OPTIMIZATION OF PIPES NETWORKS FOR DRINKABLE WATER

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Abstract: This paper proposes a solution of the problem of reducing production costs for supplied domestic water, which directly affects the reduction of the electric power consumption. The optimization process will take into account that the profitability of water distribution activity depends on the relationship between supply capability and operating costs, i.e. Therefore, the process depends on the volume of required investment, on the specific consumption electrical power for pumping, on the price of electricity, as well as on the volume of water billed on a monthly basis. The optimization calculation will use two target functions: total maximum efficiency and total electric power consumption required for transport of each cubic meter of supplied water, and cubic meter of sewage water, respectively.
Key words: Adduction, hydrophore, pipe network, pumping station, optimization and tank.

1. INTRODUCTION

A good methodology for optimizing the reinforcement of water networks based on the analytical study of the links between the parameters that characterize its operation, the geometric and structural parameters and the investment's and operation's costs in the new conditions, are elements that dictate the approach for elaborating the solution, decreases the necessary working time and guarantees the selection of the optimal ways to abate the detected shortcomings, [1].
Given the same problem it would be anticipated that individual designers would come up with different solutions based on their individual experience and judgement. Logically the best scheme would be the one giving the lowest overall cost per m^3 litre (gallon) of produce pumped, but although overall costs can be estimated, this is not necessarily a constant figure.
The paper shows a determination method about the pumping installation's average global output in the adjustment situation through hydro – pneumatic loads. It is presented an analyze method about power and economical efficiency of the pumping installations equipped with only one type of pumps.
Many systems for which a centrifugal pump is otherwise suitable may, however, have a variable demand in which case, a certain loss of efficiency may have to be accepted from part of the head or part of the capacity used for control purposes, using either discharge throttling or bypass control. Both methods will inevitably result in power loss, so if economic regulation is of primary importance, discharge regulation by speed control should be investigated first since this is less wasteful of power and there is usually a considerably smaller loss of pump efficiency. Speed control is now a particularly attractive proposition with the increasing availability of variable frequency power units.
The adaptation to variable regimes is done by the hydrophore's usage, [3].
The best power and economical performances will correspond to the pumping solution which ensures the covering of the request area (*Q*, *H*) with the best output. The theoretical considerations are accompanied by the examples concerning an under pressure station from a collective system about supplying with urban water. The mathematical methods may be improved by taking into account all active consumers in the network with simultaneous water requirements, at each moment of the day.

2. PROBLEM DEFINITION

Instead of friction head, and thus total system head, being determined for a single pipeline size or a specific combination of sizes as indicated by optimum flow conditions, it can be instructive to calculate the friction head at the flow rate required for a variety of alternative pipe sizes – spot calculations only being necessary.
A further set of data is then tabulated relating pipe size to cost of pipe work, material costs plus installation costs. Material costs will be approximately proportional to diameter, although actual figures are readily obtainable and should always be used. Material costs include the cost of both pipes and fittings.
Pumping costs should be estimated as direct cost based on a nominal gallon age selected so as to arrive at cost figures of the same order as total installation costs or based on a specific period of working, [2].
Profitability of water distribution activity depends largely on the relationships between operational

capability and service costs, related to supplier's performance, volume of distributed water and effective operating costs. The main variables that influence the total selling price are required investment value, specific consumption of electrical energy for pumping power, unit price of the electrical energy and total volume of monthly consumed water billed. The selection of rehabilitation and modernization measures must rely on market studies results that appropriately establish the quantities of water that may be distributed and billed. Present and future water requirements will be determined based on the analysis of actual operation data and on estimation of future trends in water consumption on national and international levels, [5].

The paper presents the authors efforts to find the optimum solutions to ensure proper servicing of consumers, 24 hours a day, and reduction of operation costs, proposing the following measures:

1. Rehabilitation of pumping stations, as the capacity of supply has to meet the requirements of the consumers and to take into account the present trend in domestic heating and hot water preparation by individual apartment heating units. The rehabilitation activity consists in replacing the present pumping devices with new ones that feature functional characteristics that correspond to the present and future requirements of the consumers. These new devices will exhibit technologies present today on the worldwide market.

2. Modernize the pumping station to ensure the increase of energy efficiency and economic efficiency of the domestic and industrial water supply activity, that is, introduce the process automation for a reduced specific consumption of electric energy and reduced operational workforce.

To solve the optimization problem, the authors developed a general mathematical model that will emphasize the importance of the relationship between energy side and technological side of the analyzed process.

Pump wear will inevitably result in a loss of performance, increase in the direct cost of pumping. In some systems the loss of performance may not be noticed at all as the pump is still apparently working satisfactorily. In other cases it may affect the whole process involved, [4].

Loss of performance is likely to be noticed in the case of centrifugal pumps since the working point can be shifted considerably with a substantial reduction in capacity and efficiency, [6].

Loss of pump efficiency represents a higher cost of pumping and hence an increase in gradient of the total cost curve for the pump compared with its original performance on a gross discharge basis. This can be compared with the total cost curve for a new pump (inevitably with a higher initial cost) to establish a break-even point when the new pump becomes more economic. This is an over-simplification of the problem since it assumes that the efficiencies of the old and the new pump remain constant up to breakeven point. In practice the old pump is likely to suffer a greater loss of efficiency than the new pump, so the breakeven point will occur at a lower future gross discharge figure although this could be offset by a further rise in the initial cost of the new pump in that period.

As far as the pump is concerned, a small increase in demand could very likely be met by increasing the speed of the pump and a large increase by the addition of another pump, with the system characteristics still remaining favourable. A solution, which may appeal in certain cases where a substantial increase in demand is anticipated within a relatively short period, is to install a larger pump run at a lower speed, and subsequently increase the speed and up rate the pump performance to meet rising demand. This may provide a much cheaper overall solution than the purchase of a second pump.

The efficiency of a centrifugal pump depends upon size, speed and type number. Type number (previously referred to as specific speed) is a shape number differentiating (with respect to efficiency and to head and to quantity coefficients) between narrow impellers, small volute throat areas (low type number) and wide impellers, large volute throat areas (high type number).

As a pure number the actual value is of little importance, provided it is used consistently in empirical charts of efficiency and of head and quantity coefficients.

It is, therefore, possible to indicate the change of type of pump by the varying ratio of throat diameter to the impeller diameter. From the aforementioned it can be seen that this ratio is dimensionless and is identified with the type number.

Small quantity high head pumps will have relatively large impeller diameter with narrow outlet to give small flow areas and small quantity. Efficiency will, therefore, be prejudiced by excessive loss due to disc friction.

This is because the large impeller will have a large disc friction compared with the small liquid power consequent upon the small quantity pumped.

This machine will have a low type number and a comparatively low efficiency. At the other end of the range, a pump for a large quantity and a low head will have a wide impeller and a relatively small diameter, so that although the disc friction is not great, there will be prejudice to efficiency by the lack of guidance in the short impeller passages. This pump will have a high type number. Between these limits, the efficiency will reach an optimum.

It is, therefore, possible to plot the effect of type number on efficiency thereby determining the optimum type number and consequently the running speed for a given duty. Furthermore, for certain duties it may be necessary to pump against very high heads. Some sacrifice of efficiency may therefore be necessary to obtain a reasonable number of stages or to avoid the running of two pumps in series.

3. THE APPLICATION OF THE OPTIMIZATION METHOD

The operational regimes for the pumping station supplies (ensemble of active pumps in the pumping station – open level tanks – slopes) will be analyzed taking into account required static loads / piezometric heads, which vary in a pre-established range. This will emphasize the options to increase the designed flow rate, and determine energetic and economic characteristics of the typical operational regimes. One of the goals is to increase the transport capability of gravitational supplies, [3]. To cover for the head losses in water transport of the annual volume W_o that is absorbed from the supply source, the energy required E'_p is:

$$E'_p = F \cdot E_p;\; E_p = \frac{1}{367} \cdot \left(\frac{W_o \cdot H_o}{\eta_h \cdot \eta_a} + \sum_{i=1}^{n} \frac{W_i \cdot H_i}{\eta_h^i \cdot \eta_a^i} \right),\quad (1)$$

$[\mathrm{MWh/year}]$.

The water volume absorbed from sources W_o allowance the maximum flow Q_M and the conventional time of work at maximum capacity T_c:

$$W_o = 3600 \cdot Q_M \cdot T_c\;,\; \left[\mathrm{m}^3\right]. \quad (2)$$

It is appreciated values T_c = (1000 ÷ 1500) hours/year for the conventional time of work at maximum capacity. Constant F is calculated with the form:

$$F = f^{-1} \cdot g;\; f = \sum_i q_i \cdot p(q_i);\; g = \sum_i q_i^{\gamma+1} \cdot p(q_i). \quad (3)$$

The investment in constructions and devices I_p for pressurized transport is:

$$I_p = I_{po} + i_p \cdot N_i\,, [\mathrm{RON}]. \quad (4)$$

Processing the data acquired on the dependence between the investment in pipes I_R and the rated diameter D it follows that:

$$I_R = n_N \cdot L \cdot \left(i_o + b \cdot D^{\alpha}\right), [\mathrm{RON}]. \quad (5)$$

The unitary cost of power energy is different in the vertex period of load curve against basis period:

$$p_e = p_b \cdot \left[1 + \nu_p \cdot (m_v - 1)\right], [\mathrm{RON/MWh}]\;;\qquad \nu_p = \frac{t_{vp}}{t_p};\; m_v = \frac{p_v}{p_b}. \quad (6)$$

The yearly average expenses quotas in pumping station a_{SP}'' and discharge pipe a_R'' take into account different development rates for various economic domains that affect this analysis and all expenses are computed relative to the same moment in time:

$$a''_{SP,(R)} = a'_{SP,(R)} + \frac{1}{T_r},\; T_r = \sum_{k=1}^{t} \left(\frac{1+u_e}{1+r}\right)^k. \quad (7)$$

$$a'_{SP,(R)} = a_{SP,(R)} \cdot \frac{\sum_{k=1}^{t} \left(\frac{1+u_{a,(c)}}{1+r}\right)^k}{\sum_{k=1}^{t} \left(\frac{1+u_e}{1+r}\right)^k}. \quad (8)$$

The objective function of the optimization problem is the economic function Z; it depend on economic function for the investment in pumping station Z_i and the investment in water transport pipes Z_e:

$$Z = Z_i + Z_e\;,\; [\mathrm{RON}]. \quad (9)$$

The economic function for the investment in pumping station Z_i has the following mathematical term:

$$\begin{aligned} Z_i &= a''_{SP} \cdot I_p + a''_R \cdot I_R \\ Z_i &= \frac{a_{SP} \cdot i_p \cdot K_N \cdot m \cdot Q_M^{1+\gamma} \cdot L_R \cdot 1{,}1}{\eta_{SP} \cdot n^{\gamma} \cdot D^{\beta}} + \\ &+ a_{SP} \cdot I_p + a_R \cdot L_R \cdot i_o \cdot n + a_R \cdot a \cdot n \cdot L_R \cdot D^{\alpha}; \end{aligned} \quad (10)$$

The investment in the water transport pipes Z_e can be calculated used the mathematical *form* (*1*):

$$Z_e = p_o \cdot E'_p = \frac{K_N \cdot m \cdot L_R \cdot Q_M^{\gamma} \cdot F \cdot W_o \cdot p_e \cdot 1{,}1}{3600 \cdot \eta_{SP} \cdot n^{\gamma} \cdot D^{\beta}} \quad (11)$$

The annual average total expenses Z will have the forme:

$$\begin{aligned} Z &= a_{SP} \cdot I_p + a_R \cdot i_o \cdot n \cdot L_R + a_R \cdot a \cdot n \cdot L_R \cdot D_n^{\alpha} + \\ &+ a_{SP} \cdot i_p \cdot K_N \cdot K_f \cdot 1{,}1 \cdot \frac{m \cdot L_R \cdot Q_M^{1+\gamma}}{\eta_{SP} \cdot D_n^{\beta} \cdot n^{\gamma}}\;. \end{aligned} \quad (12)$$

The solution for the pair of variables (D, n) is given by the values that minimize the economic target function $Z(D, n)$; mathematically this means:

$$\frac{\partial Z}{\partial n} = 0; \frac{\partial Z}{\partial D} = 0\;. \quad (13)$$

The optimum number of discharge pipes n_o is established by the mathematical formulae:

$$n_o = (K_t \cdot K_f)^{\frac{1}{1+\gamma}} \cdot \left[\frac{a}{i_o} \cdot \left(\frac{\alpha \cdot \gamma}{\beta} - 1\right)\right]^{\frac{\alpha+\beta}{\alpha \cdot (1+\gamma)}} \cdot Q_M \cdot \quad (14)$$

The optimum pipe diameter D_o is calculated depending on flow:

$$D_o = (K_t \cdot K_f)^{\frac{1}{\alpha+\beta}} \cdot \left(\frac{Q_M}{n}\right)^{\frac{1+\gamma}{\alpha+\beta}}, [\mathrm{m}] . \quad (15)$$

The parameters K_t and K_f have the following forms:

$$K_t = \frac{\beta \cdot a_{SP} \cdot i_p \cdot K_N \cdot m}{\alpha \cdot a_R \cdot a \cdot \eta_{SP}} ; \qquad K_f = 1 + \frac{F \cdot p_e \cdot W}{a_{SP} \cdot i_p \cdot Q_M \cdot 3600} . \quad (16)$$

The optimum pump type and dimensions (number of stages and rotational speed) is determined such as it may ensure the required flow rate, with specified head, for the highest value of efficiency; this value will become the reference maximum efficiency for pump selection.

For a given water supply system, with specified operational capacity, the same mathematical model is used, but this time the nominal diameter of the discharge pipe is known; it is possible to calculate an optimal flow Q_{opt}, and then (with imposed conditions) the minimal annual average total cost. Then, comparing with the required supply capacity Q_{Ad} , and analyzing previous data, the measures for modernizing and improving the studied water supply system may be chosen.

The maximum pump efficiency, for a certain technological level, depends on its size. This factor is determined by the nominal flow Q_o, and by the rotor geometry. Another parameter is specific speed:

$$n_q = n \cdot Q_o^{1/2} \cdot H_o^{-3/4} \cdot z^{3/4}, \quad (17)$$

that depends on the nominal head H_o, rotational frequency n and number of stages z. It follows that for the maximum theoretical output of the best pumps:

$$\eta = (\eta_o - k_Q \cdot Q_o{}^{\alpha}) - k_\eta \cdot \left[\log\left(\frac{45}{n_q}\right)\right]^2, \ [\%]. \quad (18)$$

The reduction of the electric power Δe is calculated depending on electric power specific consumption planted e and electric power specific consumption present e_a with the following mathematical term:

$$\Delta e = \left(1 - \frac{e}{e_a}\right) \cdot 100 , \ [\%] . \quad (19)$$

The energy economy it is expressed depending on the unitary specific through the mathematical form:

$$\Delta E = \frac{W_o \cdot e_a}{100} \cdot \Delta e = W_o \cdot (e_a - e) , \ [\mathrm{MWh/year}]. \quad (20)$$

The recuperation time of minimum investment $T_{RI\ min}$ and maximum investment $T_{RI\ max}$ can be calculated depending on total investment I, the reduction of the electric power Δe and electric energy unit cost p_e likeness:

$$T_{RI\ min} = \frac{I_{min}}{\Delta E_{max} \cdot p_{e\ max}} , \ [\mathrm{years}]; \qquad T_{RI\ max} = \frac{I_{max}}{\Delta E_{min} \cdot p_{e\ min}} , \ [\mathrm{years}]. \quad (21)$$

4. EXPERIMENTAL RESULTS

The optimization method is applied in the CUG Iasi pumping station for drinkable water. The pumping station is equipped with two 8NDS pumps and rotational speed of n = 1450 rpm.

The proposed analysis method is based on the system's mathematical modelling, simplified by analytic specific features of its components and the automated data processing system.

Using several original mathematical algorithms, authors developed a computer program for analysis and graphics that calculates the functional parameters of the pumping station as well as the available consumer parameters. It is selected also the best pump for the water supply of comsumers.

The computer program has analysed eight pumps variants fot the replacement of 8NDS pumps: Wilo - IL 250-160/4; Wilo IL 250-200/4; KSB CPK/HPK 300-500-504; NB, NK 150-500/489, ISO 9906 Annex A,Grundfos; NBG/NKG 150-125-250/248, 2 poli, ISO 9906 Annex A, Grundfos; NB, NK 150-125-250/248, 2 poli, Grundfos; CPK, CPKN, HPK 200-500/460, KSB; CPK, CPKN, HPK 200-500/480, KSB.

It is obtained the following diagrams: head depending on flow rate H = f(Q), *fig. 1*; pumping outturn depending on flow rate η = f(Q), *fig. 2*.

The annual average total expenses Z is calculated for the following coefficients: m = 1,6 . 10^{-3}; β = 5,09; γ = 1,97; i_o = 1,9 . 10^6; a = 4,5 . 10^6; K_N = 9,81; η_{SP} = 0,75%; α =2,75; a_R = 0,0355; i_p = 2,2 . 10^6; a_{SP} = 0,058; r = 0,08; T_r = 22,75; u_a = 0,05; u_c = 0,03; u_e = 0,06.

The Unitary cost of energy "of basis" p_b = 350 RON/MWh and the unitary cost of energy "of top" p_{vmax} = 150 RON/MWh.

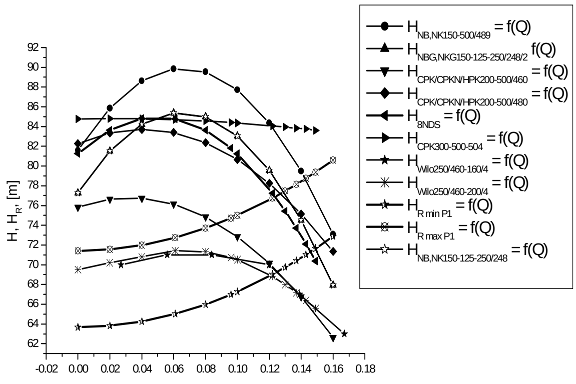

Fig. 1. Head variation depending on flow rate for pumps $H = f(Q)$ and pipes network $H_R = f(Q)$

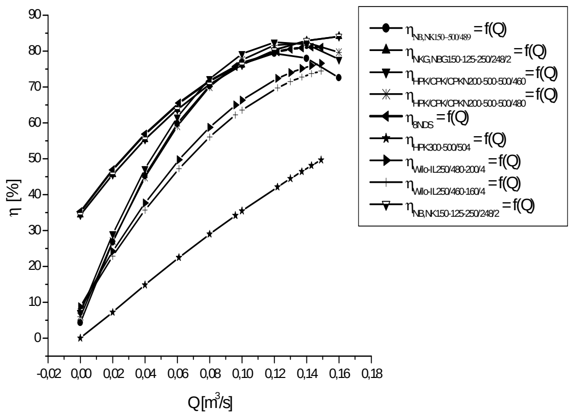

Figure 2. Outturn variation depending on flow rate $\eta = f(Q)$

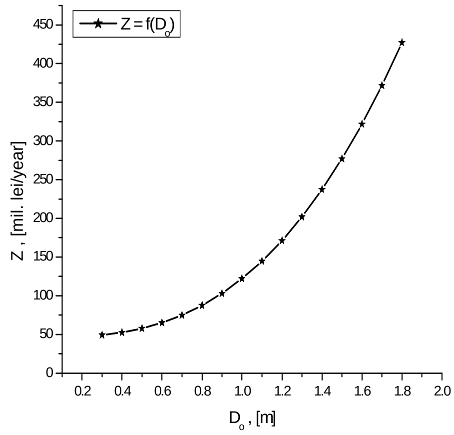

Fig.3. Annual average total expenses Z variation depending on diameter D_o

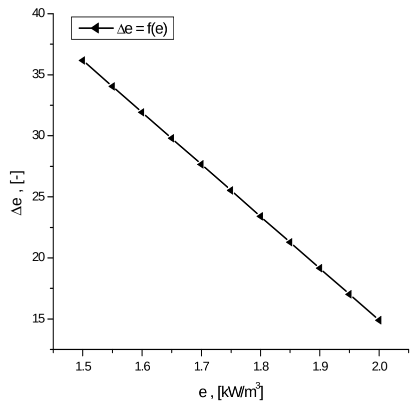

Fig.4. Energy consumption reduction Δe depending on electric power specific consumption planted e

Daily average time of water pumping “of basis” head turn t_p is estimated at (10 ÷ 15) hours. Daily average time of water pumping “of top” head turn t_{vp} is estimated at (2 ÷ 6) hours.

The hydraulic system has the parameters with values: Q_M = 0,2 m^3/s; W_o = 2,04.10^6 m^3/year; F = 0,82; L_R = 700 m.

The optimum number of discharge pipes n_o = 1 and the standard values for the optimum pipe diameter D_o = 0,25 ÷ 0,4 m, using the mathematical *terms* (*14*) and (*15*) are established.

The annual average total expenses Z is analysed for pipes with diameter D = 0,1; 0,2; 0,3; ... ; 1,8 m, (*fig. 3)*.

The energy consumption reduction Δe is established depending on electric power specific consumption planted e, (*fig. 4)*.

It is calculated the electric power economy ΔE depending on electric power specific consumption planed e; it is allowanced water volume values pumping minimum, average and maximum, (*fig. 5)*.

The investment’s recuperation time T_{RI} is calculated for the minimum W_{omin} = 1,8 . 10^6 m^3/year and maximum volume W_{omax} = 2,7 . 10^6 m^3/year values of water transported.

The electric energy unit cost varys between $p_{e\,min}$ = 330 RON/MWh and $p_{e\,max}$ = 600 RON/MWh values.

Figure 6 shows the variation of the investment’s recuperation time minimum and maximum, acordance *form* (*21*).

The total investment I is valued between (10^6 ÷ 2 . 10^6) RON for this analysis.

Figure 7 represents the variation of the investment’s recuperation time T_{RI} for the minimum I_{min} and maximum investment values I_{max} depending on total investment I, electric power economy ΔE_{med} and electric energy unit cost p_e.

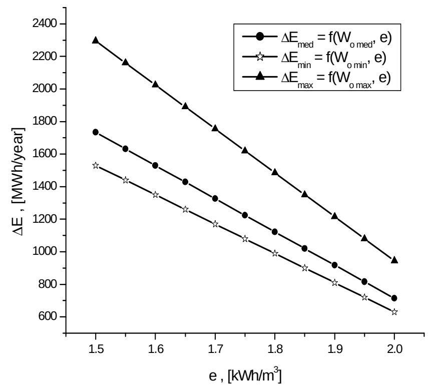

Fig.5. Electric power economy ΔE depending on electric power specific consumption planed e

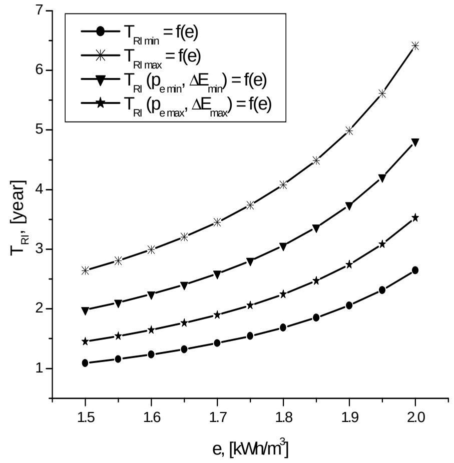

Fig. 6. Investment's recuperation time T_{RI} depending on total investment *I*, electric power economy ΔE and electric energy unit cost p_e

5. CONCLUSIONS

The replacement of the existent equipment, that is obsolete from physical and technological point of view, must be done with new equipments with performances that will meet the requirements of an optimum operation from both energetic and economic perspectives. The water transport and distribution network must have the capability to meet the requirements of the consumers.

It is recomandated the avoidance of the pumps work outside of (0,11 ÷ 0,14) m^3/s flows and maintain the outturn between (80 ÷ 82) % values.

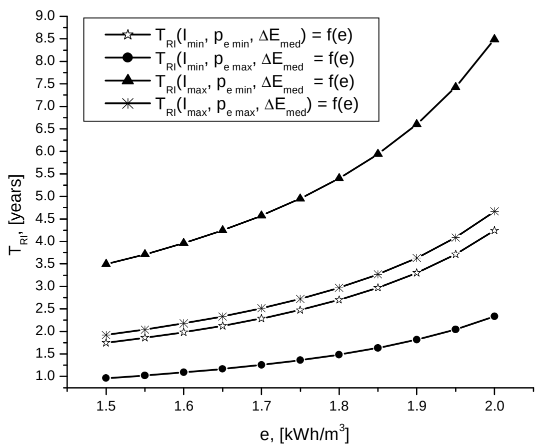

Fig.7. Investment's recuperation time T_{RI} depending on total investment *I*, electric power economy ΔE_{med} and electric energy unit cost p_e

The computer programs created by authors permit the selection of the best pumps for the water supply of hydraulic system. The following variants are available: Grundfos/NBG, NKG 150-125-250/248/2; Grundfos/NB, NK 150-125-250/248; KSB/CPK, CPKN, HPK 200-500/480.

The beneficiary of project S. C. APAVITAL S. A. Iasi will choose a variant depending on the price acquisition, the speed, the outturn of the pumps; the cost price of the investment in avatars that will be made in the pumping station CUG Iasi are very important.

The insurance of efficient operation relies on automatic supervision and control of pumping installation, as well as automatic adjustments to variable consumer requirements.

Variable demand represents a shift in the working point of the pump, which apart from the mechanical control involved, can seriously affect the efficiency of a centrifugal pump.

This may favour the choice of a pump which has variable delivery at more or less constant efficiency or, if the capacity required is outside the normal range of such pumps, the use of two or more pumps in parallel or a roto-dynamic pump with more favourable characteristics.

The investment's recuperation time is advised to be (1 ÷ 8,5) years.

The research results are used for design optimization of the water supply installation for areas with various relief forms. The proposed method for the optimization allows a reduction with 10 ÷ 15 % of the energy consumption required to operate the pumping station – network – consumers ensemble.

6. ACKNOWLEDGEMENTS

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