Optimization of the cyclic pumping of high pour point and high viscosity oil mixtures through main oil pipelines

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Abstract. This paper presents the optimization results of the cyclic pumping of batches of high-pour-point and high-viscosity oil mixtures at the Uzen-Atyrau section of the Uzen-Atyrau-Samara main pipeline, taking into account on-route heating, boosting and pumping-out. The optimization criterion was the minimum total cost of power consumption by the pumping units and the preheaters.

1. Introduction

The batching pumping is that several fluids with different physical-chemical properties and different purposes are pumped simultaneously in the same pipeline. In addition, each batch of oil mixture displaces the previous one in the pipeline section and in turn it is displaced by the next batch.

Batch pumping takes place at the Uzen-Atyrau section of the Uzen-Atyrau-Samara main pipeline for batches of Buzachi and Mangyshlak oil mixtures. The pour point of the Mangyshlak oil mixture is $T_{pp} = +27 ^\circ$C, and the pour point of the Buzachi oil mixture is $T_{pp} = -12 ^\circ$C at the output of the Uzen oil pumping station. The difference in pour point temperatures of these oil mixtures requires optimization of the heating temperature to ensure the safe cyclic pumping. Depending on the volume of the batches and their pumping time, it is possible to calculate the length of the section of oil pipeline and location of these batches within the Uzen-Atyrau section. The changes in the physical-chemical properties of the oil mixtures occur when two batches come into contact [1].

Optimization problems can be solved by the determination of optimization criterion and objective function. It is generally accepted that choosing the optimization criterion depends on the operation conditions of oil pipeline and safety of oil transportation [2], [3].

In this paper, the results of optimization calculations for cyclic pumping of batches of Mangyshlak and Buzachi oil mixtures at the Uzen-Atyrau section are presented.

2. Criterion for optimization calculations of energy-saving

For the first time, the solution of the problem of pumping of oil mixtures with on-route heating with an optimization criterion in the form (1) was obtained by V.S. Yablonsky et al. [4]:

$$
\rho g i_{in} z_{el}^{in} \frac{z_{el}}{\eta_{pu}} + k_{in} \pi D_{1} (T_{in} - T_{w}) z_{fl}^{in} = \rho g i_{k} z_{el}^{k} \frac{z_{el}}{\eta_{pu}} + k_{fl} \pi D_{1} (T_{flin} - T_{w}) z_{fl}^{k}
$$

(1)

where: $\rho, Q$ are the density of oil and the volume flow rate of oil; $g$ is the gravitational acceleration; $i_{in}, i_{flin}$ are the hydraulic gradients at the initial and final sections, respectively; $k_{in}, k_{flin}$ are the coefficients of heat transfer at the initial and final sections, respectively; $z_{el}, z_{fl}$ are the unit costs of
electric power and thermal energy, respectively; $\eta^{pu}, \eta^{ph}$ are the efficiency coefficients of the pumping units and preheaters, respectively; $T_{in}, T_{fin}$ are the initial and final temperature of oil at the section, respectively; $D_1$ is the internal diameter of the oil pipeline; $T_w$ is the temperature of the surrounding soil.

According to the results of work of V.S. Yablonsky [4], the heating temperature is optimal when the total costs for pumping and heating per unit of length at the beginning of the section is equal to the total costs for pumping and heating per unit of length at the end of the section of oil pipeline.

As it can be seen from Eq. 1, Yablonsky’s optimization criterion [4] was formulated for a fixed flow rate at a linear section and it is not fulfilled when there is a change of the pumped volume and temperature adjustment of the oil mixture at sections with several oil pumping stations (OPS) and oil heating stations (OHS).

The cyclic mode for the pumping of oil mixtures is determined by the work of pumping units and preheaters at sections of main pipeline. It can thus be concluded that the optimization criterion at section of main pipeline with several stations is determined by the minimum value of the total cost of power used by the pumping units and preheaters [5]:

$$S = \sum_{i=1}^{n} \left( z^e_i \sum_{j=1}^{m_i^{pu}} c^pu_i N^{pu}_{ij}(k_{ij}) + z^f_i \sum_{j=1}^{m_i^{ph}} c^{ph}_{ij} Q^f_{ij} \right) \Rightarrow \text{min}$$  \hspace{1cm} (2)

where $S$ is the total cost of energy used by the pumping units and preheaters; $n$ is the number of pumping and heating stations at the section; $m_i^{pu}$ is the number of pumps at the $i$-th station; $z^e_i/z^f_i$ is the cost of electricity (kzt/kW·h)/fuel (kzt/kg) at the $i$-th station, respectively; $c^pu_i/c^{ph}_{ij}$ is the integer variable, which has the value 1 if the pump/preheater is in operation, and 0 otherwise; $Q^f_{ij}$ is the fuel rate to the $j$-th preheater at the $i$-th station (kg/h); $N^{pu}_{ij}(k_{ij})$ is the power consumption of the $j$-th pumping unit at the $i$-th station (kW); $k_{ij}$ is the ratio of the rotor speed of this pump to its nominal rotor speed.

The first term in Eq. 2 determines the energy cost consumed by pumps to create the head (pressure), and the second term determines the fuel cost expended on heating high-pour-point and high-viscosity oil mixtures at every station.

Pumping units create head (pressure), and preheaters create temperature for pumping high-pour-point and high-viscosity oil mixtures. The thermal-hydraulic calculation on the linear part of the pipeline section is carried out by solving the system of equations:

$$\frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x} + \rho c^2 \frac{\partial u}{\partial x} = \frac{1}{2} \sum_{i=1}^{M} G_i(T_\omega, x_i) \delta(x - x_i)$$  \hspace{1cm} (3)

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \frac{\partial p}{\partial x} = -\lambda(Re, \varepsilon) \frac{\rho u |u|}{2D_1} - \rho g \sin \alpha(x) + \frac{1}{2} \sum_{i=1}^{M} G_i(T_\omega, x_i) \cdot (u_i \cos \beta_i - u) \delta(x - x_i)$$  \hspace{1cm} (4)

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} = -\frac{4k}{\rho_p D_1} (T - T_w) + \frac{u g i}{c_p} + \frac{1}{\rho c_p} \sum_{i=1}^{M} G_i(T_\omega, x_i) \cdot (c_{pi} T_i - c_p T) \delta(x - x_i)$$  \hspace{1cm} (5)

In the Eq. (3)-(5) $G_i(T_\omega, x_i)$ is the power of the $i$-th intermediate station of oil boosting and pumping-out, $S$ is the cross-sectional area of pipe, $p, c_p, u, T$ are the pressure, the heat capacity, the speed, and the temperature of the oil mixture, respectively, $\lambda$ is the hydraulic resistance coefficient, $Re$ is the Reynolds number, $u_i, T_i, c_{pi}$ are the speed, the temperature, and the heat capacity of pumped oil, respectively, $k$ is the heat transfer coefficient, $\delta(x - x_i)$ is the Dirac’s delta function, $ug i/c_p$ is the dissipation of kinetic energy into heat, $i = \Delta p/\rho g l$ is the hydraulic gradient, $\varepsilon, D$ are the roughness and the diameter of the pipeline.
The speed of wave propagation in the pipeline \( c \) is introduced into equation (3). According to N.E. Zhukovskyi [3], the speed \( c \) is calculated by the formula:

\[
c = \frac{1}{\sqrt{\frac{\rho_1}{\mu_1} + \frac{\rho_2}{\mu_2}}}
\]

where \( \xi \) is the bulk modulus of oil, \( E, \delta \) are the Young modulus and the wall thickness of pipe, respectively.

Dependences of the density, viscosity, and heat capacity of oil mixtures on temperature are found by the standard formulas [26]:

\[
\rho(T) = \rho_20 \left[1 + \zeta \cdot (20 - T)\right]
\]

\[
\mu(T) = a \cdot \exp(-bT)
\]

\[
c_p(T) = \frac{1}{\rho_20} (53357 + 107.2 \cdot T)
\]

where \( \rho_20 \) is the oil density at 20°C; \( a \) and \( b \) are empirical constants; \( \zeta \) is the coefficient of volumetric expansion of oil mixture (\( \zeta = 0.000738 \, 1/°C \)).

For the Buzachi oil mixture, the empirical data are equal to \( \rho_20 = 912.5 \, kg/m^3 \), \( a = 0.24 \), \( b = 0.08 \); empirical data for Mangyshlak oil are: \( \rho_20 = 851.7 \, kg/m^3 \), \( a = 1664.7 \), \( b = 0.29 \) [9].

Optimization calculations are carried out by the system of equations (3) - (9) under the condition (2) using the SmartTran software [10]. The SmartTran software is a joint development of the authors, and it is designed for forecasting, modeling and optimization of energy-saving modes of transport of oil mixtures at sections of the main oil pipelines.

At the Uzen-Atyrau section, oil pumping is carried out by pumping units of the following stations: Uzen, Beineu, Kulsary and “663 km”. Oil heating takes place by preheaters at the following stations: Uzen, Sai-Utes, Beineu, Opornaya, and Kulsary.

On-route oil boosting at Karakuduk, Kensary, Opornaya, Kulsay, KasPN and Karsak stations increases the flow rate and volume of pumped batches. When the Mangyshlak batch passes through the “663 km” station, it is pumped-out towards Atyrau refinery at a flow rate of 1000 t/h to 1290 t/h, in order to meet the requirements of the refinery.

For the safety of pumping of high-pour-point oil mixture, it is necessary that the temperature of the oil in the pipeline is 5°C higher than the pour point. However, during the cyclic pumping one batch of oil mixture is successively displaced by the next along the length of the Uzen-Atyrau section [1], [8], i.e. a high-viscosity low-temperature Buzachi oil mixture displaces the high-pour-point Mangyshlak oil mixture. Therefore, at the same heating temperature of both oil mixtures at the stations, the thermal mode of cyclic pumping can be provided at temperatures close to the pour point of the Mangyshlak oil mixture.

Optimization calculations of the technological modes of cyclic pumping are carried out by setting the lower limit of the temperature of oil mixture in the pipeline. The upper limit of the temperature of oil heating is determined when the criterion (2) is fulfilled, so that the total cost of consumed energy for heating and pumping is minimal.

3. Calculation results and discussion

It is assumed that there is a cyclic pumping of batches of Buzachi and Mangyshlak oil mixtures at the Uzen-Atyrau section. At the output of the Uzen station, the mass of the batch of Buzachi oil mixture is 24,000 tons, and the mass of the batch of Mangyshlak oil mixture is 22,000 tons.

In Fig. 1 the batch of the Buzachi oil mixture is painted in white color, and the batch of the Mangyshlak oil mixture is painted in yellow. The flow rate of cyclic pumping varies along the length of the section of pipeline due to the on-route boosting and pumping-out. Analysis of the calculations is carried out for typical periods of time within 24 hours.
Figure 1. The cyclic pumping mode of the batches of Buzachi and Mangyshlak oil mixtures.

As it can be seen from Fig.1, the calculation data describe a picture of batch pumping of Buzachi and Mangyshlak oil mixtures at the Uzen-Atyrau section. The upper graph illustrates the distribution of hydraulic slope and the route profile, the middle graph presents the pressure distribution and the lower graph presents the temperature distribution of oil mixtures and soil along the route of the section.

The distribution of pressure was obtained by creating the pressure by pumping units, reduction of pressure due to hydraulic resistance in the pipe and the preheaters, change in static pressure due to the geodesic height of the route profile at the Uzen-Atyrau section, as well as the residual pressure at the inlet of the end pumping station named after T. Kasymov. The temperature distribution shows the heating of oil mixture at the heating stations (temperature increase) and the cooling of oil mixtures due to heat exchange with the surrounding cold soil (temperature decrease).

The cyclic pumping in Fig.1 is carried out with pumping units of Uzen and Kulsary stations, and oil was heated by heaters of Uzen station (from 45.2 to 47.1 °C), Sai-Utes station (from 40.5 to 42.6 °C), Beineu station (from 36.7 to 39.2 °C), Oportnaya station (from 32.2 to 41.5 °C), Kulsary station (from 32.7 to 43.2 °C), “663 km” station (from 32.5 to 36.7 °C). The wave-like change in temperature is caused by the higher heat content of the high-pour-point Mangyshlak batch, in comparison with the high-viscosity Buzachi batch.

Figure 2 shows the calculated data (lines) of the hydraulic slope, pressure and temperature in comparison with the production data (points) of cyclic pumping according to operating parameters.
Figure 2. Distribution of hydraulic slope (upper graph), pressure (middle graph) and temperature (lower graph) of cyclic pumping.

The actual data of the hydraulic slope, pressure and temperature are obtained by measuring the parameters of the flow of oil mixtures by sensors of the SCADA system (Supervisory Control and Data Acquisition), and the calculated data are obtained by the SmartTran software. In Fig. 2 the actual data of SCADA (points) are in agreement with the calculated data of the hydraulic slope, pressure and temperature (lines).

Optimization calculations of the energy-saving mode of cyclic pumping were carried out at lower boundaries of search interval of the temperature of oil mixture in the pipeline, which are equal to 32°C and 30°C.

Figure 3 shows the calculated data of the hydraulic slope, pressure, temperature of cyclic pumping of Mangyshlak and Buzachi oil mixtures for energy-saving mode at the lower limit of the temperature interval equal to 32 °C, and the upper temperature limit is calculated as a result of the search. It can be seen from Fig. 3 that the upper limit of the heating temperature at the Uzen station equaled 45°C, 39.2 °C at the Beineu station, 41.5°C at the Oporinya station, and 43.1°C at the Kulsary station. The oil mixtures were not heated at the Sai-Utes and “663 km” stations. In this case, the specific cost of cyclic pumping for the technological mode according to the production data was 107.1 kzt/ton, and the specific cost for the energy-saving mode was 71.3 kzt/ton, i.e. savings on pumping and heating batches of Buzachi and Mangyshlak oil mixtures were 33.42%.
Figure 3. Distribution of hydraulic gradient (upper graph), pressure (middle graph), and temperature (lower graph) of cyclic pumping in energy saving mode.

The calculation results of energy-saving mode of the cyclic pumping at the lower boundary of search interval show that the temperature of oil mixture equals 30°C, which is shown in Fig. 4.

As it can be seen from Fig. 4, the temperature of the oil mixtures in the pipeline did not fall below 30°C and the upper limit of the heating temperature of oil mixtures has the following values: 45.2 °C at the Uzen station, 36.1 °C at the Beineu station, 38.2 °C at the Opornaya station, and 40.6 °C at the Kulsary station. In this case the unit costs of the energy-saving cyclic pumping mode was 64.2 kzt/ton, i.e. the savings on pumping and heating of the batches of Buzachi and Mangyshlak oil mixtures, compared with the actual production data, are equal to 40.05%.

Table 1 presents the calculation data for the unit costs for cyclic pumping in optimum conditions for the heating temperature and production conditions, depending on the average monthly temperature of the soil between stations at the section under consideration. The search for optimum conditions for the cyclic pumping has been conducted at the lower limit of the search interval for temperature of oil mixture of 32°C.

It can be seen from Table 1 that the effectiveness of optimum conditions of cyclic pumping for the batches of Buzachi and Mangyshlak oil mixtures with initial masses of 24,000 and 22,000 tons, respectively, in the Uzen-Atyrau section in comparison with real production data ranges between 30.05 % and 33.63 %.
Figure 4. Distribution of hydraulic gradient (upper graph), pressure (middle graph), and temperature (lower graph) of cyclic pumping in energy saving mode

Table 1. The economic efficiency of optimum conditions of cyclic pumping

| Month    | Calculations under optimum conditions | Calculations under production conditions | Savings (%) |
|----------|----------------------------------------|------------------------------------------|-------------|
|          | Unit costs (kzt/ton) | Unit costs (kzt/ton)                     |             |
| January  | 106.70                        | 153.00                                    | 30.26       |
| February | 109.50                        | 157.60                                    | 30.52       |
| March    | 117.00                        | 169.80                                    | 31.09       |
| April    | 103.60                        | 149.50                                    | 30.70       |
| May      | 87.10                         | 127.20                                    | 31.52       |
| June     | 78.60                         | 114.60                                    | 31.41       |
| July     | 68.00                         | 98.40                                     | 30.89       |
| August   | 49.10                         | 70.20                                     | 30.05       |
| September| 59.40                         | 89.50                                     | 33.63       |
| October  | 71.30                         | 107.10                                    | 33.42       |
| November | 81.30                         | 116.60                                    | 30.27       |
| December | 93.30                         | 137.50                                    | 32.14       |
Conclusions
1. The optimization criterion for energy-saving modes, which expresses the minimum total cost for power consumed by pumping units and preheaters, has been used in calculations. The total cost was calculated based on tariffs for electricity and fuel at the Uzen-Atyrau section.
2. Calculation data have been obtained for cyclic pumping at the Uzen-Atyrau section:
   a) Depending on the volume change of pumped batches of Buzachi oil mixture with initial mass 24,000 tons and Mangyshlak oil mixture with initial mass 22,000 tons;
   b) By searching the optimum temperature for heating of oil mixtures at stations with a lower limit of 30 and 32°C and with average monthly temperatures of soil;
   c) By determining the energy-saving modes for operating pumping units and preheaters, where Eq. 2 is fulfilled;
3. By using energy-saving operating modes for pumping units and preheaters, it is possible to reduce the unit costs for pumping and heating of oil mixtures from 30.05 to 33.63 %.

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References
[1] Nechval M V, Novoselov V F, and Tugunov P I 1976 Oil and oil products batching through main pipelines (Nedra: Moscow) 224 (in Russian)
[2] Abramzon L S 1979 Oil Industry 2 53–4 (in Russian)
[3] Agapkin V M, Krivoshein B L, and Yufin V A 1981 Heat and hydrodynamic calculations for oil and oil products pipelines (Nedra: Moscow) p 256 (in Russian)
[4] Yablonsky V S, Novoselov V F, Galeyev V V and Zakirov G Z 1965 Design, operation and repair of oil product pipelines (Nedra: Moscow) p 410 (in Russian)
[5] Bekibayev T T, Zhabbasbayev U K, Ramazanova G I 2017 Journal of Physics: Conference Series 998 44–5
[6] Zhabbasbayev U K, Makhmotov E S, Bekibayev T T, Ramazanova G I, and Rziyev S A 2015 Science and Technologies: Oil and Oil Products Pipeline Transportation 4 61–6 (in Russian)
[7] Tugunov P I, Novoselov V F, Korshak A A, and Shammasov A T 2002 Typical calculations for the design and operation of gas and oil pipelines (Design Poligraph Service: Ufa) p 658 (in Russian)
[8] Korshak A A and Nechval A M 2005 Oil, oil products and gas pipeline transportation (Design Poligraph Service: Ufa) p 516 (in Russian)
[9] Makhmotov E S, Sigitov V B, Boranbayeva L E, Didukh A G and Alexeyev S G 2009 Oil mixtures transported though main oil pipelines (KazTransOil JSC Zhibek Zholy: Almaty) p 530
[10] SmartTran software 2014 Governmental registration of the rights for an object of author’s right 1864 dated October 8