

Calculations for energy-saving modes for batching oil blends in trunk pipelines

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ABSTRACT

THIS PAPER PRESENTS the results of calculations for the technological parameters of batching oil blends with high-pour-point and high-viscosity at the Uzen-Atyrau section of the Uzen-Atyrau-Samara trunk pipeline, taking into account on-route heating, boosting and pumping-out. The optimisation criteria were the minimum total cost of power consumption by the pumping units and the preheaters.

Key words: trunk pipeline, batch pumping, energy-saving mode, optimisation criteria

1. Introduction

Batch pumping takes place at the Uzen-Atyrau section of the Uzen-Atyrau-Samara trunk pipeline for batches of Buzachi and Mangyshlak oil blends. Mangyshlak oil is the crude oil used at the Atyrau oil refinery (AOR). Depending on the volume of the batches and the time they are pumped, it is possible to calculate the length of the section of oil pipeline and location of these batches within the Uzen-Atyrau section. Where two batches come into contact, changes occur in the physico-chemical properties of the oil blends [1].

Optimisation problems can be solved by defining the optimality criterion and the target function. It is generally accepted that when choosing the optimisation criterion, the conditions which arise during oil pipeline operation shall be taken into account, as well as the safety of oil blend transportation [2-4].

Presented below are the results of optimisation calculations for energy-saving modes in batch pumping Mangyshlak and Buzachi oil blends at the Uzen-Atyrau section, according to the chosen optimisation criterion.

2. Criterion for optimisation calculations of energy-saving

The minimum cost of total operational expenses for pumping and heating was taken as the optimisation criterion; the target function was calculated in the form [4]:

$$S = \rho \cdot Q \cdot g \cdot H \frac{\sigma_H}{\eta_H} + \rho \cdot Q \cdot c_p \cdot (T_H - T_k) \frac{\sigma_{\theta}}{\eta_{\theta}} \Rightarrow \min \quad (1)$$

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where:

S is the total cost;
 Q is the volume flow rate;
 g is the gravitational acceleration;
 H is the net pressure losses at the section;
 ρ and c_p are the density and specific heat of oil;
 σ_H and σ_θ are the unit costs of mechanical and thermal energy respectively;
 η_H and η_θ are the efficiency coefficients of the pumping units and heating station respectively;
 T_H and T_k are the initial and final temperature of oil at the section.

A solution to this problem was first obtained by V.S. Yablonsky [5], and has the form:

$$\rho \cdot Q \cdot g \cdot i_H \frac{\sigma_H}{\eta_H} + k_H \cdot \pi \cdot D \cdot (T_H - T_0) \frac{\sigma_\theta}{\eta_\theta} = \rho \cdot Q \cdot g \cdot i_k \frac{\sigma_H}{\eta_H} + k_k \cdot \pi \cdot D \cdot (T_k - T_0) \frac{\sigma_\theta}{\eta_\theta} \quad (2)$$

where:

i_H and i_k are the hydraulic gradients at the initial and final sections respectively;
 k_H and k_k are the coefficients of heat transfer at the initial and final sections respectively;
 D is the internal diameter of the oil pipeline;
 T_0 is the temperature of the surrounding soil.

According to the results of work by V.S. Yablonsky [5], 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 can be seen from Equ 2, Yablonsky's optimisation criterion was formulated for a fixed flow rate at a linear section. It is not fulfilled where there is a change to the volume pumped and temperature adjustment of the oil blend at sections with several pumping stations and preheaters.

An energy-saving mode for oil blend transportation is determined by the work of technological equipment at trunk pipeline sections. It can thus be concluded that the optimisation criteria at a section of trunk pipeline with several stations are determined by the minimum value of the total cost of power used by the pumping stations and preheaters [6]:

$$F = \sum_i^n \left(\sigma_i^M \sum_j^{m_i} E_{ij} + \frac{\rho_i Q_i c_{ip} (T_i^\theta - T_i^r) \sigma_i^T}{\eta_i^\theta} \right) \Rightarrow \min \quad (3)$$

where:

F is the total cost of energy used by the pumping stations and preheaters;
 n is the number of pumping stations and preheaters at the section;
 m_i is the number of working pumps at the i -th station;
 σ_i^M is the unit cost of mechanical energy at the i -th station;
 σ_i^T and η_i^θ are the unit cost of thermal energy (fuel) and the efficiency coefficient for a preheater at the i -th station respectively;
 E_{ij} is the power used by the j -th pumping equipment at the i -th station;
 T_i^θ and T_i^r are the temperature of the oil blend at outlet and inlet of the i -th station respectively.

The first item in Equ 3 determines the cost of the energy used by all the pumps during pumping, and the second item defines the cost of energy expended on heating oil blends at

every station. According to Equn 3, an energy-saving mode for batch pumping is determined by the minimum total cost of power demanded for heating and pumping oil blends. The volume of pumped oil blends is determined by the change to its viscosity depending on the temperature and pressure losses. Therefore, both items in Equn 3 depend on the temperature of the oil blend.

The distribution of oil blend temperatures at the section of the oil pipeline between stations is calculated using V.G. Shukhov's well-known formula, taking into account frictional heat and phase transition [6-8]:

$$T = T_r + \frac{\rho Q g i}{k \pi D} + \left(T_0 - T_r - \frac{\rho Q g i}{k \pi D} \right) \exp \left(- \frac{k \pi D x}{\rho Q (c_p + \varepsilon H_f / (T_b - T_c))} \right) \quad (4)$$

The full pressure of the pumping equipment for batching oil blends is found using a pressure balance equation [6-9]:

$$h_n + \sum_{i=1}^n \sum_{k=1}^m \left(H_0 \left(\frac{n_k}{n_{nom}} \right)^2 + a_k Q_i - b_k Q_i^2 \right) = \sum_{j=1}^n (1,02 h_{\tau_j} + \Delta z_j) + \sum_{i=1}^s h_{si} + h_{res} \quad (5)$$

where:

n_c/n_{nom} is the ratio of rotor rotation frequency to the nominal rotation frequency of the k-th pump;

$\sum_{i=1}^s h_{si}$ is the pressure loss at preheaters;

h_{res} is the residual pressure at the inlet to the final station.

The dependences of the density and viscosity of the oil blend on its temperature can be found using the standard formula:

$$\begin{aligned} \rho(T) &= \rho_{20} [1 + \xi(20 - T)] \\ \mu(T) &= a e^{-bT} \end{aligned} \quad (6)$$

where:

ρ_{20} is the density of oil at 20°C;

ξ is the coefficient of volumetric expansion for the oil blend ($\xi = 0.000738$ 1/°C);

A and b are empirical constants.

For the Buzachi oil blend, the empirical data are equal to $\rho_{20} = 912.5$ kg/m³, $a = 0.2389$, $b = 0.0803$; while for Mangyshlak oil they are: $\rho_{20} = 851.7$ kg/m³, $a = 1664.69$, $b = 0.292$.

At the Uzen-Atyrau section, oil heating takes place at the following stations: GNPS Uzen, SPN Sai-Utes, NPS Beine, SPN Opornaya, and NPS Kulsary. At the preheaters the pressure (head) losses vary from 1.5 to 3.2 bar depending on the flow rate of oil. 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 NPS 663 km station, it is pumped-out towards AOR at a flow rate of 1000 t/h to 1290 t/h, in order to meet the requirements of the plant.

Where batch pumping occurs, one batch of oil blend is successively displaced by the next along the length of the Uzen-Atyrau section [1, 8, 9]. This may affect the dynamics of the thermal mode of pumping Buzachi and Mangyshlak oil batches.

Table 1. Parameters for batch pumping of oil blends

Month	Mangyshlak batch flow rate, t/h	Buzachi batch flow rate, t/h	Pump-ing-out at AOR, t/h	Batching time for Mangyshlak batch	Batching time for Buzachi batch
January	1701.4	1871.6	1267.0	12 h 45 min	11 h 15 min
February	1629.5	1803.6	1286.1	12 h 40 min	11 h 20 min
March	1594.0	1741.5	1270.9	10 h 53 min	13 h 07 min
April	1518.8	1491.1	1249.3	11 h 30 min	12 h 30 min
May	1681.7	1768.7	1278.4	11 h 38 min	12 h 22 min
June	1544.1	1641.0	1247.8	14 h 02 min	9 h 58 min
July	1495.3	1682.3	1258.7	16 h 15 min	7 h 45 min
August	1486.3	1481.3	1229.6	16 h 05 min	7 h 55 min
September	1480.3	1557.2	1158.6	12 h 58 min	11 h 02 min
October	1410.5	1529.9	1055.6	13 h 56 min	10 h 04 min
November	1527.7	1654.9	1264.6	13 h 57min	10 h 03 min
December	1251.4	1900.8	1236.2	13 h 58 min	10 h 02 min

The Mangyshlak oil blend has a high pour point and at outlet from GNPS Uzen has the pour point of TPT = 27°C, while for the Buzachi oil, TPT = -12°C [10]. The operating safety regulations for oil with a high pour point recommend that the temperature of oil in the pipe shall be 5°C higher than the pour point. Therefore optimal conditions for batch pumping can be found in the temperature interval between 32-55°C.

If the lower limit of temperature is known to be 32°C, then the upper temperature limit for heating at preheaters is found by searching where Equn 3 is fulfilled, so that the total cost of power used in heating and pumping is minimal.

3. Calculation results and discussion

Calculations were performed according to standard operating parameters at the Uzen-Atyrau section (Table 1). Rates of oil blend exiting GNPS Uzen vary from month to month and remain constant in the interval of time pumping batches of Mangyshlak or Buzachi oil blends. Therefore the speed of batch pumping changes based on time, as well as based on the length of the section due to on-route boosting and pumping-out. For the sake of brevity, the calculations are analysed for characteristic intervals of time within 24 hours.

Figure 1 presents a general picture of the distribution of pressure and temperature within 24 hours, where the soil is at the average monthly temperature for January. The ranges of their change over time were obtained depending on the volumes of pumped batches of Buzachi and Mangyshlak oil blends at the outlet from GNPS Uzen, boosting and pumping-out at the section under examination.

The temperature of oil preheating is calculated so that the temperature in the pipeline does not fall below 32°C.

As can be seen from Fig.1, calculation data describe a picture of batch pumping of Buzachi and Mangyshlak blends within 24 hours at the Uzen-Atyrau section. The distribution of pressure was obtained taking into account the pressure loss due to hydraulic resistance in the pipe and in coil pipes of the preheaters, changes to the geodesic height of the route profile at the Uzen-Atyrau section, as well as the residual pressure at the inlet of the NPS T. Kasymov pumping station. The temperature distribution can be found by taking into account the heating of oil blends at preheaters and heat exchange with the surrounding soil.

As has been noted above, the lower limit for pumping temperature must not fall below 32°C,

Fig.1. A general picture of the pressure and temperature distribution for batch pumping of Buzachi and Mangyshlak oil blends at the Uzen-Atyrau section given soil temperature for January.

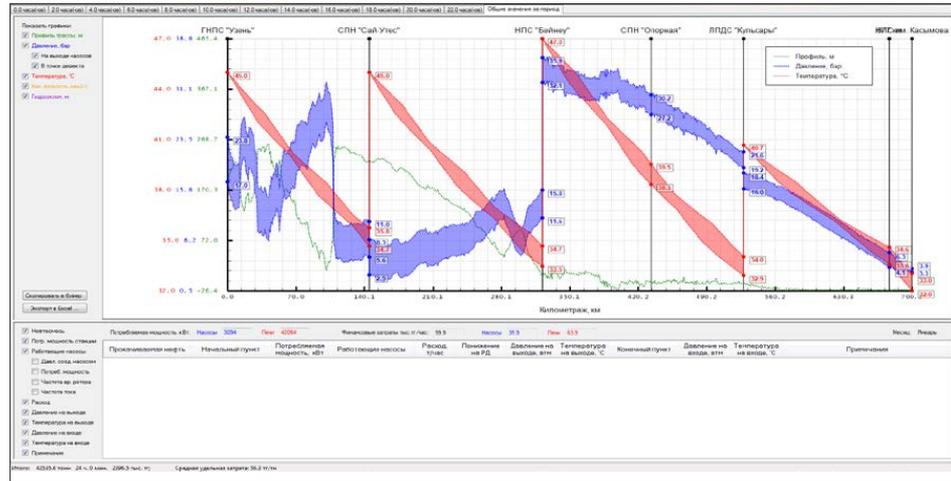
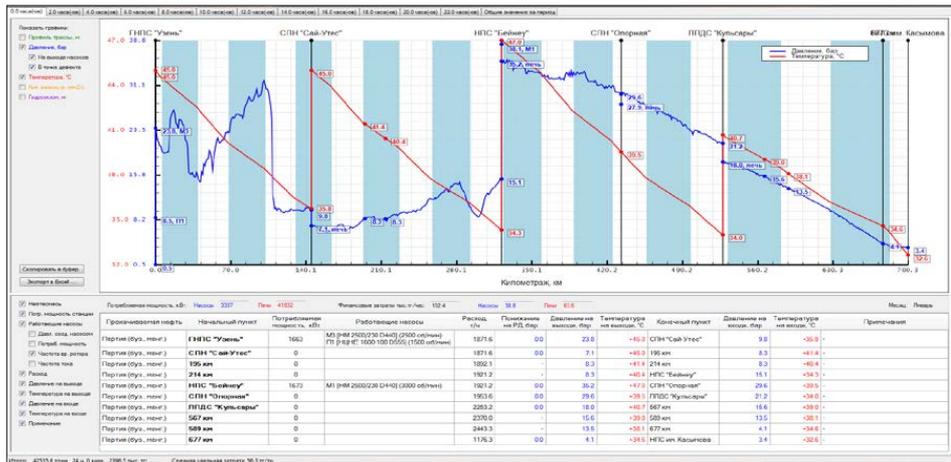


Fig.2. Calculation data for temperature and pressure in the period from 00:00 to 02:00 with batch pumping of Buzachi and Mangyshlak oil blends at the Uzen-Atyrau section, with soil temperature for January.



while the upper limit is found as the result of a search. It can be seen from Fig.1 that the upper limit for heating temperature at GNPS Uzen is equal to 45°C; at SPN Sai-Utes it is 45°C; at NPS Beineu it is 47°C; and at LPDS Kulsary it is 40.7°C. The optimum temperature for pumping oil blends is thus found as a result of a search where Equn 3 is fulfilled.

Figures 2 and 3 illustrate the results of calculations for defined intervals of time, for example from 00:00 to 02:00 and from 22:00 to 24:00 with soil temperature for January (the batch of Buzachi oil blend is shown in white, while the batch of Mangyshlak oil blend is shown in blue). In the interval of time 00:00-02:00 the Buzachi oil blend was pumped from GNPS Uzen at a rate of 1871.6 t/h, and at NPS 663 km the Mangyshlak oil blend was pumped out towards AOR at a rate of 1267 t/h taking into account the demands of the refinery (see Fig. 1).

The calculation data in Fig.3 show the distribution of parameters for batch pumping in the interval of time from 22:00-24:00, when Mangyshlak oil blend is pumped out of GNPS Uzen at a rate of 1701.4 t/h. In this time interval, Buzachi oil blend flows through NPS 663 km, and then comes to the inlet of the preheater at NPS T. Kasymova station (according to schedule, the pressure should not fall below 3 bar).

Financial cost of the power used by the pumps and preheaters is calculated based on current tariffs for electricity and fuel. The total volume of pumped oil blends over 24 hours was 42,535.6 tonnes, while financial cost was 2,396.5 thousand tenge, and the average value of unit costs for pumping and heating was 56.3 tenge/t (Figs 2 and 3).

Calculation data for batch pumping in the Spring-Autumn period were obtained for the average monthly soil temperature in April (Figs 4-6).

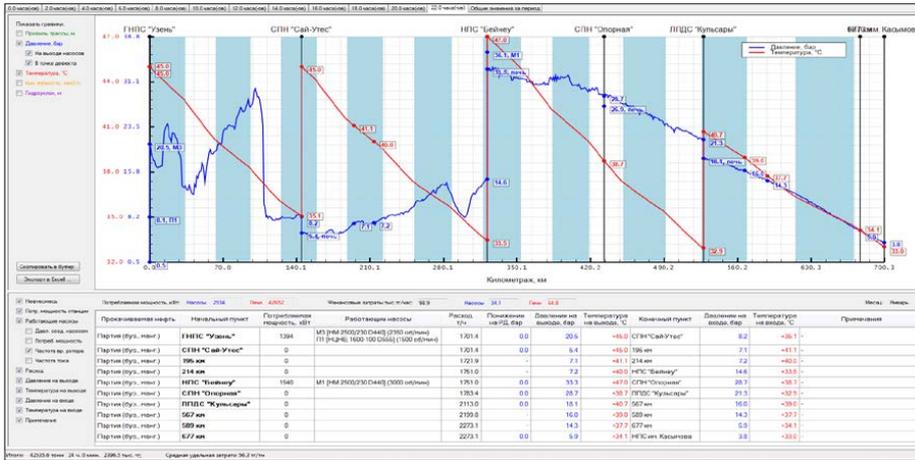


Fig.3. Calculation data for temperature and pressure in the period from 22:00 to 24:00 with batch pumping of Buzachi and Mangyshlak oil blends at the Uzen-Atyrau section with soil temperature for January.

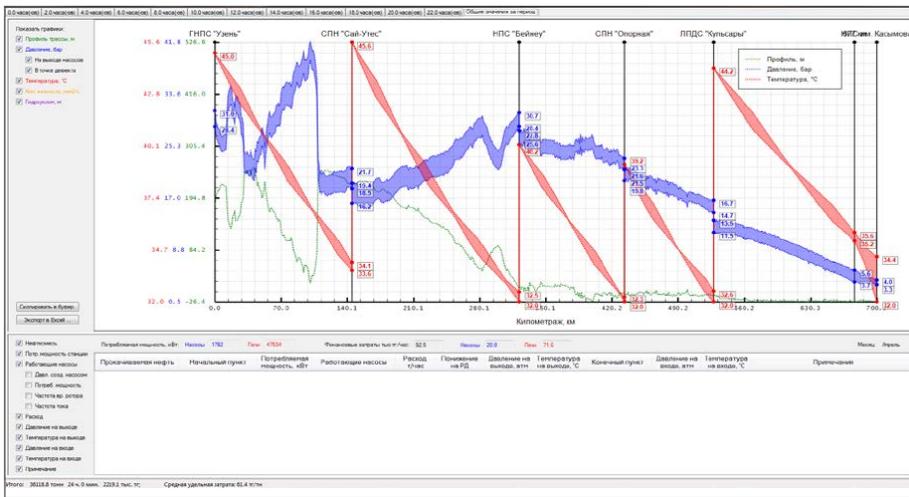


Fig. 4. A general picture of the distribution of pressure and temperature when batch pumping of Buzachi and Mangyshlak oil blends at the Uzen-Atyrau section with soil temperature for April.

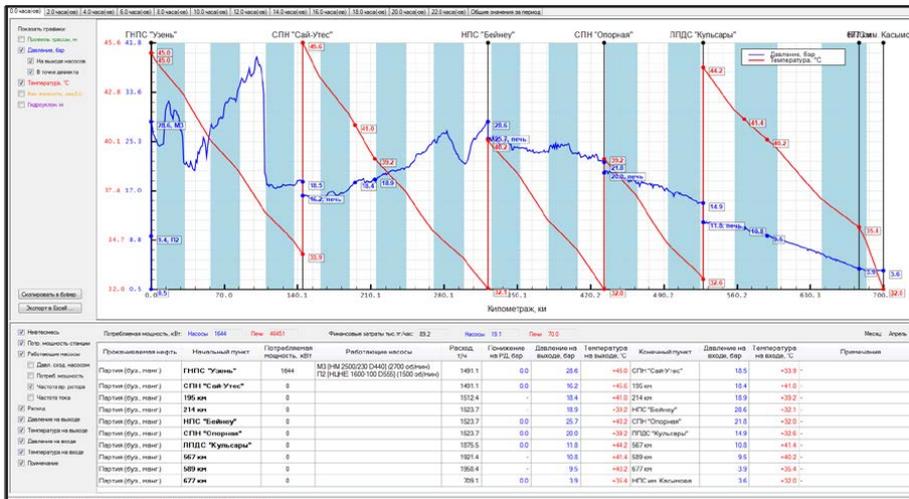


Fig.5. Calculation data for pressure and temperature in the period from 00:00 to 02:00 when batch pumping of Buzachi and Mangyshlak oil blends at the Uzen-Atyrau section with soil temperature for April.

A general picture of the change to pressure and temperature over 24 hours is shown in Fig.4. The ranges of the change in values over time were obtained dependent on the volumes of pumped Buzachi and Mangyshlak batches at the Uzen-Atyrau section, taking into account on-

Fig 6. Calculation data for pressure and temperature in the period from 10:00 to 12:00 when batch pumping Buzachi and Mangyshlak oil blends at the Uzen-Atyrau section with soil temperature for April.

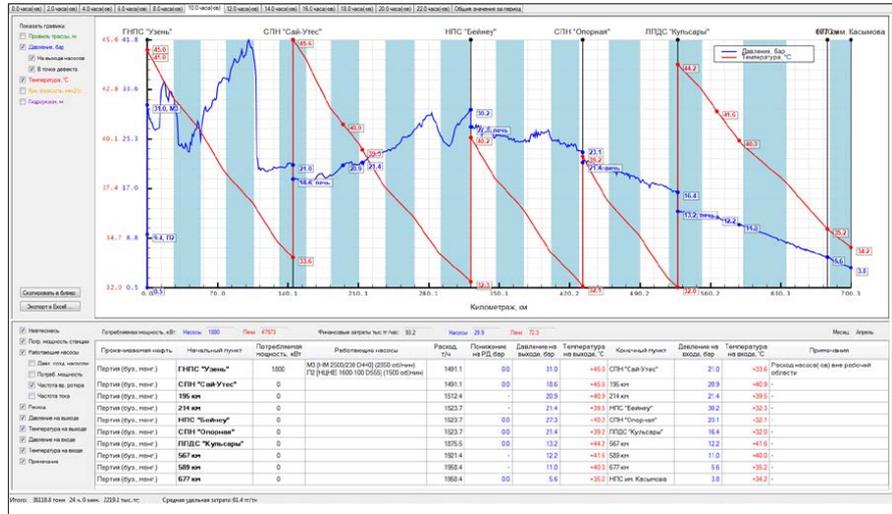
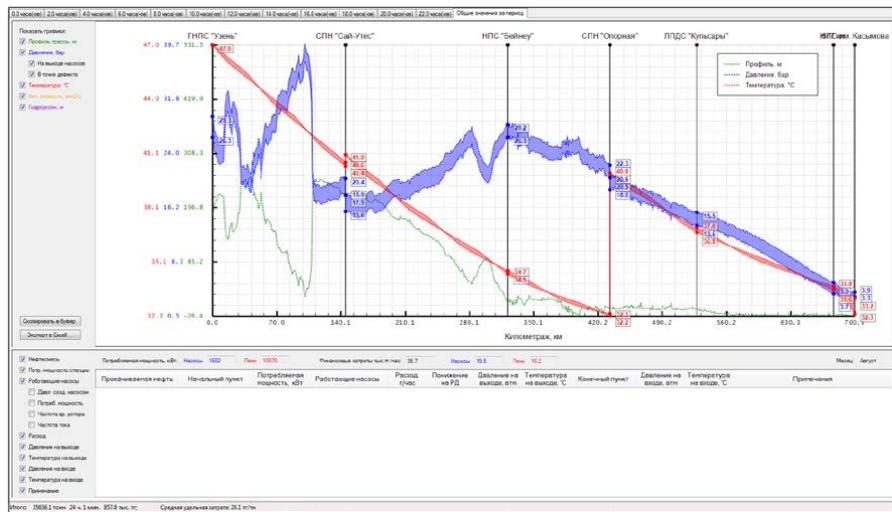


Fig.7. A general picture of the distribution of pressure and temperature when batch pumping Buzachi and Mangyshlak oil blends at the Uzen-Atyrau section with soil temperature for August.



route boosting and pumping-out.

At the Uzen GNPS from 00:00-02:00 the Buzachi batch is pumped at a rate of 1491 t/h, while at NPS “663” the Mangyshlak oil blend is pumped out at a rate of 1259.3 t/h towards AOR (Fig.5). Between 22:00-24:00 (Fig.6) the Buzachi batch comes from the head station, and flows through NPS 663 without being pumped out.

Batch pumping is performed by pumping units at GNPS Uzen without operating pumps at the intervening stations Beineu and Kulsary (Figs 5 and 6). The power used by the pumps, as well as the heating temperature and flow rate of oil blend at the pumping stations are presented in figures in the table under the graphs.

The total volume of pumped oil blends over 24 hours was 36,119 t, while the financial cost was 2219 thousand tenge. The average value of unit costs for pumping and heating was 61.4 tenge/t (Figs 5 and 6).

Calculations show (Figs 7-9) that in the summer period it is possible to switch off the preheaters at intervening stations and select the energy-saving mode of operation for pumping units at GNPS Uzen for batch pumping Buzachi and Mangyshlak oil blends at the Uzen-Atyrau section.

Table 2 presents the calculation data for the power used by pumps and preheaters, the unit costs for batch pumping in optimum conditions and in production conditions, depending on

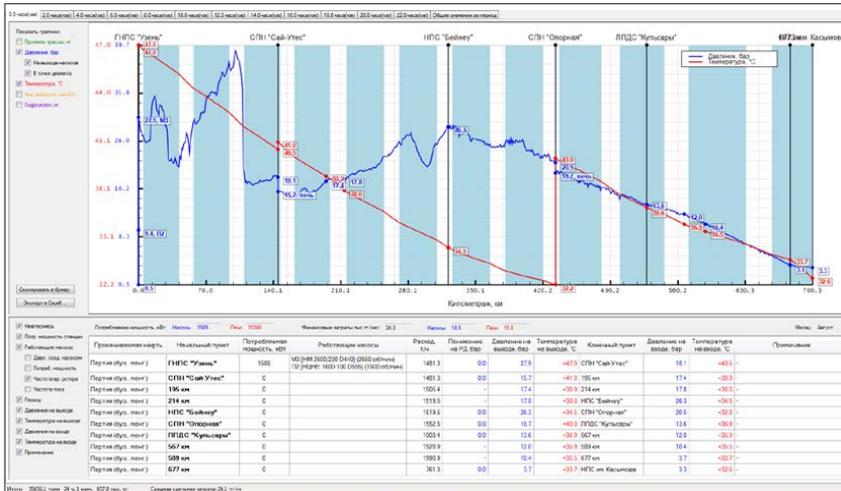


Fig.8. Calculation data for pressure and temperature in the period from 00:00 to 02:00 when batch pumping Buzachi and Mangyshlak oil blends at the Uzen-Atyrau section with soil temperature for August.



Fig.9. Calculation data for pressure and temperature in the period from 08:00 to 10:00 when batch pumping Buzachi and Mangyshlak oil blends at the Uzen-Atyrau section with soil temperature for August.

the flow rate of Mangyshlak and Buzachi oil blends (see Table 1) and the average monthly temperature of the soil between stations at the section under examination.

As has been indicated above, the search for optimum conditions for batch pumping has been conducted where criterion (3) is fulfilled in the temperature interval 32-55°C.

It can be seen from Table 2 that the optimum conditions for batch pumping at the Uzen-Atyrau section, in comparison with production data, provide a saving of between 30.14% and 32.53%.

4. Conclusions

1. The optimisation criterion for energy-saving modes was used in calculations. This expresses the minimum total cost for power used by pumping units and preheaters. The total cost was calculated based on tariffs for electricity and fuel at the Uzen-Atyrau section.

2. Calculation data have been obtained for batch pumping:

Depending on the change over time of volumes of pumped batches of Buzachi and Mangyshlak oil blends at the Uzen-Atyrau section;

Table 2. The economic efficiency of optimum conditions with batch pumping

Month	Calculations given optimum conditions		Calculations given production conditions		Saving, %
	Power used by pumps and pre-heaters, kW	Unit costs, tenge/t	Power used by pumps and pre-heaters, kW	Unit costs, tenge/t	
January	45 169	56.30	72 679	83.00	32.17
February	54 458	64.50	91 994	95.60	32.53
March	57 832	65.00	92 057	96.30	32.50
April	49 326	61.40	82 580	90.20	31.93
May	35 941	46.80	62 227	68.50	31.70
June	17 004	30.90	32 812	44.80	31.03
July	16 006	28.00	27 054	40.40	30.70
August	12 252	24.10	23 181	34.50	30.14
September	12 263	24.40	23 537	35.10	30.48
October	18 926	32.60	34 839	47.80	31.80
November	32 097	45.30	53 083	66.80	32.19
December	48 785	66.30	82 972	98.00	32.35

- By means of searching for the optimum temperature for heating oil blends at stations in the interval 32-55°C and with average monthly soil temperatures at the Uzen-Atyrau section;
- By means of determining the energy-saving modes for operating pumping units and preheaters where Equ 3 is fulfilled;
- At on-route boosting with increase in the initial flow rate of oil blends from GNPS Uzen by 15 %-30 %;
- At pumping-out Mangyshlak oil blend from NPS 663 km, taking into account the demands of the oil refinery in the range of 1000-1290 t/h.

3. By using energy-saving operating modes for pumping units and preheaters, it is possible to reduce unit costs for pumping and heating oil blends by 32.53 %-30.14 %.

Conflicts of interest

All authors have no conflicts of interest to declare.

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