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The problem of optimizing pumping units for oil transportation

[1] **Bekibayev T.T.,** [1*] **Ramazanova G.I.,** [2] **Pakhomov M.A.**

[1]*Satbayev University, Almaty, Kazakhstan*
[2] *Kutateladze Institute of Thermophysics, Siberian Branch of the Russian Academy of Science, Novosibirsk, Russia*

** Corresponding author email: gaukhar.ri@gmail.com, g.ramazanova@satbayev.university*

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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.

Information about authors:

Bekibayev Timur Talgatovich	*Master of engineering and technology, head of section. Non-commercial joint-stock company "Satbayev University", Research and Production Laboratory "Energy Modeling", Almaty, the Republic of Kazakhstan. E-mail: timur_bekibaev@mail.ru, https://orcid.org/0000-0001-7030-0015*
Ramazanova Gaukhar Izbasarovna	*Candidate of physical and mathematical sciences, Leading Researcher. Non-commercial joint-stock company "Satbayev University", Research and Production Laboratory "Energy Modeling", Almaty, the Republic of Kazakhstan. E-mail: gaukhar.ri@gmail.com, g.ramazanova@satbayev.university, https://orcid.org/0000-0002-8689-9293*
Pakhomov Maksim Aleksandrovich	*Doctor of Physical and Mathematical Sciences, Professor, Leading Researcher, Kutateladze Institute of Thermophysics, Siberian Branch of the Russian Academy of Science, Novosibirsk, Russia. h-index: 15; Scopus ID: 6602734341. E-mail: pakhomov@ngs.ru*

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:

$$\sum_{i=1}^{n}\left(z_i \sum^{m_i} c_{ij} N_{ij}^{PU}(\boldsymbol{k}_{ij}) \right) \to \min \qquad (1)$$

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 electricity 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_{ij}^{PU} is the power consumption of the j-th PU of the i-th OPS (kW); $\boldsymbol{k}_{ij}$ 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 $\boldsymbol{k}_{ij}$, it is true:

$$\boldsymbol{k}_{ij}^{\min} \le \boldsymbol{k}_{ij} \le 1 \qquad (2)$$

where $\boldsymbol{k}_{ij}^{\min}$ 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:

$$\sum_{j=1}^{m_i} c_{ij}[1-\boldsymbol{k}_{ij}] \le \quad _i \qquad (3)$$

where operator $\lceil \ \rceil$ means rounding operation to a bigger side.

The pressure drop through a group of pumps ΔP^{gr} is determined by the formula:

$$\Delta \quad ^{gr}(Q,\boldsymbol{k}) = \begin{cases} 0, & c_{oper} = 0 \\ \rho g H\left(\dfrac{Q}{c_{oper}}, \boldsymbol{k}\right), & c_{oper} > 0 \end{cases} \qquad (4)$$

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

Let's build a concrete view for the dependencies $H(Q,\boldsymbol{k})$ and $P^{PU}(Q,\boldsymbol{k})$.

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

$$Q^{VFD}/Q = \boldsymbol{k}, \quad H^{VFD}/H = \boldsymbol{k}^2, \quad N^{VFD}/N = \boldsymbol{k} \qquad (5)$$

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]:

$$\begin{gathered} H(Q) = C_0^H + C_1^H Q + C_2^H Q^2 + C_3^H Q \ , \\ \eta(Q) = C_0^\eta + C_1^\eta Q + C_2^\eta Q^2 + C_3^\eta Q \end{gathered} \qquad (6)$$

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:

$$H(Q,\boldsymbol{k}) = C_0^H \boldsymbol{k}^2 + C_1^H \boldsymbol{k} Q + C_2^H Q \ + \frac{C_3^H Q^3}{\boldsymbol{k}} \qquad (7)$$

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

$$\eta(Q,\boldsymbol{k}) = C_0^\eta + \frac{C_1^\eta Q}{\boldsymbol{k}} + \frac{C^\eta Q^2}{\boldsymbol{k}^2} + \frac{C_3^\eta Q^3}{\boldsymbol{k}} \qquad (8)$$

Thus, pump power has the form:

$$N(Q,\boldsymbol{k}) = \frac{C_0^H \boldsymbol{k}^5 Q + C_1^H \boldsymbol{k}^4 Q^2 + C_2^H \boldsymbol{k}^3 Q^3 + C_3^H \boldsymbol{k}^2 Q^4}{C_0^\eta \boldsymbol{k}^3 + C_1^\eta \boldsymbol{k}^2 Q + C_2^\eta \boldsymbol{k} Q^2 + C_3^\eta Q^3} \rho g \qquad (9)$$

Dependence (9), the efficiency of the clutch η_m and the efficiency of the electric motor η_{el} uniquely determine the power consumption of the entire pumping unit:

$$\begin{gathered} N^{PU}(Q,\boldsymbol{k}) = \frac{N(Q,\boldsymbol{k})}{\eta_m \eta_{el}} \quad \frac{N(Q,\boldsymbol{k})}{\eta_m} + \\ + \frac{1-\eta_{el\,nom}}{2\eta_{el\,nom}} \left(N_{el\,nom} \quad \frac{N^2(Q,\boldsymbol{k})}{\eta_m^2 N_{el\,nom}} \right) \end{gathered} \qquad (10)$$

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

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

$$P_{init} + \sum_{i=1}^{n} \sum_{j=1}^{m_i^{gr}} \Delta P_{ij}^{gr} = \sum_{i=1}^{n} \Delta P_i^{PR} + \sum_{i=1}^{n} \Delta P_i^{ac} + \Delta P^p + \Delta P_{res} \qquad (11)$$

where P_{init} is the initial pressure; m_i^{gr} is the number of pumping groups in OPS; ΔP_{ij}^{gr} is the pressure increase generated by the j-th pump group of the i-th OPS; ΔP_i^{pl} is the pressure loss after the pressure regulator (PR); ΔP_i^{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; ΔP^p is the amount of back pressure created by gate valve at the inlet of the final OPS; P_{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_k^{in}, and at the outlet of OPS before the PR is P_k^{out1} and after the PR is P_k^{out2}.

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

$$P_k^{in} = P_{init} + \sum_{i=1}^{k-1}\sum_{j=1}^{m_i^{gr}} \Delta P_{ij}^{gr} - \sum_{i=1}^{k-1} \Delta P_i^{PR} - \sum_{i=1}^{k-1} \Delta P_i^{ac} \geq P_k^{in\,\min} \quad (12)$$

$$P_k^{out1} = P_k^{in} + \sum_{j=1}^{m_k^{gr}} \Delta P_{kj}^{gr} \leq P_k^{out1\,\max}$$

$$P_k^{out2} = P_k^{out1} - \Delta P_k^{PR} \leq P_k^{out2\,\max} \quad (13)$$

where $P_k^{in\,\min}$ is the minimum allowable pressure at the inlet of the k-th OPS, $P_k^{out1\,\max}$ and $P_k^{out2\,\max}$ 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:

$$^{out2} - \max\_\Delta P_i^{ac} > 0 \quad (14)$$

Let be $P_*^{def\,\max}$ 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:

$$P(X\ \ ) \leq P_j^{def\,\max} \quad (15)$$

Each pump has an operating range with permissible flow rates $Q^{\min}, Q^{\max}$, which in the VFD mode depend on the rotor speed:

$$Q^{\min}(\mathbf{k}) \leq Q \leq Q^{\max}(\mathbf{k}) \quad (16)$$

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

$$P_{kl}^{in\,gr} = P_k^{in} + \sum_{j=1}^{l-1} \Delta P_{kj}^{gr} \geq P_{kl}^{\min\,in\,gr} \quad (17)$$

In the operation of the pumps, overloading of the electric motor is also not allowed:

$$N^{PU}(Q, \mathbf{k}) \leq k^{over}\ \ N^{nom} \quad (18)$$

where $k^{over} = 1.1$ 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 $Info(P)$, 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_{ij} and $\mathbf{k}_{ij}$ of pumps in condition (1).

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

$$S(P = \begin{cases} +\infty, & P \neq P_{pump} \\ zN^{PU}(Q), & P = P_{pump} \end{cases}$$
$$Info(P = \begin{cases} \varnothing, & P \quad P_{pump} \\ (pump\, number), & P = P_{pump} \end{cases} \tag{19}$$

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

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

where $[\ ]$ is the rounding to the nearest rational number with a step ε_p.

Similarly, $S(P)$ and $Info(P)$ are defined for the pump with VFD:

$$S(P = \begin{cases} +\infty, & P \notin [P^{min}, P^{\max}] \\ zN^{PU}(Q,\mathbf{k}), & P \in [P^{min}, P^{\max}] \end{cases}$$
$$Info(P = \begin{cases} , & P \notin [P^{min}, P^{\max}] \\ (pump\, number) + k, & P \in [P^{min}, P^{\max}] \end{cases} \tag{20}$$

where $p^{\min}$ and $p^{\max}$ are the minimum and maximum pressure drops.

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

$$_r(P) = \begin{cases} +\infty, & P \neq P_{pump} \\ z\sum_{i=1}^{r} N_i^{PU}\left(\frac{Q}{r}\right), & P = P_{pump} \end{cases} \tag{21}$$

where P_{pump} is the pressure drop created by pumps operating in parallel.

For pumps operating in parallel in the VFD mode, the function $S_r(P)$ and array $Info_r(P)$ will take the form similar to expressions (21).

In order to take into account the operating area condition of the pump (18), it is necessary to change the cost function according to the following principle:

$$S(P = \begin{cases} S(P), & Q^{\min}(\mathbf{k}) \leq Q \leq Q^{\max}(\ ) \\ +\infty, & \text{otherwise} \end{cases} \tag{22}$$

Similarly, the cost function is adjusted if it is necessary to take into account the operating condition of the pump motor without overload (20):

$$S(P = \begin{cases} S(P), & N^{PU}(Q,\mathbf{k}) \leq k^{over} * N^{nom} \\ +\infty, & \text{otherwise} \end{cases} \tag{23}$$

Definition 1.

The union of two functions S^A and S^B denotes such the function $S(P)$, that has the value for each P:

$$S(P) = S^A(P) \bigcup S^B(P) \quad \min(S^A(P), S^B(P)) \tag{24}$$

Similarly, the union of two arrays $Info^A$ and $Info^B$ denotes such the array $Info(P)$ that has the value for each P:

$$Info(P) = Info^A(P) \cup Info^B(P) = \\ = \begin{cases} Info^A(P), S^A(P) \leq S^B(P) \\ Info^B(P), S^A(P) > S^B(P) \end{cases}$$

If the pump has several replaceable rotors, then its cost function is determined by the expression:

$$S(P) = \bigcup_{i=1}^{n} S^{rotor\ i}(P) \tag{25}$$

where n is the number of replaceable rotors, $S^{rotor\,i}$ is the cost function of the pump, when working with the rotor i.

Similarly, its array of solutions $Info(P)$ 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":

$$\begin{aligned} S^{gr} &= \bigcup S_1 \cup \ldots \cup \bigcup S_{r-} \;\cup S \\ Info^{gr} &= \bigcup Info_1 \cup \ldots \cup \bigcup Info_{r-} \;\cup Info \end{aligned} \qquad (26)$$

where $\cup S_i$, $\cup Info_i$ are the "unions" of the function $S(P)$ and array $Info(P)$, respectively, for all samples of i pumps from the r group.

Definition 2.

The imposition of the function S^B on the function S^A denotes the function $S(P)$ that has the value (similarly, for $Info(P)$) for each P:

$$\begin{aligned} & S(P) = S^A(P) \leftarrow (S\quad) = \\ & = \min(S^A(P), S^A(P-P^*) + S^B(P\quad)) \end{aligned} \qquad (27)$$

where the variable value P^* at the specific value P is defined as:

$$\begin{aligned} & P^* = \arg\min(S^A(P-P^*) + S\quad(P^*)) \\ & \quad ^* \in [0, P] \end{aligned} \qquad (28)$$

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 $S^{st}_{in}(P)$ and its array of solutions $Info^{st}_{out}(P)$ 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 $S^{st}_{in}(P)$ and its array $Info^{st}_{out}(P)$ at the inlet of the station:

$$\begin{aligned} & S^{st}_{out}(P) = S^{st}_{in}(P) \leftarrow (S^{gr}_1) \leftarrow (S^{gr}) \leftarrow \ldots \leftarrow (S^{gr}_m) \\ & Info^{st}_{out}(P) = Info^{st}_{in}(P) \leftarrow (Info^{gr}_1) \leftarrow \\ & \leftarrow (Info^{gr}_2) \leftarrow \ldots \leftarrow (Info^{gr}_m) \end{aligned} \qquad (29)$$

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:

$$P^* \in [P - P_i^{\min in\, gr}, P] \qquad (30)$$

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

$$S^{st}_{out}(P) = \bigcup_{i=1}^{n} S^{st,\, layout\, i}_{out}(P) \qquad (31)$$

Where n is the number of pump layouts at OPS, $S^{st,\, layout\, i}_{out}$ is the cost function at the outlet from OPS in the scheme i.

Similarly, its array of solutions $Info(P)$ 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 $Info^{st}(P,v)$):

$$\begin{aligned} & S^{st}(P,v) = S^{st}(P,\quad) \leftarrow (S^{gr}) = \\ & = \min(S^{st}(P,v), S^{st}(P-P^*,\quad - N(P^*)) + S^{gr}(P^*)) \end{aligned} \qquad (32)$$

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 $Info^{gr}(P^*)$. Whether they operate in the mode with VFD is determined by the criterion $k \neq 1$ for each value $Info^{gr}(P^*)$.

The value of the variable P^* at specific values P and v is defined as:

$$P^{*} = \arg\min(S^{st}(P - P^{*}, \nu - N(P^{*})) + S^{gr}(P^{*})) \quad (33)$$
$$^{*} \in [0, P]$$

When "imposing" by formulas (32) and (33) for each ν 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":

$$S^{st}(P) = \bigcup_{\nu=0}^{p} S^{st}(P, \nu) \quad (34)$$

Definition 4.

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

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

Similarly, for an array of solutions:

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

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 $^{\text{in}\min}_{+1} + \Delta P_{k}^{ac}$, i.e. the pressure condition at the inlet in 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 $(P_{out}^{\min,k})$ has the form:

$$P_{k}^{out2} \geq P_{out}^{\min,k} = \max(P_{k+1}^{\text{in}\min} + \Delta P_{k}^{ac}, \max\_\Delta P_{i}^{ac}) \quad (36)$$

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 $P^{pipe\max}$, at which conditions (15) will be fulfilled. Then the final condition for maximum allowable pressure at the outlet of OPS (denote $P_{out}^{\max,k}$) has the form:

$$P_{k}^{out2} \leq P_{out}^{\max,k} \quad \min(P_{k}^{out2\max}, P_{k}^{pipe\max}) \quad (37)$$

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

$$S(P) = CUT(S(P), P_{out}^{\min}, P_{out}^{\max}) \quad (38)$$

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 $Info(P)$ as follows:

$$S(P \ \ = \begin{cases} S(P'), & S(P) > S(P') \\ S(P), & \text{otherwise} \end{cases} \quad (39)$$
$$Info(P) =$$
$$= \begin{cases} Info(P') + \text{"lowering in the PR by"} + (P' - P), & S(P) > S(P') \\ Info(P), & \text{otherwise} \end{cases}$$

where values P' for a specific value P are defined as:

$$P' = \arg\min(S(P)) \quad (40)$$
$$P' \in [P, P_{k}^{out1\max}]$$

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 ΔP is the function $S^{new}(\ \ )$ that has the value for each P:

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

Then the transition to the next station (similarly, for $Info(P)$) has the form:

$$S_{in}^{next\,st}(P) = \text{SHIFT}(S_{out}^{st}(P), \ \ P^{ac}) \quad (42)$$

where the function $S_{out}^{st}(P)$ should be "pruned", $_{in}^{next\,st}\ P)$ 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^k calculate $S_i^{gr,k}$ by formulas (21)-(28);

$S_{out}^{st,k}(P)=S_{in}^{st,k}(P)\leftarrow(S_1^{gr,k})\leftarrow(S^{gr,k})\leftarrow$
$\leftarrow\cdots\leftarrow(S_{m^k}^{gr,k});$

Calculation ΔP_k^{ac} (43)

$S_{out}^{st,k}(P)=CUT(S_{out}^{st,k}(P),P^{\min},P^{\max});$

$S_{in}^{st,k+1}(P)\quad SHIFT(S_{out}^{st,k}(P),\Delta P_k^{ac});$

$k=k+1$.

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

The function is used as the initial cost function:

$$S_{in}^{st,1}(\ )=\begin{cases}+\infty, & P\neq P_{init}\\ 0, & P=P_{init}\end{cases} \tag{44}$$

The initial function $S_{in}^{st,1}(\ )$ 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_{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 $S_{in}^{st,n+1}(P^{answ})$.The optimal combination of operating pumps and their operating modes will be stored in the cell of the array $Info_{in}^{st,n+1}(P^{answ})$.

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.

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Мұнай тасымалдау үшін сорғы қондырғыларын оңтайландыру проблемасы

[1] Бекібаев Т.Т., [1] Рамазанова Г.І., [2] Пахомов М.А.

[1] Сәтбаев университеті, Алматы, Қазақстан
[2] Кутателадзе атындағы Теплофизика институты, Ресей Ғылым академиясының Сібір бөлімшесі, Новосибирск, Ресей

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ТҮЙІНДЕМЕ

Магистралды мұнай құбырлары арқылы мұнайды тасымалдау кезінде тұтынылатын энергияның басым бөлігі мұнай айдау станцияларындағы магистральдық және тірек сорғы қондырғыларының жұмысына жұмсалады. Осыған байланысты мұнай құбырларындағы сорғы қондырғыларының оңтайлы жұмыс режимдерін анықтау энергия үнемдеудің өзекті мәселесі болып табылады. Мақала құбырымен мұнай тасымалдаудың энергиясын үнемдеу үшін сорғы қондырғыларының жұмысын оңтайландыру мәселесіне арналған. Сорғылардың жұмысы доңғалақтарының диаметрі әртүрлі ауыстырылмалы роторлар немесе жиілікпен басқарылатын жетек көмегімен реттеледі. Сорғы қондырғыларын пайдалану шығындарын барынша азайту үшін оңтайландыру критерийі тұжырымдалды. Доңғалақтарының диаметрі әртүрлі және жиілікпен басқарылатын жетекті сорғы қондырғыларының энергия шығынын анықтау әдістемесі ұсынылды. Сорғы қондырғыларының оңтайлы жұмыс режимін іздеу алгоритмі графтар теориясы мен динамикалық бағдарламалау анықтамаларын пайдалана отырып жасалды.

Түйін сөздер: оңтайландыру критериі, энергияны үнемдеу, мұнай тасымалдау, графтар теориясы, динамикалық бағдарламалау.

Авторлар туралы ақпарат:

Бекібаев Тимур Талғатұлы — *Техника и технология магистрі, бөлім бастығы, Сәтбаев университеті, «Энергетикадағы модельдеу» ғылыми-өндірістік зертханасы, Алматы қ., Қазақстан Республикасы. Электрондық пошта: timur_bekibaev@mail.ru, https://orcid.org/0000-0001-7030-0015*

Рамазанова Гаухар Ізбасарқызы — *Физика-математика ғылымдарының кандидаты, жетекші ғылыми қызметкер, Сәтбаев университеті, «Энергетикадағы модельдеу» ғылыми-өндірістік зертханасы, Алматы қ., Қазақстан Республикасы. Электрондық пошта: gaukhar.ri@gmail.com, g.ramazanova@satbayev.university, https://orcid.org/0000-0002-8689-9293*

Пахомов Максим Александрович — *Физика-математика ғылымдарының докторы, Ресей ғылым академиясының профессоры, жетекші ғылыми қызметкер, С.С. Кутателадзе атындағы Теплофизика институты, Ресей Ғылым академиясының Сібір бөлімшесі, Новосибирск қ., Ресей. h-индекс: 15; Scopus ID: https://www.scopus.com/authid/detail.uri?authorId=6602734341. Электрондық пошта: pakhomov@ngs.ru*

Проблема оптимизации насосных агрегатов для транспортировки нефти

[1] Бекибаев Т.Т., [1] Рамазанова Г.И., [2] Пахомов М.А.

[1] Satbayev University, Алматы, Казахстан
[2] Институт теплофизики им. С.С. Кутателадзе, Сибирское отделение РАН, Новосибирск, Россия

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АННОТАЦИЯ

При транспортировке нефти по магистральным нефтепроводам большая часть расходуемой энергии уходит на работу магистральных и подпорных насосоных агрегатов на нефтеперекачивающих станциях. В этой связи определение оптимальных режимов работы насосных агрегатов, эксплуатирующихся на нефтепроводах, является актуальной проблемой для энергосбережения. Статья посвящена оптимизации работы насосных агрегатов для энергосбережения трубопроводного транспорта нефти. Работа насосных агрегатов регулируется с использованием сменных роторов с различными диаметрами рабочих колес или частотно-регулируемым приводом. Сформулирован критерий оптимизации для минимизации эксплуатационных затрат насосных агрегатов. Представлена методика определения энергопотребления насосных агрегатов с различными диаметрами рабочих колес и частотно-регулируемым приводом. Алгоритм поиска оптимального режима работы насосных агрегатов построен с использованием определений теории графов и динамического программирования.

Ключевые слова: критерий оптимизации, энергосбережение, транспортировка нефти, теория графов, динамическое программирование.

Информация об авторах:

Бекибаев Тимур Талгатович — *Магистр техники и технологии, руководитель отдела, Некоммерческое акционерное общество «Satbayev University», научно-производственная лаборатория «Моделирование в энергетике», г. Алматы, Республика Казахстан. E-mail: timur_bekibaev@mail.ru, https://orcid.org/0000-0001-7030-0015*

Рамазанова Гаухар Избасаровна — *Кандидат физ.-мат. наук, ведущий научный сотрудник, Некоммерческое акционерное общество «Satbayev University», научно-производственная лаборатория «Моделирование в энергетике», г. Алматы, Республика Казахстан. E-mail: gaukhar.ri@gmail.com,*

	g.ramazanova@satbayev.university, https://orcid.org/0000-0002-8689-9293
Пахомов Максим Александрович	*Доктор физико-математических наук, профессор РАН, ведущий научный сотрудник, Институт теплофизики им. С.С. Кутателадзе, Сибирское отделение РАН, г. Новосибирск, Россия. h-индекс: 15; Scopus ID: https://www.scopus.com/authid/detail.uri?authorId=6602734341. E-mail: pakhomov@ngs.ru*

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