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OPTIMIZATION OF HEATING OF MIXTURES OF OIL AND GAS CONDENSATE BY HOT FLOWS OF FRACTIONS IN TUBULAR HEAT EXCHANGERS

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Abstract:

Background of the problem. The constant increase in the cost of energy resources determines the search for ways to efficiently use thermal and electrical energy and thereby reduce production costs for the production of petroleum products. In this aspect, research aimed at improving the thermal efficiency of oil refineries by optimizing the technological modes of distillation of hydrocarbon raw materials is important.

Goal. Optimization of the process of heating mixtures of oil and gas condensate by hot flows of fractions in a tubular heat exchanger of an atmospheric oil distillation unit.

Methodology. Based on the mathematical model of the statics of thermal preparation (heating) of the oil and gas condensate mixture for distillation, the objective function of the optimality criterion is formulated - the specific technological cost of the heated mixture, which includes the cost of electricity for pumping raw materials and depreciation deductions for the heat exchanger and pump, depending on the parameters of the process. The computational and experimental study was carried out in accordance with the data of the technological regulations for the installation of atmospheric distillation of a mixture of oil and gas condensate of the Bukhara oil refinery (refinery).

Scientific novelty. A technique for optimal calculation and design of the process of heating local hydrocarbon feedstock - oil, gas condensate and their mixtures with pairs of light fractions in tubular heat exchangers of refineries is proposed, taking into account temperature changes in the properties of feedstock and coolant.

Received data. The process of heating the oil and gas condensate mixture in a horizontal shell-and-tube heat exchanger-condenser 10E-04 refinery, having a heat transfer surface of 243 m^2, formed from tubes with a diameter of 20/25 mm, was studied. The study was carried out at regulated flow rates of the working mixture of 105508 kg/h, within the temperature of its heating 96,1÷111,7 °C at the condensation temperature of vapors of common naphtha 136,6 °C. The results of the study of the process statics on the model showed that at a given plant capacity, the optimal temperature of the heated mixture at the outlet of the heat exchanger is equal to 107,3 °C, required heating surface of the device 178 m^2 and the minimum technological cost of the heated mixture is C_{ud} = 285,12 sum/kg.

Conclusion. Comparison of the identified optimal and regulated values of the design and technological parameters of the process indicated the insufficient use of the thermal power of the apparatus, which made it possible to formulate a compromise task - further increasing the flow rate of the mixture heated in the apparatus by 1.4 times or replacing it with a more compact heat exchanger, which will reduce costs while operation of the device.

Keywords: oil, gas condensate, hydrocarbon raw materials, distillation, fraction, naphtha, heating, condensation, heat exchanger, modeling, optimization, technological cost.

Introduction. As is known, the thermal preparation of hydrocarbon raw materials for distillation and rectification is characterized by high heat and electricity consumption. Therefore, with the constant growth of tariffs for energy resources, the operating conditions of large-capacity oil refineries at refineries do not always meet modern requirements for the efficient use of energy. This circumstance indicates the need to improve most of the technological processes of oil refining, including the process of thermal preparation of raw materials for distillation, and to optimize the operating mode of the oil refinery.

According to the existing production technology at refineries, raw materials are initially heated in three blocks of tubular heat exchangers, then they are heated in a coil furnace, and then the raw materials are physically separated into fractions by distillation in an environment of superheated water vapor [1-5]. To heat the feedstock in the refinery, hot process streams leaving the distillation column are used - distillates of fuel fractions of naphtha, kerosene, diesel fuel and fuel oil [2-4].

As is known, tubular heat exchangers used for heating hydrocarbon raw materials are characterized by high operational reliability [2,4,5]. However, these devices are characterized by large weight and size parameters (diameter - 0,63÷1,8 m, tube length - 5÷10,6 m, weight - up to 35÷40 t) and low heat transfer efficiency (50÷100 W/m^2K) [4;6].

Therefore, further research aimed at the efficient organization of processes in heat exchangers and the refinement of methods for their optimal design, based on the principles of system analysis and mathematical modeling, which contributes to significant energy savings and operating costs, acquire important scientific and practical significance [6].

The purpose of this work is to determine the optimal design and technological parameters for heating hydrocarbon raw materials during the condensation of naphtha vapor in a tubular heat exchanger of an atmospheric oil distillation unit.

Research methods and techniques. The paper proposes a method for optimal calculation and design of the process of heating hydrocarbon raw materials with pairs of light fractions in tubular heat exchangers, taking into account temperature changes in the properties of local raw materials and coolant. This contributes to the development of energy-optimal designs of heat exchangers, a significant reduction in the technological cost of heated raw materials by reducing the consumption of heat and electricity for the process, as well as the synthesis of a rational scheme for the block of apparatus for thermal preparation of raw materials for an oil refinery [6-8].

This computational and experimental study was carried out in accordance with the data of the technological regulations for the installation of atmospheric distillation of a mixture of oil and gas condensate at the refinery [9]: the technical parameters of the industrial tubular heat exchanger-condenser 10E-04, the limit values of the mixture heating mode were determined (concentration of the mixture, flow rate of the mixture G_o and the heating flow of naphtha, the temperature of condensation of its vapors $t_{кн}$, the temperature of the initial $t_{вх}$ and the heated mixture $t_{вых}$) and indicators of the main properties of the mixture and coolant.

As is known, according to the existing method for calculating the heat transfer and heat transfer coefficients K in heat exchangers [4,6,10-12], the indicators of the physicochemical and thermophysical properties of the raw material and the heating agent (density ρ, viscosity ν and μ, heat capacity c, thermal conductivity λ, etc.) are taken at average values of their temperature t. However, the value of these indicators of hydrocarbon coolants depends on the value of the process temperature [1-3,6,11-13]. Therefore, taking into account the continuous change in the indicators of the properties of heat carriers from temperature, which forms the basis of the proposed method for calculating thermal coefficients in heat exchangers [6, 8], helps to increase the accuracy of the calculations performed by 20–30 %.

Based on the analysis of the phenomena that take place during the heating of hydrocarbon feedstock in heat exchanger tubes [6, 7], a mathematical model of the statics of this process is obtained, which includes equations for changes in the temperature of the feedstock t along the length of the pipes l (1) and indicators of its properties - heat capacity (2) and density (3) during this process [7,14,15]:

$$\begin{cases} G_o\, d(ct)/dl = \alpha_2 \pi d_{vn} n\, (t_{st} - t), & (1)\\ \rho_4^t = 1000\rho_4^{20} - \frac{0{,}58}{\rho_4^{20}}(t-20) - \frac{|[t-1200(\rho_4^{20}-0.68]}{1000}\cdot(t-20); & (2)\\ c_p = 1{,}5072 + \frac{T-223}{100}\times(1{,}7182 - 1{,}5072\,\rho_4^{20}); & (3)\\ t \le t_{ogr}. & (4) \end{cases}$$

where G_o - consumption of hydrocarbon raw materials, kg/c; c - heat capacity of raw material at temperature t, J/(kg °C); $T = t + 273{,}15$ - raw material temperature, K; α_2 - heat transfer coefficient from the pipe wall to the heated liquid, W/(m^2.°C); d_{vn} - pipe inner diameter, m; n - number of tubes in the machine, per.; $t_{ст}$ - temperature of the inner surface of the pipe wall, °C; ρ_4^{20} - raw material density, kg/m^3.

The temperature limit of raw material preheating t_{ogr} is determined in accordance with the requirements of the technological regulations for the operation of an oil refinery [9] and the company's standards for the types of fuel fraction distillates produced - common naphtha, straight-run kerosene and diesel fuel. The tube wall temperature t_{st} depends on the temperature of the hot coolant - distillates of fractions in the liquid or vapor phases. The value of the coefficient α_2 is determined according to the refined method [8], using the temperature dependences of the properties of raw materials [6,13].

The process statics model (1-4) makes it possible to study the nature of the distribution of technological parameters for heating hydrocarbon feedstock along the length of heat transfer pipes l, to design heat exchangers with the optimal heating surface $F_{op} = \pi d_{vn} n l_{op}$, and also to analyze the degree of efficiency of operation of tubular heat exchangers operated at refineries at a given flow rate of raw materials and its heating temperature.

When solving the problem of optimizing the heating of hydrocarbon raw materials, either the rational boundaries of the technological parameters of the process or the minimum heat transfer surface of the apparatus, which provides its specified performance G_o, are determined.

To identify the optimal boundaries for heating oil feedstock with the heat of fractions, the technological cost of heated feedstock $C_т$ was chosen as an optimality criterion, which includes the cost of raw materials, heat carriers, heat and electricity, wages of maintenance personnel and other costs [6,19,20].

Since oil is not subjected to technological processing during heating, its cost C_o does not depend on the mode of operation of the heat exchanger. It should also be taken into account that the hot flows of fractions and fuel oil leaving the distillation column of an oil refinery are subject to cooling to their storage temperature [1-3]. Based on this, in order to improve the thermal efficiency of the oil refinery, these hot streams are used for sequential multi-stage heating of oil in heat exchangers. Therefore, the costs associated with the use of heat from hot streams do not affect the technological cost of the heated mixture $C_т$ in the apparatuses. In addition, the salary of technical personnel for maintenance of heat exchangers is fixed and it also does not depend on the intensity of operation of the devices.

Taking into account the above circumstances, the costs associated with the purchase of raw materials, heat carriers and the salary of technical personnel are not included in the expression of the optimality criterion of the process under study. In this case, the objective function of the chosen optimality criterion - the technological cost of heating the oil feedstock - is formulated by us in the form [6,20]:

$$C_{\text{Т}} = C_e\,(N_p+N_d) + F_a\,A_a + F_{kn}\,A_{kn} + (N_p+N_d)\,A_{\text{P}}. \qquad (5)$$

where, N_{P} and N_{D} - capacity of pumps for pumping oil and distillate fractions; C_e - cost of electricity; F_a and F_{kn} - heating surface of heat exchangers and condensers; A_a , A_{kn} , A_p и A_d - depreciation deductions for apparatus and pumps.

It is known that tubular heat exchangers in the raw material heating blocks of an oil refinery have different designs and performance [2,4,5]. Therefore, for the synthesis of the optimal composition of the heat exchanger block of the installation and its energy-saving technological scheme, it is advisable to take the specific technological cost of the heated raw material as an optimality criterion $C_{ud} = C_{\text{Т}}/G_o$ [6,20]. In this case, (5) can be expressed as:

$$C_{ud} = 1/G_o[C_e(N_p+N_d) + A_aF_a + A_{kn}F_{kn} + A_{\text{н}}\,(N_p + N_d)]. \qquad (6)$$

A comparative assessment of the impact of the cost item on the technological cost of the heated mixture was carried out by analyzing the equations for calculating the parameters included in the expression of the objective optimality function (6).

Pump power N (kW) for pumping streams of crude oil and distillate fractions through the tubes of the heat exchanger is determined by the expression [10]:

$$N = [G_o\;0{,}5\upsilon^2\rho\;(\lambda n{\cdot}l\;/d_{ekv}+\Sigma\varphi_i)]/(1000\;\rho\;\eta_n), \qquad (7)$$

where, ΔP - hydraulic resistance of the pipeline for pumping flow, P; ρ - flux density, kg/m^3; η_n - efficiency pump; $\upsilon = 4G_o/(\pi d_{vn}^2\rho)$ - raw material flow rate in apparatus tubes, m/s; $\lambda = f(Re)$ - coefficient of friction, determined depending on the mode of flow in the tubes by the number Re [10]; $Re = (\upsilon d_{vn}\rho)/\mu$ - Reynolds number; μ - dynamic coefficient of viscosity of raw materials, Pa s; Σ - the total coefficient of local resistance in the apparatus and in pipelines to them [10].

The heat transfer surface F_a of the heat exchanger, taking into account its performance in terms of raw materials G_o, is determined by the expression [6]:

$$F_a = G_o\,(c_{\text{вых}}\,t_{out} - c_{in}\,t_{in})/(K\,\Delta t_{sr}), \quad (8)$$

where, $G_o(c_{out}\;t_{out} - c_{in}\;t_{in})$ - thermal load of the device, W; c_{in} и c_{out} - heat capacity of raw materials at temperatures of its inlet to the apparatus t_{in} and at its outlet t_{out}, J/(kg·^{o}C); K - heat transfer coefficient in the apparatus, W/(m$^2\,^o$C); Δt_{cp} - useful temperature difference between raw material and coolant, ^{o}C.

The value of depreciation deductions for the heat exchanger A_a and the pump $A_{\text{н}}$ depends on the duration of their operation T [6,20]:

$$A_a = (E_n\text{Ц}_a)/24\;T\,F\,, \qquad (9)$$

$$A_{\text{н}} = (E_n\text{Ц}_n)/24\;T\,N\,, \qquad (10)$$

where, E_n = 0,15 - normative coefficient of efficiency of capital investments in the industry; Ц_a and Ц_n - heat exchanger and pump cost, sum.

Thus, the objective function of the optimality criterion for heating a mixture of oil and gas condensate by the heat of the fuel fractions flow in a shell-and-tube heat exchanger is formulated as a system of equations:

$$
\begin{array}{lr}
C_{ud} = \left\{ \begin{array}{l}
1/G_o\,[C_{\text{э}}\,N_n + A_a\,F_a + A_n\,N_n]\,; \\
\end{array}\right. & (6) \\
\rho_4^t = 1000\rho_4^{20} - \frac{0{,}58}{\rho_4^{20}}(t-20) - \frac{|[t-1200(\rho_4^{20}-0.68]}{1000}\cdot(t-20); & \mathbf{(2)} \\
c_p = 1{,}5072 + \frac{\mathrm{T}-223}{100}\times(1{,}7182 - 1{,}5072\rho_4^{20}); & (3) \\
N_n = [G_o\,0{,}5\upsilon^2\rho\,(\lambda n{\cdot}l\,/d_{ekv}+\Sigma\varphi_i)]/(1000\,\rho\,\eta_n); & (7) \\
\qquad F_a = G_o\,(c_{out}\,t_{out} - c_{in}\,t_{in})/(K_{kn}{\cdot}\Delta t_{sr}); & (8) \\
\qquad A_a = (E_n \text{Ц}_t)/24T\,F; & (9) \\
\qquad A_n = (E_n \text{Ц}_n)/24T\,N; & (10) \\
t \le t_{ogr}. & (4)
\end{array}
$$

Constraints (6) in the area of the study of the objective function are set by the temperature of the heated mixture at the outlet of the heat exchanger $t_{out} \le t_{ogr}$ [9].

The solution of the above system of equations (2-10) is reduced to identifying the optimal boundaries of the technological regime for heating the oil and gas condensate mixture in the heat exchanger-condenser 10E-04, operating in the mode of efficient use of the heat of condensed naphtha vapor.

Research results and discussion. The statics of the process of heating the oil and gas condensate mixture, consisting of 30 % oil and 70 % gas condensate, by the heat of condensing vapors of the total naphtha fraction, leaving the upper parts of the columns for the preliminary fractionation of raw materials and atmospheric distillation of oil at the Bukhara Oil Refinery, was studied.

The industrial heat exchanger-condenser 10E-04 used for heating the working mixture has the following design parameters [9]: d = 20/25 мм, l = 6,0 м и n = 644 per, and its heating surface in size d_{vn} is F_{vn1} = 243 m^2.

The heating of the mixture in the tubes of this apparatus was studied at the following values of the technological parameters of the process [9]: G_o = 105508 kg/h, ρ_{20} = 768 kg/m^3, t_{in} = 96,1 ^{o}C, t_{out} = 111,7 ^{o}C and t_{kn} = 136,6 ^{o}C. The calculated value of the heat transfer coefficient from the pipe wall to the mixture is α_2 = 878 W/(m^2·K), and the value of the heat transfer coefficient in the apparatus is equal to K = 270 W/(m^2· K).

Based on the results of the study of the process on a mathematical model, a distribution curve of the heating temperature t of the oil and gas condensate mixture along the length of the tubes l of the heat exchanger was constructed for a given performance G_o (Fig. 1).

It can be seen from Figure 1 that at a given flow rate of the working mixture G_o = 105508 kg/h its temperature t in the heat exchanger smoothly rises to 107,3 ^{o}C with increasing speed at a pipe section $l \le$ 4,4 м. At the same time, the rate of rise in the temperature of the mixture along the length l in the initial section is 2,6 ^{o}C/m, and closer to the temperature equilibrium point - 3,5 ^{o}C/м. In the future, with the achievement of a constant temperature difference between the oil and gas condensate mixture and the coolant, the rate of change in the temperature of the mixture along the remaining length of the pipes (up to 6.0 m) becomes unchanged.

Analysis of the curve $l = f(t)$ shows that the main process of heating the oil and gas condensate mixture to the required temperature $t_{\text{вых}}$ = 107,3 ^{o}C takes place in the initial section of pipes with a length of $l \le$ 4,4 m, which is 63.7 % of the total length of the tube bundle in apparatus, and the rest of the tubes in the bundle runs idle (section from 4.4 to 6.0 m). Whence it follows that with a given productivity of the apparatus G_o = 105508 kg/h of the mixture, its required heating surface is F_2 = 178 m^2. Comparison of the values of heat exchange surfaces F_1 = 243 m^2 ≥ F_2 = 178 m^2 indicates insufficient use of the heat output of the apparatus. It follows that the 10E-04 heat exchanger-condenser has a reserve for further increase in the flow rate of the mixture heated in it by 36.4 % (1.36 times).

Subsequently, the objective function of the optimality criterion for heating the oil and gas condensate mixture (2-10) in this apparatus was studied in relation to the operating conditions of the atmospheric oil distillation unit of the Bukhara Oil Refinery [13]. The calculation of the objective function of the optimality criterion according to (6) was carried out with the above values of the process parameters - G_o, G_d, t_{in}, t_{out} and t_{kn}.

Based on the results of the calculations, curves were plotted for changes in the components of the specific cost of heating the working mixture C_{ud} in the heat exchanger (sum/kg) - depreciation deductions for the heat exchanger (curve *1*) and the cost of pumping liquid by the pump (curve 2), depending on the temperature of the mixture t_{out} at t_{out} = 96,1÷111,7 °C and condensation of total naphtha vapor t_{kn} = 136,6 °C (Fig. 2).

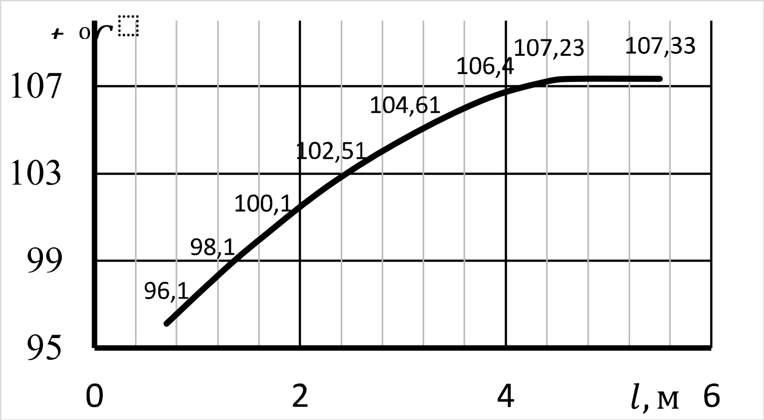

Fig. 1. Distribution of the heating temperature of the oil and gas condensate mixture *t* along the length of the pipes *l* of the 10E-04 heat exchanger at its flow rate G_o = 105508 kg/h

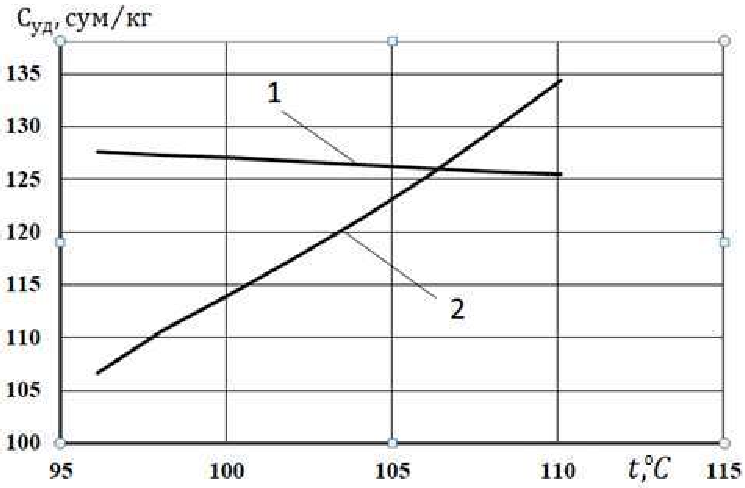

Fig. 2. Change in depreciation deductions for heat exchanger *1* and costs for pumping oil and gas condensate mixture *2* depending on the temperature of its heating t_{out}

Analysis of the values of the components of the unit cost of the heated working mixture C_{ud} is as follows. According to the calculations, the amount of depreciation deductions for the heat exchanger $A = A_aF_a$ (curve *1*), depending on the mode of operation of the heat exchanger, intensively increases along an inclined curve from 106.66 to 134.39 sum/kg. To pump a given amount of the mixture Go = 105508.3 kg/h through the tubes of the apparatus and the process pipe adjacent to it, N_n = 15,4 kW of power will be required. Taking into account the cost of electricity for the refinery C_e = 440,52 sum/kW and depreciation of pumping equipment, the total costs for pumping a given flow rate of the mixture $\text{Э}_n = N_n(C_e+A_n)$ drops from 127.62 to 125.45 sum/kg (curve 2). In our opinion, the point of intersection of curves *1* and 2, where the values of the parameters F_2 = 178 m^2, Э_n = 125,58 sum/kg, A = 127,55 sum/kg, C_{ud} = 285,12 sum/kg and t_{out} = 107,3 ^{o}C, characterizes the optimal operating conditions of the 10E-04 heat exchanger-condenser at its given productivity G_o = 105508,3 kg/h.

Conclusion. Thus, according to the results of studies on the model of the statics of heating the oil and gas condensate mixture, the optimal design and technological parameters of the process in the heat exchanger-condenser 10E-04 with a capacity of G_o = 105508 kg/h were revealed: mixture heating temperature t = 107,3 ^{o}C, device heating surface F_{vn1} = 178 m^2 and mixture heating cost C_{ud} = 285,12 sum/kg. Comparison of the working heating surface of the apparatus F_1 = 243 m^2 with its optimal value F_2 = 178 m^2 indicates insufficient use of its thermal power, which also allows solving a compromise problem - further increasing the consumption of the heated mixture in the apparatus up to 1.4 times or replacing it with a more compact heat exchanger. Such a solution helps to improve the operating conditions of the apparatus, reduce operating costs and develop energy-efficient technological schemes for heat exchangers of the feedstock heating unit of an oil refinery.

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