determined by the known expression [16]:

$$N = (G_o \cdot \Delta P)/(1000\, \rho\, \eta_p), \qquad (7)$$

Where $_{rm}$ is the mass flow rate of the stream, kg/s; Δ is the hydraulic resistance of the flow passage, Pa; is the density of the flow, kg/m³; $_p$ is the efficiency of the pump.

The pressure drops ΔP to overcome the forces of internal friction in the heat exchange tubes of the apparatus is determined by the well-known formula [17]:

$$\Delta P = 0{,}5 \upsilon^2 \rho\, (\lambda L_{tl}/d_{экв} + \sum \varphi_i), \qquad (8)$$

Where = /(0.785 · $_{id}{}^2\rho$) is the flow velocity in the apparatus tubes, m/s; $_{id}$ is the internal diameter of the tubes, m; = ( ) is the friction coefficient determined depending on the flow regime of the substance in the tubes by the Reynolds number =(· $_{id}$ ·)/ ; is the dynamic viscosity coefficient of the substance, Pa·s; $_{tl}$= n · l is the total length of the tubes, m; is the number of tubes in the apparatus, pcs; l is the working length of one tube, m; $\sum \varphi_i$ is the total coefficient of local resistances.

Taking into account the performance of the heat exchange apparatuses for the raw material $_{rm}$, their heat transfer surface $_{he}$ is determined by the expression:

$$F_{he} = Q/(K\, \Delta t_d) = G_{rm}\, (c_{out}\, t_{out} - c_{in}\, t_{in})/(K\, \Delta t_d), \qquad (9)$$

Where: = $_{rm}$($_{in}$ · $_{in}$ − $_{out}$ · $_{out}$) is the heat load of the apparatus, W; $_{in}$ and c_{out} are the specific heats of the raw material at the inlet and outlet temperatures, J/(kg·°C); K is the heat transfer coefficient in the apparatus, W/(m²°C); Δ $_d$ is the useful temperature difference, °C.

The coefficients of heat transfer from the heating heat carrier to the tube wall $_1$ and from the wall to the heated liquid $_2$, as well as the heat transfer coefficient K in the heat exchange apparatuses, are calculated using a refined methodology [18], taking into account the operating conditions and using temperature variations of the properties of the raw material such as density ρ, viscosity ν, and μ, specific heat c, thermal conductivity , etc.

It's worth noting that currently in oil refining plants (refineries), depreciation charges $_{he}$ are taken as a conditionally constant value from the cost of equipment $_{he}$. In reality, however, $_{he}$ is a variable quantity depending on the intensity of operation of the heat exchange apparatuses T. [7]:

$$A_p = (E_n C_{he})/24T\, F_{he} = (E_p C_{he})/24T_p\, [G_{rm}\, (c_{out}\, t_{out} - c_{in}\, t_{in})/(K\, \Delta t_d)], \qquad (10)$$

Where: =0.15 is the normative coefficient of efficiency of capital investments in the industrial sector; C_{he} is the cost of the apparatus, total. Similarly, depreciation charges for pumps A_p are determined [7].

$A_p = (E_p C_p)/24\ T_p\ N = (E_p C_{he})/24\ T_p\ [(G \cdot \Delta P)/(1000\, \rho\, \eta_p)]$, (11)

Where C_p is the cost of the pump, in sum.
The constraints in the area of investigation of the optimization criterion function are set based on the temperature of the heated product at the outlet of the heat exchanger unit org (t_{out} ≤220−240 °C) and the specifics of the operation of the coil furnace (minimum temperature of the product at the furnace inlet ≤120−150°C).

Results of the research.

The heat exchanger has the following structural parameters and operational modes:

d – diameter of tubes	20/25 mm
l - length of heat transfer tubes	4,8 m
n - number of tubes	580 units
F - heat transfer surface area of the apparatus	219 m^2
$_{20}$ - density of the mixture	768 kg/m³
- productivity	29.3 kg/s
t_{in} - temperature of the mixture at the inlet	25,6 °C
t_{out} - temperature of the mixture at the outlet	49,1 °C
$t_{кн}$ - temperature of oil condensation	148,7 °C
- convective heat transfer coefficient	526,4 W/ (m^2·K)
К - overall heat transfer coefficient	259 W/ (m^2· K)

The provided technological parameters correspond to the conditions of the Unit No. 10 of the Bukhara Oil Refinery Plant (BORP) in the first quarter of 2013 [19]. To assess the efficiency of the heat exchange equipment involved in the process of heating the raw material, an analysis can be conducted using mathematical models that take into account their operational performance G and the temperature of the material at the outlet $_{out}$ [16, 17].
Using the equations (1, 2, 3, 4, 5, 6, 7, 8, 9, 10) provided above, we calculated the technological cost of the crude oil, i.e., the objective function of the optimality criterion for heating hydrocarbon heat carriers in the shell-and-tube heat exchanger. Additionally, based on the research results from the mathematical model, a curve representing the distribution of the temperature of the oil-gas-condensate mixture along the length of the heat transfer tubes l of the heat exchanger was plotted at the specified technological performance G (Figure 2).

Results of the analysis of the mixture heating process optimization.

№	t_m, °C	Δt_d, °C	K, W/(m^2°C)	F, m^2	$A_{he}F_{he}$, sum/kg	$C_eN_p+A_pN_p$, сум/кг	C_{stc}, sum/kg
1	25,6	37,35	255,53	213,39	293,42	300,15	593,57
2	27,25	38,175	256,05	214,56	295,04	300,92	595,96
3	28,9	39	256,58	215,75	296,67	301,70	598,38
4	30,55	39,825	257,11	216,96	298,33	302,47	600,81
5	32,2	40,65	257,64	218,18	300,02	303,25	603,27
6	33,85	41,475	258,18	219,43	301,72	304,02	605,75
7	35,5	42,3	258,72	220,69	303,46	304,80	608,26
8	37,15	43,125	259,26	221,96	305,21	305,57	610,79
9	38,8	43,95	259,81	223,26	307,00	306,35	613,35

10	40,45	44,775	260,37	224,57	308,80	307,12	615,93
11	42,1	45,6	260,41	226,36	311,26	308,52	619,79
12	43,75	46,425	260,44	228,18	313,76	309,93	623,70
13	45,4	47,25	260,48	230,02	316,30	311,36	627,66
14	47,05	48,075	260,52	231,90	318,88	312,79	631,68

The nature of changes in the components of the specific technological cost of heating the working mixture $_{stc}$ in the heat exchanger with respect to temperature - energy costs for the process $= _e \, _p + \, _н \, _н$ and depreciation charges for equipment $= A_{he}F_{he}$ is reflected in Figure 1. The analysis of the values of these components of the heating cost of the mixture can be summarized as follows.

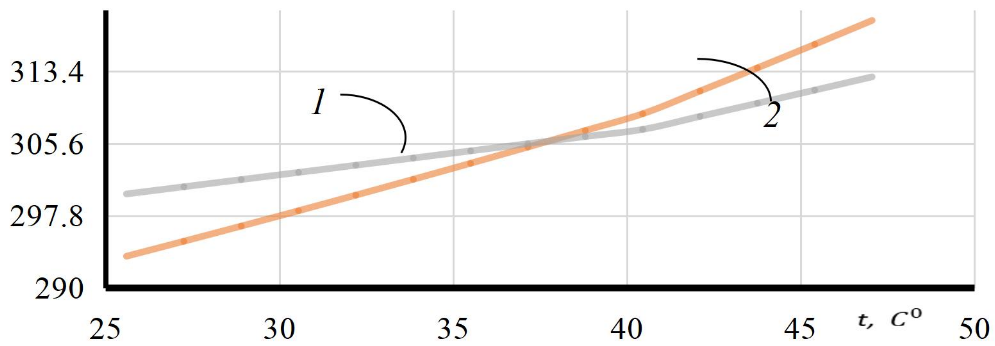

Figure 1. Energy costs and depreciation charges for heating the oil-gas-condensate mixture with heavy oil steam in the heat exchanger.

For pumping the mixture through the apparatus tubes at a flow rate of G = 105508.3 kg/h, a pump power of N = 15.4 kW is required. Considering the cost of electricity to be C = 440.52 sum/kW, the optimal operating conditions of heat exchanger 10E-02 at this flow rate can be described by the intersection point of curves 1 and 2. At this heat exchange surface value of F = 221.9 m^2, the energy expenditure amounts to Э = 305.57 sum/kg, while the depreciation expenses are A = 305.21 sum/kg. The temperature of the heated mixture at the outlet of the apparatus is t = 37.5°C, confirming the optimal operating conditions of this heat exchanger.

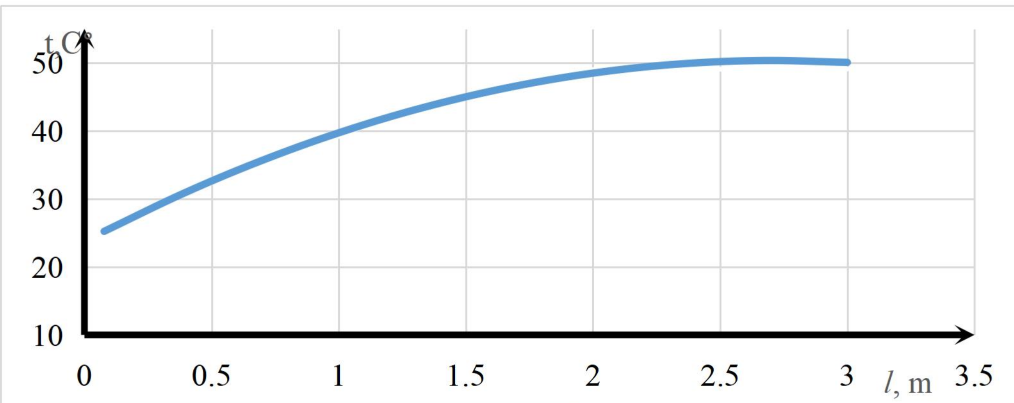

Figure 2. Distribution of the temperature of the oil-gas-condensate mixture (t) along the length of the heat exchanger tubes (l).

From Figure 2, it can be observed that at the given flow rate, the temperature of the oil-gas-condensate mixture (t) gradually increases with increasing speed up to a section of the tube with a length of l = 1.96 meters. Subsequently, upon reaching a constant temperature difference between the heat carriers, the rate of temperature change of the mixture acquires a constant character (from 2 to 4.8 meters).

Analysis of the curve l = f(t) shows that to achieve the required temperature of heating the mixture at the outlet (t_{out} = 49.1°C), a section of the tube bundle with an active length of l_{al} = 1.9567 meters is sufficient, which constitutes 41% of the total length. The main heating process of the mixture occurs in the first half of the tube section (l ≤ 1.97 meters), while the remaining part operates idle. This circumstance indicates insufficient utilization of the thermal power of the apparatus and suggests the possibility of further doubling the flow rate of the heated mixture in the apparatus.

Conclusion.

The solution of the system of equations boils down to identifying the optimal operating conditions of the oil heating exchangers, ensuring minimal 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-gas-condensate raw materials is obtained, equal to Cst = 610.8 sum/kg. At the same time, the optimal heat transfer surface F = 222 m2 is calculated for a length of heat transfer tubes equal to 2 meters. Additionally, the optimal temperature of the gas-condensate raw material is determined to be 38°C for efficient operating conditions. Upon analyzing the mathematical model, a direct relationship between the heat transfer coefficient and the length of the heat transfer tubes was identified: the shorter the tube length, the higher the heat transfer coefficient.

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