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Optimization Of Operating Modes of Pumping Stations Equipped With Parallel-Operated Centrifugal Pumps

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Abstract:

The article examines the issues of reducing head losses and optimizing electricity consumption in pumping stations operating in parallel pump mode. A method is proposed to increase energy efficiency by reducing the hydraulic resistances of the pipeline system for parallel-operated pumps and selecting the pipe diameter at an economically optimal value. Using the example of three D1600–90 pumps, capital and operational costs were analyzed for various pipe diameters, and optimal options were identified. The calculations show that correct selection of the pipe diameter ensures that the pumps operate within their optimal working range and allows a significant reduction in electricity consumption over the season.

Keywords: pumping station, parallel-operated pumps, head loss, hydraulic resistance, pipe diameter, energy efficiency, optimal operating mode, electricity consumption.

Introduction

Currently, in the Republic of Uzbekistan, 48% of the 1,687 operating pumping stations are equipped to allow parallel operation of pumps (i.e., multiple pumps simultaneously supplying water to a single pressure pipeline) [1]. Although operating multiple pumps on a single pressure pipeline can reduce costs associated with large-diameter pipelines, this mode of operation results in increased electricity consumption due to head losses. To prevent this, the operation of pumping stations must be optimized by selecting pumps appropriately, adjusting their operating modes, and choosing the optimal diameters of internal pressure pipelines, including pipes and check valves.

The optimization of operating modes for parallel-operated pumps (i.e., multiple pumps operating simultaneously on a single pressure pipeline) is carried out using two approaches: improving the hydraulic characteristics of the pipeline system and adjusting the operating modes of the pumps [2], [3].

Minimizing head losses in parallel pump operation is an important issue, as the parallel operation of pumps serves to increase the supplied water volume, while head losses can significantly reduce the efficiency of water delivery. Therefore, this issue must be addressed together with the determination of the pumps' optimal operating modes.

Methodology.

What this paper adds This paper uses a hybrid analytical–economical optimization to find the best pumping station operation with respect to overall cost for parallel operated centrifugal pumps. Potential Methodology: The methodology is based on hydraulic analysis of head losses in pressure pipelines and economic assessment of capital and operational costs for the alternative pipe diameter. First of all, the hydraulic energy losses due to friction and local resistances in the pipeline system are determined by the existing hydraulic resistance equations, considering pipe length, diameter, roughness coefficient, operating time and pump discharge [4]. With these calculations, it is possible to define the extra energy necessary to overcome head losses in a parallel operating pump. Then, the impact of decreased head losses on pump operating points is assessed through the examination of displacement of the combined pump and pipeline characteristic curves, which guarantee that pumps work within their optimal range of efficiencies.

Simultaneously, an economicevaluation is performed to find the favourable pipe diameter [5]. Annual capital costs (pipe purchase and installation prices, discount rates, depreciation allowance, maintenance costs) and operational costs (electricity consumption, calculated from target data using the relevant tariff) are calculated for each diameter option. One arrives at the total annual cost per meter of pipeline as the total of capital and energy related costs as shown in the above-equation [6]. The best solution is determined as the one that shows all the lowest cost out of the total and the maximum pump efficiency through the rest of the analysis of all these values which then has been repeated for several diameters assuming each time a constant desired water flow rate. The application of the methodology is demonstrated through a case study on three parallel D1600–90 type pumps with actual technical and economic parameters of pumping stations in Uzbekistan [7]. This combination of hydraulic reliability and economic feasibility of the proposed optimization strategy

Result and Discussion.

The energy expended to overcome the hydraulic resistances in the pipeline system can be determined using the following equation.

$$\Delta E_{H,hyd.i} = 9{,}81 \cdot Q_i \cdot \Delta H_i \cdot \frac{T}{\eta_i} = 9{,}81 \cdot Q_i \left[0{,}0827 \left(\sum \xi_m + \lambda \frac{L_{pipe}}{D_{pipe.i}}\right) \frac{Q_i^2}{D_{pipe.i}^4}\right] \frac{T}{\eta_i} \qquad (1)$$

where, $\sum \xi_m$– local resistance coefficients in the pipeline, L_{pipe}, $D_{pipe.i}$ – the length and diameter of the pipe, T – the operating time of the pump on the pipeline, in hours, and λ – the hydraulic coefficient of the pip.

This equation can be simplified and written in the following form.

$$\Delta E_{H,hyd.i} = K_1 \frac{Q_i^3}{D_{pipe.i}^4} \frac{T}{\eta_i} \qquad (2)$$

where $K_1 = 0{,}811 \left(\sum \xi_m + \lambda \frac{L_{pipe}}{D_{pipe.i}}\right)$

The negative effect of head losses in the pipeline system of parallel-operated pumps on operating efficiency can be observed from the pump operating schedule shown in Figure 1.

When the pumps operate at the overall working point A1, their characteristics are determined at points 1, 2, and 3. It can be seen that the pumps, with the exception of pump 3, operate outside the optimal working range and have low efficiency values [8]. If measures are taken to reduce the head loss ΔH in the pipeline system, the overall working point of the pumps shifts to point A2, and their characteristics are then determined at points 4, 5, and 6. In this case, it can be observed from the graphs that all three pumps operate within their optimal working range, and their efficiency values are higher.

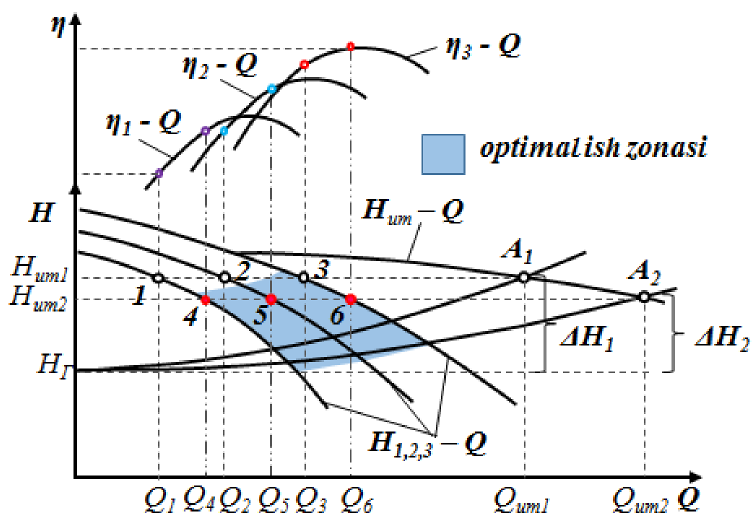

Figure 1. Effect of head loss on the operating mode of parallel-operated pumps

From the above equation (2), it can be seen that the value of $\Delta E_{H,hyd}$ depends on the hydraulic resistances and the pipe diameter. That is, to reduce the energy wasted, it is necessary to increase the pipe diameter and decrease hydraulic resistances. However, selecting an excessively large pipe diameter increases its capital costs, making the use of such a pipe economically unjustified [9]. Taking this into account, the economically optimal diameter of the pipe and the equipment and fittings installed in it can be determined based on the minimum of the total costs, calculated using the following equation.

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$$PC_i = CE_i(d + c + r) + t_e \cdot K_1 \frac{\Delta t}{\eta_i} \frac{Q_i^3}{D_{pipe.i}^4} \rightarrow min \qquad (3)$$

where, PC_i – annual costs per 1 meter of pipe, CE_i - costs for purchasing and installing 1 meter of pipe, *d* – discount rate used for financing the pipe construction, ccc – depreciation allowance, *c* – depreciation allowance, *r* – current maintenance costs, and, t_e – electricity tariff.

The above equation (3) is used to determine the minimum of PC. This involves calculating capital and operational costs for various pipe diameters at a constant water flow rate and selecting the diameter that corresponds to the minimum total costs [10].

Based on this methodology, calculations are presented for optimizing the parallel operation of three D1600–90 pumps (pipe diameter = 540 mm, n =1450 rpm) to ensure minimal energy losses and determine the economic efficiency of the system.

For the calculations, the pipe length is taken as L_{pipe} = 1.0 m, and the pipe roughness coefficient is 0.012. The total water delivery capacity of the three pumps is Q_{total} = 1.02…1.36 m³/s, with head varying in the range *H* = 88.5…96.7 m.

The operating time of the pumps is *T* = 1500 hours, and the electricity tariff is assumed to be t_e = 1000 UZS/kWh.

The calculations are carried out using equations (2) and (3).

The indicators for calculating PC_i are determined in the following order.

The capital costs for the pipes, CE_i, are taken based on the prices in effect in the Republic of Uzbekistan in 2024. These values are adopted according to information from the construction portal Stroyka.uz, which provides prices for pipes from Metall Asia LLC [11].

Annual investment payments for capital funds may include bank interest, investor-required returns, discount rates, and other forms. Currently, these payments range widely from 8% to 25%, with most values between 10% and 15% [12]. Therefore, the value of *d* is taken as 0.12.

The normative amounts of depreciation allocations for depreciation expenses are accepted as *c = 8 %* based on the depreciation expenses implemented in the Republic of Uzbekistan in 2022 [13].

The allocations for current maintenance costs are accepted as *r = 7 %* according to another applicable regulatory document [14].

The results of the calculations are presented in Table 1.

Among the four options considered in the calculations, the option with a pipe diameter of 900 mm shows the lowest costs. However, in the case of a 1000 mm diameter, although the capital costs are slightly higher, the amount of lost electrical energy is lower. Therefore, if this option meets the investment conditions, it is advisable to select it.

Table 1.

Determination of Optimal Parameters in Parallel Pump Operation

D_{pipe}, mm	*CE*, thousand soms	K_1	*Q*, m^3/s	η	*H*, m	$\Delta E_{H,hyd.i}$ kW·h	*PC*, UZS
800	1690	0,136	1,02	0,83	96,7	635,44	1091740
900	1893	0,135	1,08	0,84	94,8	463,03	974140
1000	2104	0,133	1,22	0,85	91,1	426,22	994300
1100	2315	0,130	1,36	0,84	88,5	403,60	1028650

ased on the calculations presented above, the operating graph of the parallel operation of three D1600–90 pumps (pipe diametr = 540 mm, *n* = 1450 rpm, ΣL_{pipe}=*2800 m*) and the head characteristics of the pipeline system for various options are constructed to determine the pump parameters (Figure 2).

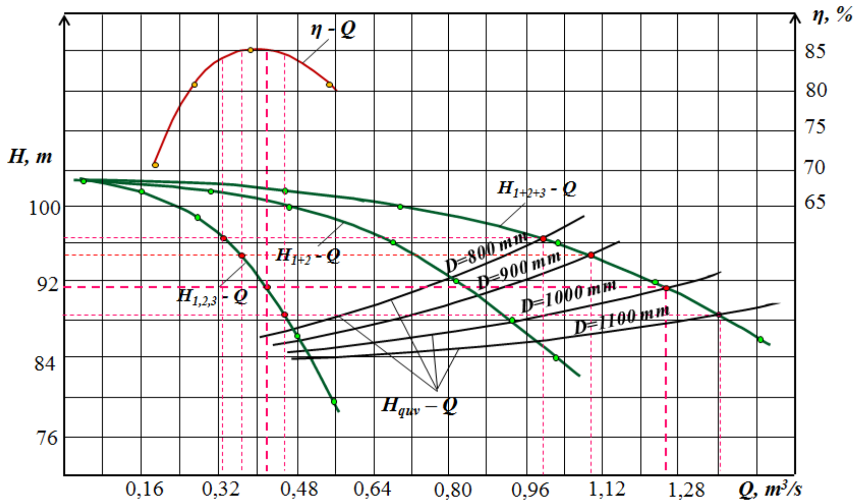

Figure 2. Determination of the operating mode of parallel-operated D1600–90 pumps in pressure pipelines of different diameters

Based on these graphs, the amount of electrical energy consumed to deliver the same water volume *V* = 8,000,000 m³ over the season is calculated for two options, with pressure pipe diameters of *D* = 900 mm and *D* =1000 mm.

$$E_{900.} = \frac{V \cdot H}{367 \cdot \eta} = \frac{8000000 \cdot 95}{367 \cdot 0.848} = 2442034\ kW \cdot h$$

$$E_{1000.} = \frac{V \cdot H}{367 \cdot \eta} = \frac{8000000 \cdot 91.4}{367 \cdot 0.85} = 2343965\ kW \cdot h$$

In this case, the values of *H* and η are obtained at the coordinates of the operating points where the pump head characteristics intersect with the head characteristics of the pressure pipelines for *D* = 900 mm and *D* = 1000 mm [15].

Conclusion.

This study shows that the economic hydraulic (EHD) optimal design with co-iteration of hydraulic and economical parameters for parallel pumping station can improve their efficiency significantly. The results confirmed the excessive head losses that pressure pipelines transmit, moving pump operating points away from the maximum efficiency zone and resulting in higher electricity consumptions, while their correct pipe diameter can reduce hydraulic resistance and is capable to work on their maximum efficiency range. The case analysis of three D1600–90 pumps indicates that increasing the pipeline diameter from values that were validated to be suboptimal up to economically justifiable larger diameters leads to significant energy savings over the entire operating season, and reductions of electricity consumption of this spatial extent equate to considerable economic savings under current tariffs. This behaviour suggests that a life cycle cost perspective that balances capital expenditure with long term operational performance should be applied when making decisions on investment in tying pumping station modernisation to least initial capital expenditure. From a practical perspective, the proposed approach supplies water management agencies and engineers with an accurate decision making instrument for the design and upgrading of pumping station pressure pipelines under parallel operation conditions. Future work should build upon this approach including the integration of variable speed drives, varying seasonal demand profiles, and real time control strategies, and should be validated for different pump types and at larger scale pipeline networks to improve the generality and robustness of the methodology.

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