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THE COEFFICIENT OF EFFICIENCY OF A COMPLEX HYDRAULIC CIRCUIT

О.Г. Бутенко, А.В. Карамушко, Т.С. Подуфала. Коэффициент эффективности сложной гидравлической сети. У статті розглядається один з можливих методів оцінки ефективності використання енергії у складній гідравлічній мережі. Показано, що для характеристики енергетичної досконалості складної гідравлічній мережі не може використовуватися лише коефіцієнт корисної дії насосної установки, оскільки він не враховує усіх можливих гідравлічних втрат та взаємного впливу елементів системи «насос – трубопровід». Для цієї мети запропоновано використовувати коефіцієнт енергетичної досконалості мережі, який є відношенням потужності потоку рідини на виході із гідравлічній мережі до потужності на валу насоса. Цей показник враховує втрати як у елементах насосної установки так і в трубопроводній системі і завдяки цьому дає об'єктивну і комплексну оцінку енергетичній ефективності цієї системи в цілому. Шляхом використання балансу потужностей елементів системи виведено формулу розрахунку цього показника для розгалуженої гідравлічній мережі, що складається із послідовних і паралельних ділянок. Проведений аналіз отриманої формули, котрий показав, що перевагою запропонованої формули є врахування прихованої взаємної залежності між величинами, що визначають коефіцієнт енергетичної досконалості. Зокрема формула враховує вплив опору складної гідравлічній мережі на робочі параметри насоса (напір і подавання) і на його коефіцієнт корисної дії. Показано, що у деяких випадках зростання гідравлічного опору мережі, а отже і втрат потужності у системі, компенсується зростанням напору, що розвиває насос, і зростанням його коефіцієнта корисної дії. Таким чином доведено, що негативна дія у трубопроводній системі може таким чином вплинути на показники насосної установки, що коефіцієнт енергетичної досконалості мережі не тільки не зменшиться, а й зросте. Формула дозволяє порівнювати енергетичну досконалість складних гідравлічних мереж з різними параметрами і різними насосними установками та дозволяє проводити оптимізацію системи за сумарними енерговитратами.

Ключові слова: складна гідравлічна мережа, корисна потужність, потужність на валу, опір мережі, коефіцієнт енергетичної досконалості мережі

O. Butenko, A. Karamushko, T. Podufala. The coefficient of efficiency of a complex hydraulic circuit. The article discusses one of the possible methods for assessing of energy efficiency in a complex hydraulic network. It is shown that to characterize the energy excellence of a complex hydraulic network, only the efficiency of the pumping unit cannot be used, since it does not take into account all possible hydraulic losses and the mutual influence of the elements of the “pump pipeline” system. For this purpose, it is proposed to use the coefficient of energy perfection of the network, which is the ratio of the power of the fluid flow at the outlet of the hydraulic network to the power on the pump shaft. This indicator takes into account losses both in the elements of the pumping unit and in the pipeline system and, therefore, gives an objective and comprehensive assessment of the energy efficiency of this system as a whole. By using the power balance of the system elements, a formula for calculating this indicator for an extensive hydraulic network consisting of sequential and parallel sections is derived. The analysis of the obtained formula, which showed that the advantage of the proposed formula is to take into account the hidden mutual dependence between the quantities that determine the coefficient of energy perfection. In particular, the formula takes into account the influence of the resistance of a complex hydraulic network on the operating parameters of the pump (pressure and flow) and its efficiency. It is shown that in some cases, the increase in the hydraulic resistance of the network, and hence the power loss in the system, is compensated by the increase in pressure developed by the pump and its efficiency. Thus, it is proved that the negative impact in the pipeline system can thus affect the performance of the pumping unit, that the coefficient of energy perfection of the network will not only not decrease, but also increase. The formula allows you to compare the energy excellence of complex hydraulic networks with various parameters and different pumping units and allows you to optimize the system with total energy consumption.

Keywords: complex hydraulic circuit, useful power, shaft power, resistance of the circuit, coefficient of the energy perfected circuit

Introduction. In today's world, hydraulic networks have a length of millions of kilometers. They have varying degrees of complexity (branching) and provide water for both domestic and industrial needs. As a rule, fluid energy in these networks is transmitted from electrically driven pumps. Several tens of billions of kWh of electricity are consumed each year to power them. Despite such considerable amounts of electricity consumed in hydraulic networks, designers do not use any universal indicator that would generally characterize the efficiency of conversion of electrical energy into hydraulic and the efficiency of use of this hydraulic energy.

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Analysis of recent publications. To characterize the energy efficiency of hydraulic networks, the efficiency of the discharge equipment has traditionally been used. This significantly complicates the optimization of the hydraulic criterion of the hydraulic network parameters in its design or verification calculation and is methodologically incorrect [1]. Designing hydraulic networks (including branching) consists of several basic steps. According to the terms of reference, the diameters of the water sections of individual sections are selected from the standard series, then the power required to pump a given flow rate of fluid through the piping system is calculated and, finally, a discharge unit is selected that is capable of providing the specified power with maximum efficiency [2]. Even when it comes to optimizing energy costs for fluid transportation, it is only the pumping installation that is considered [3, 4, 5, 6]. In particular, it is proposed to use as a criterion electricity costs per unit volume of pumped liquid. This is also methodologically incorrect, since the distance to which the fluid is pumped is not taken into account. This, as we see, takes into account the efficiency of the conversion of mechanical energy on the shaft into the hydraulic energy of the fluid in the pump, but does not consider the efficiency of the use of this hydraulic energy during the movement of the fluid through the pipeline to the end consumer. In other words, the performance of a system is judged by the corresponding indicator of only one element, which is a flawed approach.

The efficiency of the supercharger is the ratio of the useful power N_u to the power on the shaft N_s :

$$\eta_p = \frac{N_u}{N_s}.$$

Useful power:

$$N_u = \rho g Q_p H_p,$$

where ρ – the density of the pumped liquid, kg/m³;

Q_p and H_p – flow (m³/s) and pump head (m).

The pressure of the pump directly in the pipeline part of the network is spent on overcoming the static height H_{st} and on losses $\Delta h = SQ_p^2$ (S is the resistance of the hydraulic network, s²/m⁵). That is, for a simple pipeline [6]:

$$H_p = H_{st} + SQ_p^2.$$

This means that an increase in the resistance of the network and consequently a loss of energy in the pipeline part of it always leads to an increase in the useful power of the pump and in certain modes – to an increase in its efficiency. Since this increase in power is spent on losses, it is impossible to find it useful. This contradiction is one example of the fact that it is not enough to use the parameters of a pumping installation alone to characterize the overall energy efficiency of a hydraulic network. In addition, in pipelines running “from the reservoir”, i.e. the flow occurs under the action of hydrostatic pressure, due to the absence of the pump this indicator cannot be used in principle.

In article [7], for the general characterization of the energy efficiency of the hydraulic network, the authors introduced a new concept – the efficiency of its individual elements and, as a result, proposed the formula:

$$\frac{1}{\eta_s^2} = \frac{1}{\eta_p^2} + \sum_{n=1}^k \left(\frac{1}{\eta_n^2} - 1 \right) \frac{w_j^2}{w_i^2}, \quad (1)$$

where η_s , η_p , η_n – efficiency of the hydraulic system as a whole, the pump and the n -th element of the system respectively;

w_i i w_j – cross-sectional areas of individual sections.

Formula (1) makes it possible to estimate the energy efficiency of the hydraulic system, but is not very convenient for real networks where the number of elements can reach polynomials. In addition, for example, when closing a valve, its efficiency is zero, which results in the need to divide by zero.

Alternatively, for the overall energy efficiency of the hydraulic network, work [8] proposes a network energy perfection coefficient (NEPC) ε , which is the ratio of the output power from the hy-

drahlic network N_{inp} to the power input N , which is the power on the pump shaft. Since the output power is equal to the difference of the useful power and the power loss in the pipeline $\Delta N_l = \rho g S Q_p^3$, and the power on the shaft:

$$N_s = \frac{\rho g Q_p H_p}{\eta_p},$$

then NERC is obtained for a simple pipeline:

$$\varepsilon = \eta_p \left(1 - \frac{S Q_p^2}{H_p} \right). \quad (2)$$

The first factor in it takes into account the energy efficiency of the pump, and the second – the pipeline part of the network.

The purpose of the work is to find a general indicator of the efficiency of transportation of fluid over a complex (branched) hydraulic network, which would generally take into account the losses both in the pumping equipment and in the elements of the pipeline part of the network.

Main part. If we consider a pipeline consisting of series-connected sections in which the total resistance is the sum of the resistances of these sections, then (2):

$$\varepsilon = \eta_p \left(1 - \frac{Q_p^2 \sum_{i=1}^n S_i}{H_p} \right).$$

Consider a complex hydraulic network with n consecutive and k - m parallel sections (Fig. 1).

Power losses in successive sections, the volume flow of which is equal to the supply of the pump Q_p ,

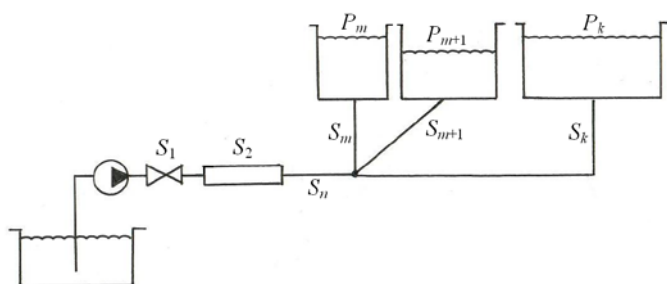


Fig. 1. Schematic of complex hydraulic network

$$\left. \begin{aligned} \Delta N_1 &= \rho g S_1 Q_p^3 \\ \Delta N_2 &= \rho g S_2 Q_p^3 \\ &\dots \\ \Delta N_n &= \rho g S_n Q_p^3 \end{aligned} \right\},$$

where S_1, S_2, S_n – hydraulic supports of corresponding consecutive sections, s^2/m^5 ;

Power losses in parallel sections:

$$\left. \begin{aligned} \Delta N_m &= \rho g S_m Q_m^3 \\ \Delta N_{m+1} &= \rho g S_{m+1} Q_{m+1}^3 \\ &\dots \\ \Delta N_k &= \rho g S_k Q_k^3 \end{aligned} \right\},$$

where S_m, S_{m+1}, S_k – hydraulic supports of corresponding parallel sections, s^2/m^5 ;

Q_m, Q_{m+1}, Q_k – the volumetric flow in them m^3/s .

Then the total power loss in the branched hydraulic system:

$$\Delta N_s = \sum_{i=1}^n \rho g S_i Q_p^3 + \sum_{j=m}^k \rho g S_j Q_j^3.$$

Based on the definition of NERC and the considerations above:

$$\varepsilon = \frac{N_u - \Delta N_s}{N_s} = \frac{\eta_p (\rho g Q_p H_p - \Delta N_s)}{\rho g Q_p H_p} = \eta_p \left(1 - \frac{\Delta N_s}{\rho g Q_p H_p} \right).$$

The sections of the pipeline system are considered to be parallel if they have two points in common. The condition of pressure equality $P_m = P_{m+1} = \dots = P_k$ corresponds to this definition. Then:

$$S_m Q_m^2 = S_{m+1} Q_{m+1}^2 = \dots = S_k Q_k^2.$$

Where

$$\left. \begin{aligned} Q_{m+1} &= Q_m \sqrt{\frac{S_m}{S_{m+1}}} \\ Q_{m+2} &= Q_m \sqrt{\frac{S_m}{S_{m+2}}} \\ &\dots \\ Q_k &= Q_m \sqrt{\frac{S_m}{S_k}} \end{aligned} \right\}.$$

Then

$$\sum_{j=m}^k \rho g S_j Q_j^3 = \rho g (S_m Q_m^3 + S_{m+1} Q_{m+1}^3 + \dots + S_k Q_k^3) = \rho g \left(S_m Q_m^3 + S_{m+1} \left(Q_m \sqrt{\frac{S_m}{S_{m+1}}} \right)^3 + \dots + S_k \left(Q_m \sqrt{\frac{S_m}{S_k}} \right)^3 \right),$$

And after simple transformations:

$$\sum_{j=m}^k \rho g S_j Q_j^3 = \rho g S_m Q_m^3 \left(1 + \sum_{j=m+1}^k \sqrt{\frac{S_m}{S_j}} \right).$$

So

$$\varepsilon = \eta_p \left(1 - \frac{\rho g Q_p^3 \sum_{i=1}^n S_i + \rho g Q_m^3 S_m \left(1 + \sum_{j=m+1}^k \sqrt{\frac{S_m}{S_j}} \right)}{\rho g Q_p H_p} \right),$$

or

$$\varepsilon = \eta_p \left(1 - \frac{\sum_{i=1}^n \Delta h_i}{H_p} + \frac{Q_m \Delta h_m}{Q_p H_p} \left(1 + \sum_{j=m+1}^k \sqrt{\frac{S_m}{S_j}} \right) \right),$$

where Δh_i and Δh_m – loss of head on the respective sections, m.

Since

$$Q_p = Q_m + Q_{m+1} + \dots + Q_k,$$

and

$$\frac{Q_p}{Q_m} = 1 + \frac{Q_{m+1}}{Q_m} + \dots + \frac{Q_k}{Q_m} = 1 + \sqrt{\frac{S_m}{S_{m+1}}} + \dots + \sqrt{\frac{S_m}{S_k}} = 1 + \sum_{j=m+1}^k \sqrt{\frac{S_m}{S_j}},$$

then

$$\frac{Q_m}{Q_p} = \frac{1}{1 + \sum_{j=m+1}^k \sqrt{\frac{S_m}{S_j}}}.$$

Wherefrom

$$\varepsilon = \eta_p \left(1 - \frac{\sum_{i=1}^n \Delta h_i + \Delta h_m}{H_p} \right),$$

or

$$\varepsilon = \eta_p \left(1 - \frac{Q_p^2 \sum_{i=1}^n S_i + Q_m^2 S_m}{H_p} \right). \quad (3)$$

Formula (3) indicates that the efficiency of a complex hydraulic network will be greater, the greater the efficiency of converting the mechanical energy of the actuator into hydraulic energy of the fluid (greater η_n) and the smaller the loss of hydraulic energy as the fluid moves to the consumer (less network resistance). However, given that the quantities included in (3) are partially interdependent, conclusions about the value of ε can be made only on the basis of a complete analysis of the specific problem.

Analysis of the results. Let us analyze the obtained dependence (3) on the example of a branched hydraulic network in which two consecutive sections ($H_{st1}=2$ m, $S_1=9 \cdot 10^4$ s²/m⁵ and $H_{st2}=0$ m, $S_2=3.5 \cdot 10^4$ s²/m⁵) and two parallel sections ($H_{sm}=10$ m, $S_m=8 \cdot 10^5$ s²/m⁵ and $H_{st(m+1)}=20$ m, $S_{m+1}=2.2 \cdot 10^5$ s²/m⁵).

The pump X45/240 with a diameter of the impeller $D_2=262$ mm, which is often used in systems of water supply [9]. Characteristic construction (Fig. 2) allows to obtain the following parameters: $Q_p=16.1$ m³/s, $Q_m=10.3$ m³/s, $Q_{m+1}=5.8$ m³/s, $H_p=129$ m, $\eta_p=0.325$. The calculations according to (3) give the value of the energy efficiency coefficient of the network $\varepsilon=0.0297$.

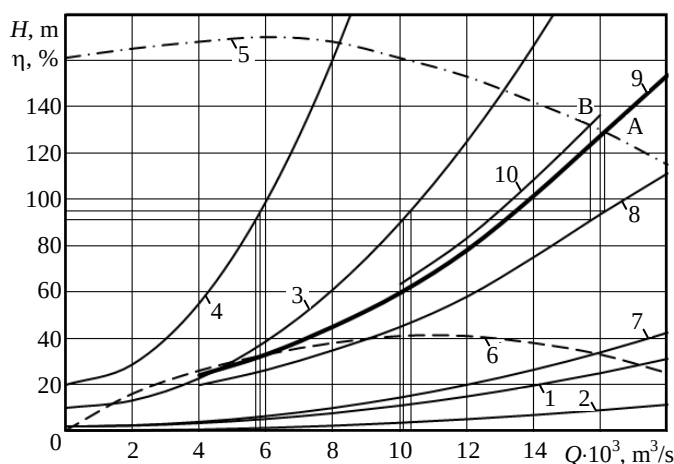


Fig. 2. Determination of parameters of complex hydraulic network with pump X45/240: 1 – the head of the first series, 2 – the head of the second series, 3 – the head of the first parallel section, 4 – pressure characteristic of the second parallel section, 5 – pressure characteristic of the pump X 45/240, 6 – characteristic of the efficiency of the pump X45/240, 7 – summary characteristic of two consecutive sections, 8 – summary characteristic of two parallel sections, 9 – summary characteristic of complex hydraulic network, 10 is the total characteristic of a complex hydraulic network after increasing the resistance S_2

Let's replace the conditions of the example – double the resistance of the second consecutive section ($S'_2=7 \cdot 10^4 \text{ s}^2/\text{m}^5$). Now, as can be seen from the graph in Fig. 2 $Q'_p=15.6 \text{ m}^3/\text{s}$, $Q'_m=10 \text{ m}^3/\text{s}$, $Q'_{m+1}=5.6 \text{ m}^3/\text{s}$, $H'_p=132.5 \text{ m}$, $\eta'_p=0.349$. The calculations for (2) give the value of the network energy efficiency coefficient $\varepsilon=0.0358$. So, we get a paradoxical result: an increase in the resistance of one of the branches of the branched network leads to an increase in the NERC, although given the structure of formula (3) one would expect the opposite result. Indeed, the increase in resistance in this example quite naturally leads to an increase in total head losses (fractional numerator in brackets), but the shift of the operating point from position A to position B is accompanied by changes in the pump parameters. In this case, both the pump head and its efficiency increase. This change not only compensates for the increase in losses, but also outweighs this negative consequence of the increase in S .

It is easy to see that in the extreme case, when the resistance of the elements of the network is zero (the flow of the ideal fluid), NERC is equal to the efficiency of the pump:

$$\lim_{S \rightarrow 0} \left[\eta_p \left(1 - \frac{Q_p^2 \sum_{i=1}^n S_i + Q_m^2 S_m}{H_p} \right) \right] = \eta_p ,$$

and when all the pump's specific energy is spent on hydraulic losses in the network:

$$\lim_{\Delta h_{\Sigma} \rightarrow H_p} \left[\eta_p \left(1 - \frac{Q_p^2 \sum_{i=1}^n S_i + Q_m^2 S_m}{H_p} \right) \right] = 0 .$$

That is, in extreme cases, the resulting formula gives quite natural and physically reasonable results.

Conclusions. The method of calculating of the complex efficiency index, which is the ratio of the flow power at the outlet of the hydraulic network to the power of the blower on the shaft, can be used for the analysis of a complex (branched) hydraulic network. Derived for this case, formula (3) allows to quantify the value of this indicator. Thus, the optimization of the hydraulics system for the total energy consumption should be performed not by the efficiency of the supercharger, but by the magnitude of the energy efficiency coefficient of the network as a whole.

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