The problem of optimizing pumping units for oil transportation

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ABSTRACT

During pipeline transportation of oil through main oil pipelines, the greater part of the energy consumed is spent on the operation of main and booster pumping units at oil pumping stations. In this regard, the determination of the optimal operating modes of pumping units is an urgent problem for energy saving. The article is devoted to the optimization of the operation of pumping units for energy saving of oil pipeline transport. The operation of pumping units is regulated using removable rotors with different diameters of impellers or a frequency-controlled drive. An optimization criterion has been formulated to minimize the operating costs of pumping units. A technique for determining the energy consumption of pumping units with different diameters of impellers and a frequency-controlled drive is presented. An algorithm for finding the optimal operating mode of pumping units is presented, which was built using the definitions of graph theory and dynamic programming.

Keywords: optimization criterion, energy-saving, oil transportation, graph theory, dynamic programming.

Introduction

The main consumers of electricity when pumping oil through main oil pipelines are pumping units (PU) at oil pumping stations (OPS). Problems of optimizing operating modes of pumping units are considered in [1, 2, 3, 4, 5, 6, 7].

Several oil pumping stations can be located in the oil pipeline section. Regulating the operation of main pumping units (MPU) is controlled by variable frequency drives (VFD) or removable rotors. Such control conditions of MPU in the MOP section lead to difficulties in determining the objective function [8].

Algorithm development for optimizing calculations is the main problem for determining energy-saving pumping modes. In this paper, a general optimality criterion is formulated when controlling MPU with VFD and removable rotors, an algorithm for calculating the energy-saving pumping mode without intermediate heating of oil is developed.

A problem statement

The optimal combination of operating pumps is being sought. At the same time, some pumps can operate with VFD.

The optimization criterion is defined as:

$$\sum_{i=1}^{n} z_i \sum_{j=1}^{m} c_{ij} N_{ij}^{PU} (k_j) \rightarrow \min \ (1)$$

where $n$ is the number of OPS in the section, $m_i$ is the number of pumps in the i-th OPS, $z_i$ is the cost of pumps in the i-th OPS tg/(kW-h); $c_{ij}$ is the
integer variable that takes the value 1, if the pump is in operation, and 0 otherwise; $N_{i,j}^{PU}$ is the power consumption of the $j$-th PU of the $i$-th OPS (kW); $k_{ji}$ is the ratio of the rotor speed to the nominal speed for the given pump.

The criterion (1) is considered together with the conditions of safe pumping: satisfaction of the setpoint chart; safe operation of pumps; prevention of gravity flow of oil; accounting for pipeline defects.

For any value of $k_{ji}$, it is true:

$$k_{ji}^\min \leq k_{ji} \leq 1$$

where $k_{ji}^\min$ is the lower limit of the rotation speed for any pump.

The number of simultaneously operating pumps with VFD is limited by the number of drives $p$ in OPS. The number of pumps with VFD cannot be greater than the number of drives themselves. Therefore, for each $i$-th OPS, it is necessary to set a limit on the number of simultaneously operating pumps with VFD:

$$\sum_{j=1}^{m} c_{ij}[1-k_{ji}] \leq p$$

where operator $[ ]$ means rounding operation to a bigger side.

The pressure drop through a group of pumps $\Delta P_{g}^{vis}$ is determined by the formula:

$$\Delta P_{g}^{vis}(Q,k) = \begin{cases} 0, & c_{oper} = 0 \\ \rho_g H \left( \frac{Q}{c_{oper} k}, c_{oper} > 0 \right) & \end{cases}$$

where $c_{oper}$ is the number of operating pumps in the group, $\rho$ is the oil density, $H(Q,k)$ is the head dependence on the flow rate for any pump in the group.

Let’s build a concrete view for the dependencies $H(Q,k)$ and $P_{g}^{PU}(Q,k)$.

To recalculate characteristics of the pump with VFD, the well-known similarity formulas are used [11]:

$$Q^{VFD} / Q = k, \quad H^{VFD} / H = k^2, \quad N^{VFD} / N = k$$

where $Q,H,N$ and $Q^{VFD},H^{VFD}, N^{VFD}$ are the flow rate, head and power of the pump without VFD and with VFD, respectively.

The curves of head and efficiency of pumps can be approximated by polynomials of the third degree [9]:

$$H(Q) = C_0^H + C_1^H Q + C_2^H Q^2 + C_3^H Q^3$$
$$\eta(Q) = C_0^\eta + C_1^\eta Q + C_2^\eta Q^2 + C_3^\eta Q^3$$

where $C_0^H,C_1^H,C_2^H,C_3^H$ and $C_0^\eta,C_1^\eta,C_2^\eta,C_3^\eta$ are the coefficients of approximation of head and pump efficiency, respectively.

The characteristic of pump head when working with VFD:

$$H(Q,k) = C_0^H k^2 + C_1^H k Q + C_2^H Q^2 + C_3^H Q^3$$

The characteristic of pump efficiency when working with VFD can be written in the form [11]:

$$\eta(Q,k) = C_0^\eta k + C_1^\eta Q + C_2^\eta Q^2 + C_3^\eta Q^3$$

Thus, pump power has the form:

$$N(Q,k) = C_0^{PV} k^3 + C_1^{PV} k^2 Q + C_2^{PV} k Q^2 + C_3^{PV} Q^3$$

Dependence (9), the efficiency of the clutch $\eta_m$ and the efficiency of the electric motor $\eta_e$ uniquely determine the power consumption of the entire pumping unit:

$$N^{PU}(Q,k) = \frac{N(Q,k)}{\eta_m \eta_e} + \frac{1 - \eta_{e, nom}}{2 \eta_{e, nom}} N_{e, nom}^2 \frac{(Q,k)}{\eta_e^2 N_{e, nom}}$$

where $N_{e, nom}$, $\eta_{e, nom}$ are the nominal values of power and efficiency of the electric motor, $k_3 = N / (\eta_m N_{e, nom})$ is the load factor of the electric motor.

The pressure balance equation [9] can be written in the form of pressure:

$$P_{ini} + \sum_{i=1}^{N_{PU}} \sum_{j=1}^{n_{pu}} \Delta P_{ij}^{vis} = \sum_{i=1}^{N_{PU}} \Delta P_{i,PV}^{vis} + \Delta P_{PV} + \Delta P_{res}$$

where $Q,H,N$ and $Q^{VFD},H^{VFD}, N^{VFD}$ are the flow rate, head and power of the pump without VFD and with VFD, respectively.
where \( P_{\text{init}} \) is the initial pressure; \( m_{ij}^{\text{pr}} \) is the number of pumping groups in OPS; \( \Delta P_{ij}^{\text{pr}} \) is the pressure increase generated by the \( j \)-th pump group of the \( i \)-th OPS; \( \Delta P_{ij}^{\text{pr}} \) is the pressure loss after the pressure regulator (PR); \( \Delta P_{ij}^{\text{ac}} \) is the pressure loss in the pipeline taking into account hydrostatic pressure drop between the \( i \)-th and \((i+1)\)-th OPS at the flow rate \( Q \); \( \Delta P_{ij}^{\text{pr}} \) is the amount of back pressure created by gate valve at the inlet of the final OPS; \( P_{\text{res}} \) is the residual pressure.

The values of pressure drops through OPS and pressure losses through the PR are the optimization problem solution.

It is necessary to determine the limitation imposed on the optimization problem solution by pressure at the inlet and outlet of OPS. The pressure at the inlet of the \( k \)-th oil pumping station is equal to \( P_{\text{init}}^k \), and at the outlet of OPS before the PR is \( P_{\text{out}1}^k \) and after the PR is \( P_{\text{out}2}^k \).

Then, based on (11), we can write:

\[
P_{\text{out}}^k = P_{\text{init}}^k + \Delta P_{ij}^{\text{pr}} - \sum_{i=1}^{k-1} \Delta P_{ij}^{\text{pr}} - \sum_{i=1}^{k-1} \Delta P_{ij}^{\text{ac}} \geq P_{\text{min}}^k
\]  
(12)

\[
P_{\text{out}1}^k = P_{\text{out}1}^k + \sum_{j=1}^{m_{ij}^{\text{pr}}} \Delta P_{ij}^{\text{pr}} \leq P_{\text{max}1}^k
\]  
(13)

\[
P_{\text{out}2}^k = P_{\text{out}1}^k - \Delta P_{\text{PR}}^k \leq P_{\text{max}2}^k
\]  
(14)

where \( P_{\text{min}}^k \) is the minimum allowable pressure at the inlet of the \( k \)-th OPS, \( P_{\text{max}1}^k \) and \( P_{\text{max}2}^k \) are the maximum allowable pressure before and after the PR at the outlet of the \( k \)-th OPS.

A necessary and sufficient condition for the forced oil flow in the \( i \)-th pipeline section with a saddle point:

\[
\Delta P_{ij}^{\text{ac}} < 0
\]  
(15)

Let be \( P_{\text{def} \text{ max}} \) is the maximum allowable pressure in the place of the pipe defect, which does not cause its damage/deformation.

Then the necessary condition for taking into account each \( j \)-th defect is as follows:

\[
P(X_j) \leq P_{\text{def} \text{ max}}
\]  
(16)

Each pump has an operating range with permissible flow rates \( Q_{\text{min}}^k, Q_{\text{max}}^k \), which in the VFD mode depend on the rotor speed:

\[
Q_{\text{min}}^k(k) \leq Q \leq Q_{\text{max}}^k(k)
\]  
(17)

The condition for the cavitation-free operation of each \( l \)-th group of pumps and the \( k \)-th OPS has the form:

\[
P_{\text{min}l}^k = P_{\text{init}}^k + \sum_{j=1}^{m_{ij}^{\text{pr}}} \Delta P_{ij}^{\text{pr}} \geq P_{\text{min}l}^k
\]  
(18)

where \( k_{\text{over}} = 1.1 \) is the overload coefficient of the electric motor.

The optimal solution search algorithm

The search algorithm is a nonlinear problem programming, objective function (1) and constraints (2, 3, 12-18) are non-linear functions.

In the optimization theory, the Lagrange method is widely used for nonlinear programming problems. In the considered problem, constraints imposed on variables are inequalities, therefore, to modify the method, the Karush-Kuhn-Tucker conditions must be satisfied [10]. Constraint functions are not continuously differentiable, which contradicts the mandatory conditions of the Lagrange method.

We have proposed an approach based on the ideas of dynamic programming. The search problem for the energy-saving mode can be divided into many overlapping subtasks with finding the optimal substructure. Using the problem solution for \( n \) pumps, we can efficiently find solutions for \( n+1 \) pumps.

The graph of the state of the operation of PU is built. Each node of the graph contains data on the number of used PU and their parameters, pressure drop in the PR. Graph nodes are connected based on the pressure characteristics of pumps and the rotational speeds of their rotors. The subtask solution transition to the general problem solution is found and the correctness of the approach is proved.
The object of each subtask is the cost dependence function of consumed electricity \( S(P) \) from the generated differential pressure of the pump.

Naturally, that \( P \geq 0 \). In the search for the solution, instead of the continuous function \( S(P) \), its discrete version is used. The pressure value is presented discretely with a fairly small step \( \varepsilon_p = 0.01 \) bar.

The problem solution is stored in the discrete array \( \text{Info}(P) \), which, for each value \( P \), contains a list of necessary pumps to create this pressure drop. This array has rotational speed, used rotors, as well as pressure loss values after the PR. Array parameters for the particular \( P \) are determined by unknowns \( c_i \) and \( k_i \) of pumps in condition (1).

The cost function \( S(P) \) and the array of solutions \( \text{Info}(P) \) for the pump without VFD are written as:

\[
S(P) = \begin{cases} 
+\infty, & P \neq P_{\text{pump}} \\
\sum_{i=1}^{N_{pu}} \left( \frac{Q}{r} \right), & P = P_{\text{pump}} 
\end{cases} \quad \text{Info}(P) = \begin{cases} 
\emptyset, & P = P_{\text{pump}} \\
\{ \text{pump number} \}, & P = P_{\text{pump}} 
\end{cases}
\]

(19)

Where \( z \) is the cost of electricity \( \text{tg}/(\text{kW} \cdot \text{h}) \), \( N_{pu} \) is the consumed power of PU (kW), \( Q \) is the flow rate, which passes through the pump \( (\text{m}^3/\text{h}) \), \( P_{\text{pump}} \) is the pressure drop generated by the pump, which is found as:

\[ P_{\text{pump}} = [\rho g H(Q)] \]

where \([ \ ]\) is the rounding to the nearest rational number with a step \( \varepsilon_p \).

Similarly, \( S(P) \) and \( \text{Info}(P) \) are defined for the pump with VFD:

\[
S(P) = \begin{cases} 
+\infty, & P \not\in [P_{\text{min}}, P_{\text{max}}] \\
\sum_{i=1}^{N_{pu}} \left( \frac{Q}{r} \right), & P \in [P_{\text{min}}, P_{\text{max}}] 
\end{cases} \quad \text{Info}(P) = \begin{cases} 
\emptyset, & P \not\in [P_{\text{min}}, P_{\text{max}}] \\
\{ \text{pump number} + k \}, & P \in [P_{\text{min}}, P_{\text{max}}] 
\end{cases}
\]

(20)

where \( P_{\text{min}} \) and \( P_{\text{max}} \) are the minimum and maximum pressure drops.

If pumps are operating simultaneously in parallel, then their cost function is defined as:

\[
S(P) = \sum_{i=1}^{n} S_{\text{rotor } i}(P) \quad (25)
\]
where \( n \) is the number of replaceable rotors, \( S_{i}^{\text{out}} \) is the cost function of the pump, when working with the rotor \( i \).

Similarly, its array of solutions \( \text{Info}(P) \) is determined.

For each pressure value that a group of parallel operating pumps can create, it is possible to find a combination of pumps at which there will be a minimum of costs. Obviously, the answer and solution to this problem for a group of \( r \) pumps will be "unions":

\[
S^{\text{gr}} = \bigcup S_{i} \bigcup \bigcup S_{r-} \bigcup S
\]

\[
\text{Info}^{\text{gr}} = \bigcup \text{Info}_{i} \bigcup \bigcup \text{Info}_{r-} \bigcup \text{Info}
\]

where \( \bigcup S_{i} \), \( \bigcup \text{Info}_{i} \) are the "unions" of the function \( S(P) \) and array \( \text{Info}(P) \), respectively, for all samples of \( i \) pumps from the \( r \) group.

**Definition 2.**

The imposition of the function \( S^{\text{gr}} \) on the function \( S^{A} \) denotes the function \( S(P) \) that has the value (similarly, for \( \text{Info}(P) \)) for each \( P \):

\[
S(P) = S^{A}(P) \leftarrow (S ) =
= \min(S^{A}(P), S^{A}(P - P') + S^{\text{gr}}(P))
\]

where the variable value \( P' \) at the specific value \( P \) is defined as:

\[
P' = \arg\min(S^{A}(P - P') + S (P'))
\]

\[
* \in [0, P]
\]

**Definition 3.**

Let’s call the cost function \( S(P) \) optimal for any set of pumps if, for any value of its argument \( P \), it contains the minimum cost that is necessary to create pressures with the value \( P \) using some pumps from the required set.

The optimal cost function \( S_{\text{out}}^{\text{gr}}(P) \) and its array of solutions \( \text{Info}_{\text{out}}^{\text{gr}}(P) \) at the outlet from stations will be the "imposition" of cost functions and arrays of solutions of all pump groups available in the station to the optimal function \( S_{\text{out}}^{\text{gr}}(P) \) and its array \( \text{Info}_{\text{out}}^{\text{gr}}(P) \) at the inlet of the station:

\[
S_{\text{out}}^{\text{gr}}(P) = S_{\text{out}}^{\text{gr}}(P) \leftarrow (S_{\text{out}}^{\text{gr}}(P) \leftarrow (S_{\text{out}}^{\text{gr}}(P) \leftarrow \ldots \leftarrow (S_{\text{out}}^{\text{gr}}(P))
\]

\[
\text{Info}_{\text{out}}^{\text{gr}}(P) = \text{Info}_{\text{out}}^{\text{gr}}(P) \leftarrow (\text{Info}_{\text{out}}^{\text{gr}}(P) \leftarrow \ldots \leftarrow (\text{Info}_{\text{out}}^{\text{gr}}(P))
\]

The limitation on the minimum head at the inlet to the pump or to the group of pumps (18) is taken into account by "imposing" (30) group functions strictly in the order in which groups are located on OPS, as well as in the "imposing" operation by changing the condition (28) for each \( i \)-th group for:

\[
P^* \in [P - P_{\text{min}}^{\text{gr}}, P]
\]

If OPS has several pump layouts, then its overall cost function at the outlet of the station is defined as:

\[
S_{\text{out}}(P) = \bigcup_{i=1}^{n} S_{\text{out}, \text{layout } i}(P)
\]

Where \( n \) is the number of pump layouts at OPS, \( S_{\text{out}, \text{layout } i}(P) \) is the cost function at the outlet from OPS in the scheme \( i \).

Similarly, its array of solutions \( \text{Info}(P) \) is determined.

If the number of VFD is less than the number of pumps at OPS, then the cost function and the array of solutions for OPS will have an additional argument \( v \) for pumps operating with VFD. The value \( v \) should not exceed the number of drives \( p \) on OPS.

Then, to take into account the limitation of the form (3), the "imposition" of the cost function for the groups of pumps has the form (similarly, for \( \text{Info}^{\text{gr}}(P, v) \)):

\[
S^{\text{gr}}(P, v) = S^{\text{gr}}(P, v) \leftarrow (S^{\text{gr}}(P, v) \leftarrow \ldots \leftarrow (S^{\text{gr}}(P, v))
\]

\[
= \min(S^{A}(P, v), S^{A}(P - P', -N(P')) + S^{\text{gr}}(P'))
\]

where \( N(P') \) is the number of pumps in a group operating with VFD to create pressure \( P' \).

The number of operating pumps in a group can be determined from the solution array of the group \( \text{Info}^{\text{gr}}(P') \). Whether they operate in the mode with VFD is determined by the criterion \( k \neq 1 \) for each value \( \text{Info}^{\text{gr}}(P') \).

The value of the variable \( P' \) at specific values \( P \) and \( v \) is defined as:
\[ P^* = \arg \min (S^u(P - P^*, v - N(P^*))) + S''(P^*) \quad \in [0, P] \] (33)

When "imposing" by formulas (32) and (33) for each \( v \) the cost function will retain its own optimality. After "imposing" the cost functions of all pump groups and their arrays of solutions, it is necessary to switch to the form with one pressure argument by the following "combining":

\[ S^u(P) = \bigcup_{v=0}^{P} S^u(P,v) \] (34)

**Definition 4.**

By pruning the function \( S^{old}(P) \) by pressures \( P^A < P^B \) is the function \( S^{new}(P) \) that has the value for each \( P^* \):

\[ S^{new}(P) = \text{CUT}(S^{old}(P), P^A, P^B) = \begin{cases} +\infty, & P \notin [P^A, P^B] \\ S^{old}(P), & P \in [P^A, P^B] \end{cases} \] (35)

Similarly, for an array of solutions:

\[ \text{Info}^{new}(P) = \text{CUT}(\text{Info}^{old}(P), P^A, P^B) = \begin{cases} {}^* \text{ "no pumps"}, & P \notin [P^A, P^B] \\ \text{Info}^{old}(P), & P \in [P^A, P^B] \end{cases} \]

Taking into account that pressure drop in the section between two OPS at the fixed value \( Q \) does not depend on pressure at the outlet of the initial OPS, it is possible to determine minimum allowable pressure at the outlet of OPS so that the pressure condition at the inlet to the next station is fulfilled (12). Obviously, the value of such pressure for the \( k \)-th OPS should be no less \( P_{\text{out}k}^{\text{min}} + \Delta P^k_{\text{pipe}} \), i.e. the pressure condition at the inlet to the station is determined through the condition at the outlet from the previous station.

Taking into account the condition of non-gravity flow (14), the final condition for minimum allowable pressure at the outlet from the station \( P_{\text{out}k}^{\text{max}, k} \) has the form:

\[ P_{\text{out}k}^{\min, k} \geq P_{\text{out}k}^{\text{max}, k} = \max(P_{\text{out}k}^{\text{min}, k} + \Delta P^k_{\text{pipe}}, \max \Delta P^k_{\text{pipe}}) \] (36)

Taking into account pressure drop in the section and pressure conditions at the points of the pipe defect (16), it is possible to calculate in advance maximum pressure at the outlet of OPS \( P_{\text{pipe}\text{max}} \), at which conditions (15) will be fulfilled. Then the final condition for maximum allowable pressure at the outlet of OPS (denote \( P_{\text{out}k}^{\text{max}, k} \)) has the form:

\[ P_{\text{out}k}^{\text{max}, k} \geq P_{\text{out}k}^{\text{max}, k} = \min(P_{\text{out}k}^{\text{max}, k}, P_{\text{pipe}\text{max}}) \] (37)

If you do not take into account the operation of the PR at stations, i.e. \( \Delta P^k_{\text{PR}} = 0 \), then it is obvious that all pressure conditions are taken into account in functions \( S(P) \) and the array \( \text{Info}(P) \) by the next "pruning" (similarly, for \( \text{Info}(P) \)):

\[ S(P) = \text{CUT}(S(P), P_{\text{out}k}^{\text{min}}, P_{\text{out}k}^{\text{max}}) \] (38)

If we take into account the possible benefit of the PR in solving the optimal problem, then before "pruning" (35) to take into account the condition (16) for outlet pressure up to the PR, it is necessary to change \( S(P) \) and \( \text{Info}(P) \) as follows:

\[ S(P) = \begin{cases} S(P), & S(P) > S(P) \\ S(P), & \text{otherwise} \end{cases} \] (39)

\[ \text{Info}(P) = \begin{cases} \text{Info}(P) + \"\text{lowering in the PR by}\" + (P - P), & S(P) > S(P) \\ \text{Info}(P), & \text{otherwise} \end{cases} \]

where values \( P^* \) for a specific value \( P \) are defined as:

\[ P^* = \arg \min(S(P)) \]

\[ P^* \in [P, P_{\text{out}k}^{\text{max}, k}] \] (40)

In other words, these operations mean that if higher pressures were obtained at a lower cost, then with the help of the PR with the same costs, lower pressures can be obtained.

**Definition 5.**

The shift of the function \( S^{old}(P) \) by an amount \( \Delta P \) is the function \( S^{new}(P) \) that has the value for each \( P^* \):

\[ S^{new}(P) = \text{SHIFT}(S^{old}(P), \Delta P) = S^{old}(P - \Delta P) \] (41)

Then the transition to the next station (similarly, for \( \text{Info}(P) \)) has the form:

\[ S_{\text{out}k}^{\text{new}}(P) = \text{SHIFT}(S_{\text{out}k}(P), P_{\text{pipe} \text{max}}) \] (42)
where the function \( S^{\text{out},k}_{\text{in}}(P) \) should be "pruned", \( S^{\text{next},k}_{\text{in}}(P) \) is the cost function at the inlet of the next station.

Above-listed operations must be done for all OPS in the order of their location on the MOP section except for the last OPS. The calculation algorithm has the form:

\[
k = 1
\]

For \( i = 1 \) to \( m^2 \), calculate \( S^{\text{out},k}_{\text{in}} \) by formulas (21)-(28);

\[
S^{\text{out},k}_{\text{in}}(P) = S^{\text{out},k}_{\text{in}}(P) \leftarrow (S^{\text{out},k}_{\text{in}}(P)) \leftarrow (S^{\text{out},k}_{\text{in}}(P)) \leftarrow \cdots \leftarrow (S^{\text{out},k}_{\text{in}}(P));
\]

Calculation \( \Delta P_{\text{AC}}^{k} \)

\[
S^{\text{out},k}_{\text{in}}(P) = \text{CUT}(S^{\text{out},k}_{\text{in}}(P), P_{\text{min}}, P_{\text{max}}); \quad S^{\text{out},k+1}_{\text{in}}(P) = \text{SHIFT}(S^{\text{out},k}_{\text{in}}(P), \Delta P_{\text{AC}}^{k});
\]

\( k = k + 1 \).

If, \( k \neq n + 1 \) then go to step 1, otherwise exit the loop.

The function is used as the initial cost function:

\[
S^{\text{out},1}_{\text{in}}(\ ) = \begin{cases} +\infty, & P \neq P_{\text{init}} \\ 0, & P = P_{\text{init}} \end{cases} \quad (44)
\]

The initial function \( S^{\text{out},1}_{\text{in}}(\ ) \) is the simplest and contains an obvious zero cost to create static head from the reservoir. This function is optimal because there is no a cheaper option for creating pressure \( P_{\text{init}} \). Therefore, the further "imposition" of the cost function of pumps or pump groups to it preserves its optimality.

So, the minimum amount of costs for performance \( Q \) will be the value of functions \( S^{\text{out},n+1}_{\text{in}}(P_{\text{anew}}) \). The optimal combination of operating pumps and their operating modes will be stored in the cell of the array \( Info^{\text{out},n+1}_{\text{in}}(P_{\text{anew}}) \).

In the present algorithm, the presence of VFD is no longer a problem: VFD only expands the domain of definition of the cost function \( S(P) \) and does not affect the complexity of this algorithm in any way. In contrast to genetic algorithms, the approach described above makes it possible to obtain guaranteed the most optimal result.

The algorithm for calculating energy consumption was used to carry out thermal-hydraulic calculations and showed its effectiveness in determining the rational operating modes of pumping units \([11],[12],[13]\).

**Conclusions**

The establishment of energy-saving operating modes of pumping units is important for the efficiency of oil transportation through main oil pipelines. A method has been developed for determining the energy consumption of pumping units with different diameters of impellers and a frequency-controlled drive. The algorithm for calculating the methodology is built using graph theory and dynamic programming. The advantage of the proposed algorithm in comparison with the simple enumeration algorithm and the genetic algorithm in determining the optimal operating conditions of pumping units has been proved.

**Conflict of interests.** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Мунай тасымалдау ушін сорғы қондырғыларының онтайландыру проблемасы

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Problema opyimizatsii nasosnykh agragatov dlya transportirovki neftey

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ANOTATION


Klyuchevые слова: kriteriy opyimizatsii, energosbergeniya, transportirovka nefti, teoriya grafov, dinamicheskoe programmirovaniya.

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