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ENERGY SAVING OPPORTUNITIES IN PUMP SYSTEMS

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Abstract: *This paper represents an overview of some energy-saving factors having significant impact on the effective energy use in pump systems. It also pays attention to the need of good knowledge about these factors and their interaction each other. Acquiring these specific knowledge and competencies helps to better design and operate pump systems, enabling their full energy saving potential to be used.*

Keywords: *pump systems, energy efficiency, energy-saving factors.*

INTRODUCTION

In the twenty-first century, two main factors dominate - meeting the energy needs of humanity and protecting the environment. Therefore, efforts are primarily referred to saving and efficient use of energy and water resources. Alignment with the market economy sets a new stage in the processes of their planning, assimilation and exploitation. A study commissioned by the EC (European Commission SAVE Study on Pumps) indicates that globally more than 20% of the energy used for electric drive is consumed by pump systems in the industrial and utility sectors. Analyzes show that in some industrial companies this indicator exceeds 50%. According to (Engineering Review Journal, 2010), the share of turbopumps represents ≈73% of the total amount of energy consumed, while the share of positive displacement pumps ≈27%. However, this trend increases continuously.

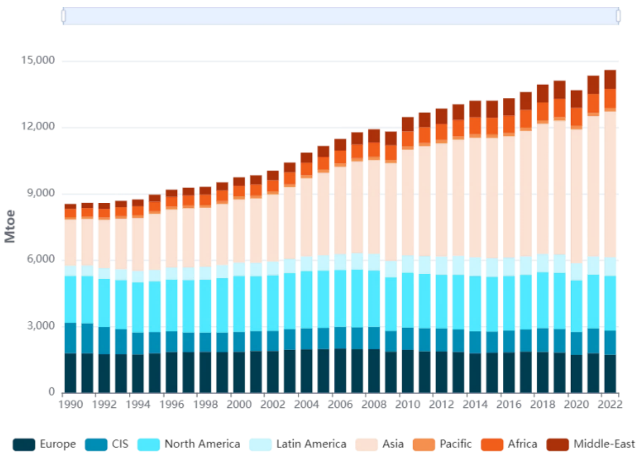

Fig. 1. Global energy consumption trend over 1990-2022 (World Energy & Climate Statistic, 2022*)*

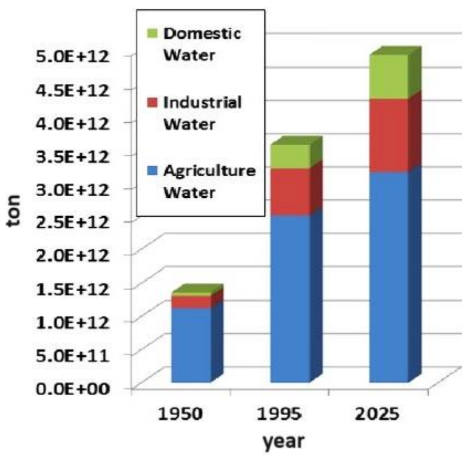

Fig. 2. Global water consumption by sectors (Shigehiro N. et al., 2013)

Often, pump systems (PS) operate inefficiently and the generated energy consumption is unreasonably high, due to various reasons - from design flaws to improper operation. Even if the requirements for correct design are met, it is possible to release excess energy costs as a result of the variation in the system operating parameters. Ensuring efficient operation of a pump system requires a good knowledge of the interaction between their main operating elements, such as pipe system, pump, driving electric motor, as well as the coordination of their joint operation. The aim of the present work is to present a detailed analysis of some main factors determining the energy saving potential in this type of systems.

EXPOSITION

The main reason for the inefficient operation of a pump system is the failure to use its full capacity, mainly related to the poor utilization of the input energy. The costs of constructing a pump system depend on constant factors related to the specific features of the location area and variable factors: the lengths of the pipes and materials used in their manufacturing; the requirements to ensure a certain flow rate and the pressure at the end of the pipe.

Pipe systems → The pipeline diameter does not depend on the features of the location area. Various formulas and methods related to solving optimization tasks are offered for calculating an economical correct diameter (Gama C. et al., 2019, Gessa G., 2021, Kowalski M., & Wernik J., 2014, Zocoler J. et al., 2006, Kalyoncu E., 2019). The approach is to be individual for each system, and as a criteria of economic efficiency, the minimum of the function representing the variation in total costs when varying the diameter is selected (fig.3).

$$\frac{dK_{tot}}{dD} = \frac{d(K_f + K_t)}{dD} = 0$$

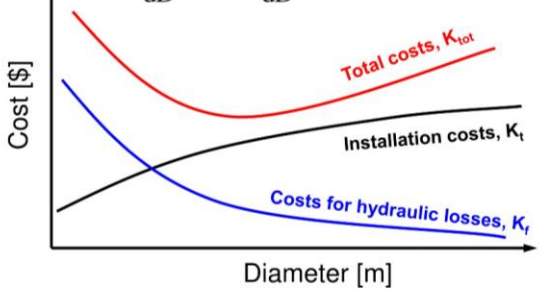

Fig. 3. Calculation of the economical correct diameter of a pipe

To solve a problem of this type, a simplified methodology may be used, based on the one proposed in (Zocoler J. et al., 2006). It contains of the following steps:

- ***Step 1*** is to calculate the annual costs C_p for transporting the required amount of water:

$$C_p = 0{,}736\frac{1000QH}{75\eta}Et_y, \tag{1}$$

where $H = H_{ST} + SL$, provided that S characterizes the steepness of the pipe resistance curve ($S = h_v/L$, i.e. the head losses per unit length (1 m) of the pipeline (this the so-called hydraulic slope), and h_v – the head loss in the pipeline and L – the length of the studied pipeline section); $Q, [m^3/s]$ – the required flow rate, ensured by the pump; η – a pump coefficient of efficiency (at first approximation it is assumed that $\eta \approx 0{,}65$); $E, [BGN/kWh]$ – price of energy (in BGN) per 1 kWh; $t_y, [h]$ – working hours per year. In such a case, the equation for calculating C_p can be represented as follows:

$$C_p = 0{,}736\frac{1000Q(H_{ST} + SL)}{75.0{,}65}Et_y. \tag{2}$$

For the system static head H_{ST} it is well-known that it does not depend on the diameter of the pipeline, i.e. for the given pipe $H_{ST} = const$. Thus, C_p is to be estimated into the following way:

$$C_p = 0{,}736\frac{1000QSL}{75.0{,}65}Et_y, [BGN/m.year]. \tag{3}$$

If $C_{CT}$is used to denote the price per unit length (1 m) of the pipe, and by C_C – the annual construction costs per unit length (1 m) of the pipe, then:

$$C_C = (\text{additional costs} + \text{amortization})C_{CT}, \tag{4}$$

where the value of additional costs (all potential financial costs + servicing) and amortization are pre-set to be 6% and 3% of the annual costs, respectively. Therefore, for C_C it is obtained:

$$\boldsymbol{C}_{\mathrm{C}} = \frac{3+6}{100} C_{\mathrm{ст}} = 0{,}09 C_{\mathrm{CT}}. \tag{5}$$

Then is to use the Hazen-Williams equation to calculate the hydraulic slope:

$$\mathrm{S} = \frac{\mathrm{h_v}}{\mathrm{L}} = \frac{4^{3,019}}{\pi^{1,852}\mathrm{k}^{1,852}} \frac{\mathrm{Q}^{1,852}}{\mathrm{c}^{1,852}\mathrm{d}^{4,8704}}. \tag{6}$$

where $c = 90 \dots 110\ (for\ steel\ pipes); 150\ (for\ PVC\ pipes)$ is the Hazen-Williams roughness factor used for calculating the hydraulic slope and $k = 0{,}849$ is a conversion factor.

- ***Step 2*** is to calculate the cost of transporting the desired amount of water through the pipeline for several different diameter values, determining the construction costs.

The diameter values at which the calculations will be done are in accordance with the flow velocity, which must be within certain limits. Their definition is related to not allowing too low or high velocities: low ones lead to the accumulation of sediments in the pipes, obstructing the free passage of the fluid flow and changing its features; high ones induce corrosion and are associated with greater head loss. According to the existing regulations in Bulgaria, the recommended velocity range is given as 1...3 m/s (it may be modified according to the regulations of each country).

Taking into account the above statement, let $\vartheta_{1,CR} = 1\ m/s$ and $\vartheta_{2,CR} = 3\ m/s$ be the two critical velocities by which the largest and smallest possible values for a potential economic correct pipe diameter will be determined, respectively. Then, the following equation is to be applied:

$$\vartheta_{\mathrm{CR}} = \frac{4\mathrm{Q}}{\pi \mathrm{d}_{\mathrm{MAX}}^2} \rightarrow \mathrm{d}_{\mathrm{MAX}} = \sqrt{\frac{4\mathrm{Q}}{\pi\vartheta_{\mathrm{CR}}}}. \tag{7}$$

As a result, the selection must be limited to pipes with standard diameters d falling within the range: $\mathrm{d} \in \left(\mathrm{d}_{2,\mathrm{MIN}} < \mathrm{d} < \mathrm{d}_{1,\mathrm{MAX}}\right)$.

- ***Step 3*** is to select a number of pipes of standard diameters from the product catalog of any manufacturer that meet the constraint of falling within the predetermined range.
- ***Step 4*** is to perform the required calculations (according to the proposed method, previously described) concerning the determination of the parameters C_p and C_C.
- ***Step 5*** is to specify the most economic correct diameter, which represents the one with the lowest value of the total costs $C_{MIN} = C_p + C_C$.

Drive power and efficient energy use are affected by hydraulic energy losses, which can be calculated using the Shezy formula, taking into account corrosion and deposits in pipes:

$$\mathrm{h_t} = \mathrm{h_H}(1 + \mathrm{k_H}\mathrm{t}), \tag{8}$$

where h_t are head losses obtained after $t$years; h_H – head losses at the beginning at $t = 0$ and k_H - coefficient, the values of which are determined by the type of material and the diameter of the pipe (Klimentov K., et al., 2003).

Pumps → Of significant importance concerning the pump efficiency is its compliance with the system elements involved in the operating process, at specific flow rate, head, range of operation, pump unit positioning, etc. The energy-efficient qualities of each pump are determined its coefficient of efficiency – η_P:

$$\eta_P = \mathrm{P_{OUT}}/\mathrm{P_{IN}}, \tag{9}$$

where P_{OUT} and P_{IN} – are the pump output and input powers, respectively. A pump unit total coefficient of effieincy η_{AGG} can be estimated as follows:

$$\eta_{\mathrm{AGG}} = \eta_P \eta_{TR} \eta_M, \tag{10}$$

where η_M and η_{TR} are the efficiency coefficients of the motor and the transmission, respectively.

As a criteria of system performance effectiveness, the energy invested in transporting of a unit volume of fluid, can be used (Popov G. et al., 2011):

$$e_V = \frac{E}{V}, \frac{kWh}{m^3}, \quad (11)$$

where e_V is the specific energy consumption; E - the invested system input energy, usually electrical, that a pump system needs to get started; V - the transported fluid's volume, most measured in $[m^3]$. After performing mathematical calculations and substitutes in eq. (11) are done, the following equation obtained can be used to estimate the specific energy consumption (Popov G. et al., 2011):

$$e_V = k_{ev}\frac{H}{\eta}, \frac{kWh}{m^3}, \quad (12)$$

where k_{eV} is a coefficient of the specific energy consumption (*k_{eV}=0,002725).* When the flow rate is known, using the equations describing the pump head and efficiency curves, enables to estimate e_V:

$$e_V = k_{ev}\frac{(a + bQ + cQ^2)}{(d + eQ + fQ^2)}, \quad (13)$$

where a, b, c and d, e, f are the coefficients of the equations of head and efficiency curves.

Motors → Most industrial pumps are driven by asynchronous motors, the choice of which depends on the system parameters. The use of new and better materials for manufacturing of modern engines slightly changes their operating curves, and the improvement of efficiency is expressed in the extension of their life cycle. A significant part of the power that an induction motor gain from the electrical network is lost in the stator and rotor, affecting its operating effectiveness (Dinolov O., 2008). To improve the efficiency of asynchronous electric drives, the following applies: production of energy-efficient motors; limiting idling, streamlining the load schedule, optimal drive load and providing high quality electrical power (Krasteva A., 2005).

Effective pump operating modes → The operating mode of a pump system is determined by the intersection of the pump head curve and and pipe system resistance curve (fig. 4).

Achieving efficient operation of a pump system requires that the pump operating mode is as close as possible to that in which it operates with maximum efficiency, i.e. *best efficiency point* (BEP). An efficient operating mode is considered to be anyone falling into the so-called *operating part* of the head curve limited by the restriction: $\eta \geq 0{,}9\eta_{MAX}$ (fig. 5).

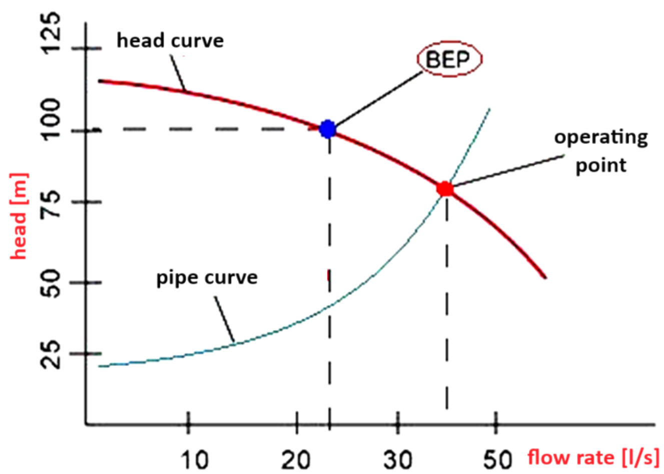

Fig. 4. Determining a pump operating mode

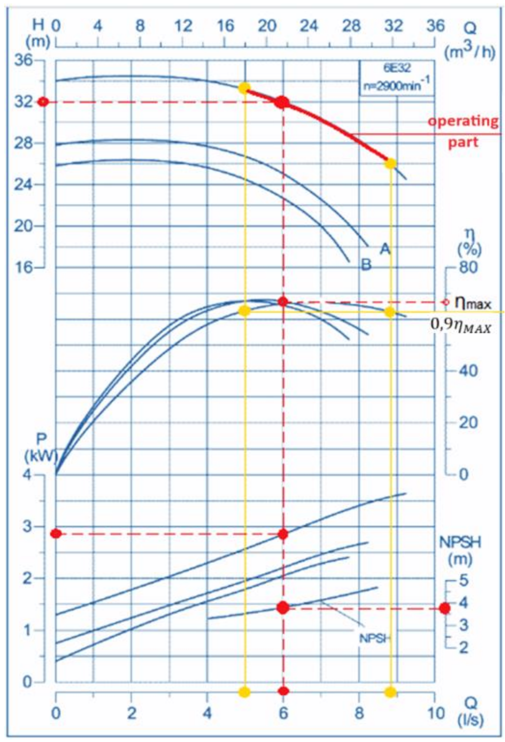

Fig. 5. Determination of the operating part of a pump of the type 6E32

The energy saved depends on some technological parameters characterizing the operating mode of the pump unit (Zalutsky E., 2002):

- range of flow rate variation for considered time period:

$$\lambda = Q_{LB}/Q_{UB}, \tag{14}$$

- where Q_{UB} and Q_{LB} are the upper and lower flow rate limits, respectively – respectively the largest and smallest flow rates for the calculation period, for example - one year.

- slope of the pipe system resistance curve:

$$H_{П}^{*} = H_{ST}/H_{UB}, \tag{15}$$

where $H_{П}^{*}$ is a coefficienct characterizing a pipe curve slope; H_{UB} – head at maximum flow rate Q_{UB}. In case of proper pump selection: $H_{UB} \approx H_{NOM}$ (pump nominal head).

- slope of the pump head curve:

$$H_{П}^{*} = H_{ST}/H_{UB}, \tag{16}$$

where H_{Φ} is a coefficient, characterizing a pump head curve slope;

- largest pump power consumed:

$$P_{P} = \rho g Q_{UB} H_{UB}/\eta_{NOM}. \tag{17}$$

- a pump unit time of operation during the calculation period T;

- the number of pumps m participating in the flow rate regulation process before using variable frequency drive (VFD) in the pump system, which is to be determined as follows:

$$m = 1 + (m_{UB} - m_{LB}), \tag{18}$$

where m_{UB} and m_{LB} are the number of pumps providing the largest and smallest flow rates, respectively. To simplify the calculation, computational curves of the type $W_{EK}^{*} = f(\lambda, H_{П}^{*})$ are introduced. Reading the value of W_{EK}^{*} is sufficient to calculate the potential energy savings:

$$W_{EK} = [(P_{pUB} T/\eta_{M,nom})][W_{EK}^{*} - (1 + \zeta - \eta_{VFD,nom})]\phi, \tag{19}$$

where $\eta_{M,nom} \approx 0{,}88 \ldots 0{,}9$; $\eta_{VFD,nom} \approx 0{,}97 \ldots 0{,}98$; $\zeta \approx 0{,}02 \ldots 0{,}03$ – a coefficient accounting for additional losses in the engine; ϕ - a decreasing factor taking into account the number of pumps m, which is selected from a table.

Effective flow control → Despite the undoubted advantages of applying VFD flow control, other methods are also used, mostly throttle and bypass. To evaluate the effect of using one or another method of flow rate regulation, a methodology proposed by (Popov G. et al., 2011), can be used. The specific energy consumption for a new and smaller flow rate can be determined in different ways for the different methods of regulation applied.

The specific energy consumption when throttle method of wlow control has been used:

$$e_{V1,tr} = k_{ev}\frac{H_1}{\eta_1} = k_{ev}\frac{(a + bQ_1 + cQ_1^2)}{(d + eQ_1 + fQ_1^2)}. \tag{20}$$

The specific energy consumption when VFD flow control method has been used:

$$e_{V1,n} = k_{ev}\frac{H}{(d + eQ_N + fQ_N^2)}\left[\frac{H_{st}}{H} + \left(1 - \frac{H_{st}}{H}\right)\left(\frac{Q_1}{Q}\right)^2\right]. \tag{21}$$

The specific energy consumption when “bypass” method of flow control has been used:

$$e_{V1,b} = k_{ev}\frac{H}{\left(d + eQ_p + fQ_p^2\right)}\left[\frac{H_{st}}{H} + \left(1 - \frac{H_{st}}{H}\right)\left(\frac{Q_1}{Q}\right)^2\right]\frac{Q_p}{Q_1}, \tag{22}$$

where Q_1 - the pump flow rate after it has been regulated, Q_N - the pump flow rate when it works with its nominal speed of rotation, Q_P - the pump flow rate before the regulation.

Using the equations (20), (21) and (22) it can be found a relatively quick and easy way to estimate the specific energy consumption of pump systems operating with turbopumps. For this purpose it is necessary to know the equations of a pump head and efficiency curves. To analyse how effective a particular method used to regulate the flow rate will be, it is necessary to estimate its specific energy consumption by applying some of the equations, previously mentioned. For a given flow rate the specific method flow control that produces the lowest energy consumption is the most effective method in terms of energy efficiency (Popov G. et al., 2011).

CONCLUSION

The energy invested in the operation of pump systems can be significantly reduced, which requires a good knowledge of the specific features of the system individual elements and their interaction. The necessity to design and construct new pump systems and/or to ensure more efficient operation of existing ones requires specific knowledge about the factors affecting energy consumption in these systems.

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