The Use of Variable Frequency Drives of Centrifugal Pumps atthe Pumping Station

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Abstract: The article presents the experience of operating real pumping stations in urban water
supply. The basic principles of practical modeling of the operation of a group of pumps for a
common load are considered. The main errors in the modernization of pumping equipment of
water supply units are analyzed.

Introduction
Today, many pumping stations (PS) are equipped with a group or individual speed controller of the
pump drive motor. In most cases, the rotation speed controller is an electronic device that controls the
frequency of the supply voltage of the electric motor of the pump unit (variable frequency drive).
Firms distributing variable frequency drives (VFD) have an active policy of introducing their products
into the energy product market. The fashion for high technology leads to the fact that sometimes a
VFD becomes an end in itself, and not a means of achieving efficient operation of the station. Practical
experience of using a VFD shows that there are specific operating features that should be taken into
account when a group of controlled pumps as part of a PS operates in conjunction with unregulated
pumps.
   The task of optimizing energy consumption is to ensure the operation of such a number of pumping
units and such a combination of their parameters so that the efficiency of the PS is as high as possible.
We will consider the overall efficiency to be a criterion for the quality of the PS operation, although in
practice, a part of the reporting documents is drawn up according to such an indicator as the specific
energy consumption per cubic meter of water supplied to the consumer — specific energy
consumption.

Methods
Satisfaction of both indicators simultaneously is impossible. The desire to reduce the specific energy
consumption often leads to the fact that the impeller pumps installed on the PS are operated outside
the operating range in the area of high flows, i.e. in overload modes. This is accompanied by a number
of negative consequences both for the pumps themselves and for the PS as a whole [1]. Fig. 1 shows
the characteristic of a D4000-95 centrifugal pump with an impeller diameter of 825 mm at a reduced
rotation frequency ($n=$ 730 rpm) reproduced according tothe catalog [2]; the specific energy

consumption $E = N/Q$ is additionally plotted, where N — power on the pump shaft, Q — flow rate. A decrease in this indicator from 0.17 kW·h/m^3 with an optimal Q = 3300 m^3/h to 0.155 kW·h/m^3(only 9%) will be accompanied by an increase in flow rate to 4400 m^3/h and a decrease in pump efficiency by 5%. The characteristic shows that at feeds exceeding the optimum, the NPSH Δh_d sharply increases. By extrapolating the dependence Δh_d to Q = 4400 m^3/h, we obtain Δh_d of 9.5 m. Type D pumps are usually installed with a positive suction lift and a minimum positive suction head, therefore, the available NPSHdoes not exceed 8 ... 9 m. Thus, the pump is guaranteed to fall into the mode of developed cavitation, in which intense erosion of the surfaces of the wet part will occur. An additional decrease in the pump life will occur due to a sharp increase in the radial force of hydraulic origin acting on the shaft and bearings.

In addition, the criterion of specific energy consumption does not allow an objective comparison of PSs with different pressures in the discharge line: for PSs with high pressure, this indicator will always be higher. It is advisable to use this criterion as a reference indicator in relation to the same PS at different periods of its operation. Therefore, from both the technical and economic points of view, when comparing enterprises, one should base on the general efficiency of the station, which is the ratio of the useful hydraulic power to the consumed electric power. The higher this indicator, the higher the technical and economic efficiency of this pumping station.

One can determine the overall efficiency of the pumping station by the ratio

$$\eta_{PS} = \eta_p \eta_m \eta_{vfd}, \quad (1)$$

where η_p is the efficiency of the pump group, η_m is the efficiency of the group of electric motors, η_{vfd} is the efficiency of the power supply, including the frequency control.

PS operating personnel can affect the efficiency of the pumping group only by turning on or off the pumps and setting certain parameters of their work. To solve the task of optimizing energy consumption, we briefly outline the basic principles of hydraulic calculation using simple hydraulic systems as an example, in which all components are connected in series in a single line.

The main purpose of the hydraulic calculation is to determine the parameters of the operating modes, i.e. flow rates and pressures for the hydraulic system as a whole and for its individual elements under typical operating conditions. These parameters can be determined by solving the system of equations:

$$\begin{cases} \Sigma H_s = f(Q), \\ H_r = \varphi(Q) \end{cases} \quad (2)$$

where ΣH_s — total head of elements that are sources of energy, H_r — the required head of the hydraulic system. According to the energy conservation principle at the equilibrium state of the system (i.e., with the steady motion of the fluid flow), these heads must be equal to each other.

The sources of energy can be pumps and the initial elements of the system: various kinds of capacities and collectors. We believe that a pump installed in the considered simple hydraulic system develops a head H, depending on the flow rate Q, and the first element has a head H_f. Then, in the general case, the head of energy sources

$$\Sigma H_s = H(Q) + H_f, \quad (3)$$

The dependence H_r, usually called the hydraulic system characteristic, is written as

$$H_r = H_l + \Sigma h = H_l + kQ^2 \quad (4)$$

where H_e is the pressure of the last element, Σh is the pressure loss on the intermediate elements, which for the turbulent regime in the quadratic flow zone [3–20] are proportional to the squared flow rate, k is the proportionality coefficient.

The head of the end elements H_f and H_l in equations (3) and (4) represent the specific potential energy of the liquid, referred to the unit of its weight and having the dimension "meter". This energy consists of two components: potential energy z equal to the geometric (geodesic) height of the liquid level in the tank (for the collector z is the height of its axis) above a certain reference plane, and the pressure energy $p/(\rho g)$, , where ρ is the density of the liquid, g is the acceleration of gravity. When carrying out hydraulic calculations in most cases, pressure is understood not as absolute, but as manometric pressure, and the reference plane is taken in such a way that for the first element of the hydraulic system $z_f = 0$.

The system of nonlinear equations (2) is difficult to solveanalytically, but it is solved quite simply with the use of graphical method. The dependence of the head of the energy sources (3) either coincides with the characteristic of the pump, or differs from it by a constant value of H_i. The characteristic of the hydraulic system (4) is a quadratic parabola with a vertex on the head axis at a point with coordinate H_f. The intersection point of these characteristics on the graph allows you to determine the parameters of the operating mode of the pump (flow and head). Knowing the flow rate in the hydraulic system is equal to the pump flow rate, it is possible to determine the pressure drop on any of its elements.

A similar approach can be implemented when performing a hydraulic calculation for any complex hydraulic system with branches. In this case, one can compose equations similar to equations (3) and (4) for energy sources and for all of the elements of the hydraulic system, and solve the resulting system of two equations graphically or numerically using a computer with appropriate programs.

For some complex hydraulic systems withloop lines, other techniques are used.

Let us consider the operation of the PS in the water supply system, using the simplified model as an example. Water flows from an open or underground reservoir (depending on the type of PS) into the intake manifold. The pumping units installed on the PS take this water from the suction and supply it to the discharge manifold. We suppose that two identical pumping units are installed on the PS. The hydraulic losses in the pipelines connecting the pumps to the manifolds are neglected due to their insignificance compared to losses in the rest of the hydraulic system. Pressure pipelines are connected to the discharge manifold, supplying water to the next stage of the heating system or to the water supply system of a city or industrial enterprise, i.e. to consumers. We believe that the serviced hydraulic system consists of two identical pipelines that connect the pressure manifold of the PS with a reservoir located near consumers. The characteristic of such a hydraulic system containing two parallel pipelines has the form of equation (4), as well as the characteristic of a simple hydraulic system.

Fig. 2 shows the layout of this PS and the hydraulic system it serves.

In the operation of each hydraulic system, it is possible to distinguish characteristic operating modes. Sometimes this is one main mode, but moreoften, there are several. For the water supply system, one can distinguish three regimes, shown in Fig. 3: daytime, nighttime, and peak. In most cases, these modes are ensured by setting the corresponding pressures in the discharge manifold.

The control of the PS operation modes according to a given pressure in the discharge manifold is apparently explained by the relative cheapness and wide distribution of pressure measuring devices (gauges, vacuum gauges, pressure sensors, etc.), as compared to flowmeter devices. Pressure monitoring devices are the basis of measuring systems that allow monitoring and controlling the operation of hydraulic systems and their elements and creating automatic control systems for the operation of the entire station. Often, these tasks are solved without due consideration of factors such as the efficiency and reliability of the machines and other devices that make up the hydraulic system, as well as the PS as a whole. The lack of proper consideration of these factors relates primarily to the

operation of pumping units. Let us explain what the reduction in profitability and reliability of their work is.

Let each of the two pumps at the rated speed of rotation have dependences of head, efficiency and NPSH, respectively, H, η and Δh_a, as shown in Fig. 4. Since they are connected to the manifolds in parallel, when the pumps work together with the same pressure, their flow rates add up, and the pressure characteristic of the PS will have the form H_Σ. The intersection point of the characteristics of the hydraulic system H_r and the pump station H_Σ will determine the operating point **A** of the entire system, and will determine the operating point **M** and the operating parameters of each of the pumps, which will correspond to the Q_M flow rate. By the way, this mode is the main or one of the main ones, according to which the selection of pumping equipment for PS is carried out.

We suppose that in a given period in a hydraulic system it is required to have a flow rate less than Q_A, for example, $Q_B = Q_F$. If there is no VFDs, this mode is achieved by partially closing the valve (or several valves) on the pressure part of the hydraulic system, as a result of which the part of the head developed by the pumps, determined by the **BF** section, will be lost on this valve (these valves). The PS will enter the operation mode, determined by point **F**, and the operating mode of the pumps will move to point **N**. The efficiency of the PS will decrease in proportion to the ratio H_B / H_F, which characterizes the decrease in the PSefficiency with this method of regulation. However, the operating modes of pumps will remain within the range of their intended use, limited to lines H_l on the left and H_r on the right(Fig. 4), which will not adversely affect the reliability of their work.

If there is a VFD on the PS, two options of its application are possible with respect to the considered circuit (Fig. 2):

1. Only one pump has VFD.
2. Both pumps have VFDs.

Fig. 4 shows the operation of the PS according to option 1. The dispatching service sets the pressure (head) in the discharge manifold corresponding to mode **B**. The speed of the VFD decreases until the PS characteristic H_Σ' passes through point **B** on the characteristic of the hydraulic system; in this case, the head and efficiency of the pump with VFD will take the position of H' and η'. The parameters of the operating modes of each pump can be determined by drawing a horizontal line through point **B** and finding the points of its intersection with the pressure characteristics of both pumps. These points will be **C** for unregulated and **D** for regulated pump. Both modes are completely unacceptable for operation and are far from the operating range, especially mode **C** for an unregulated pump. The overall efficiency of the PS due to a decrease in the efficiency of each pump will not be higher (rather, lower) than when regulating the valve.The unregulated pump will work in the developed cavitation mode or will not be able to work at all; both pumps will undergo increased wear.

Fig. 5 shows the PS operation in option 2. The speed of both pumps is simultaneously reduced until the PS characteristic H_Σ' passes through the same given point **B** on the characteristic of the hydraulic system, while the dependences of the head and efficiency of the pumps will take the position of H' and η'. The parameters of the operating modes of the pumps are determined by the position of point **C** on the pressure characteristic H', which is in the range of the appropriate use of the pump near the maximum efficiency (or coincides with it). The operation of the pumps in this mode is not associated with any negative consequences, and the efficiency of the PS operation will be maximal. However, for the implementation of this operational option, it is necessary to solve the synchronization problem when changing the speed of the pump units while regulating the PS.

Results

For real PS with a large number of pumping units, the specified mode can be obtained not only with the help of one or several pumps with VFDs, but also by turning on or off unregulated pumping units. The number of possible options for operating conditions and the corresponding design schemes at a

given pressure (head) in the discharge manifold will be much more thantwo. Moreover, when individual variable frequency drives of pumping units simultaneously operating as part of the PS, inconsistency of their dynamic characteristics is manifested, which is accompanied by a violation of the design operation modes of the PS. Nevertheless, in order to increase the cost-effectiveness and reliability of the operation of pumping equipment at the PS, it is necessary to perform the hydraulic calculations at least for the most characteristic modes of its operation and subsequently use the obtained results in the practical implementation of these modes.

The economic effect of performing hydraulic calculations and subsequent accounting and implementation of their results can be significant at relatively low cost. This is proved by the experience of examining one water supply PS near Moscow. At the examined PS, despite the use of a variable frequency drive for most of the pumping units, the overall efficiency of the station over a significant period of operation turned out to be 52%. There is reason to believe that the quality of the PS operation can be raised to at least 65%, while ensuring both an improvement in the technical performance of the station and significant savings in energy costs.

Discussion
Summing up, we note that the use of a variable frequency drive is an urgent and promising direction in solving the problems of economical operation of such energy facilities as pumping stations. However, in the practice of using such a drive, caution should be taken because a change in the pressure characteristic of a regulated pump (or a group of regulated pumps) leads to a redistribution of the flow rate of the rest of the pumps operating in this hydraulic system. The maximum effect of the variable frequency drive use can be obtained by taking into account the results of hydraulic calculation of the hydraulic system under typical operating conditions.
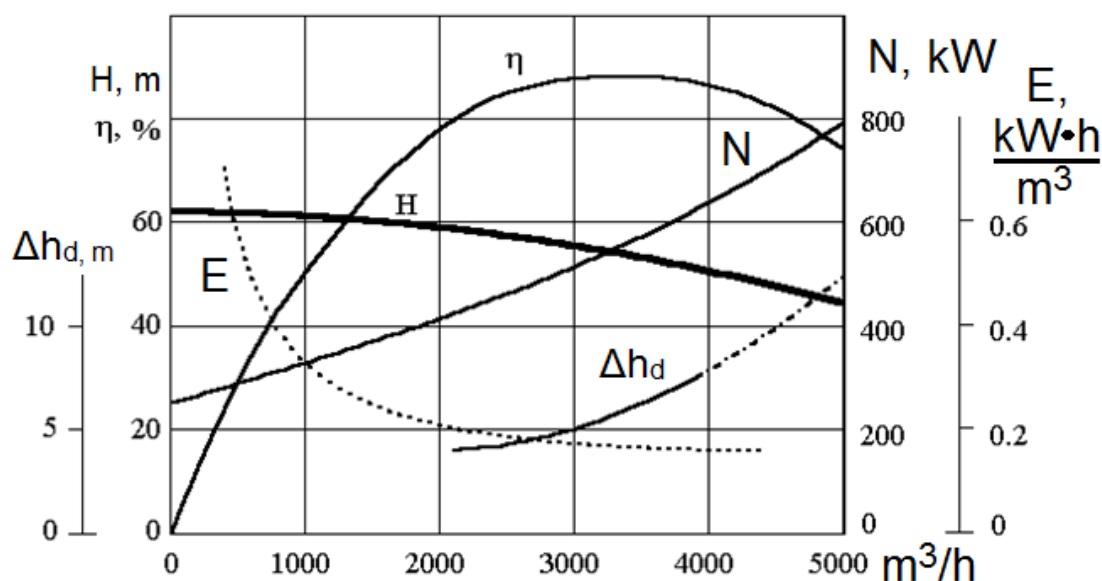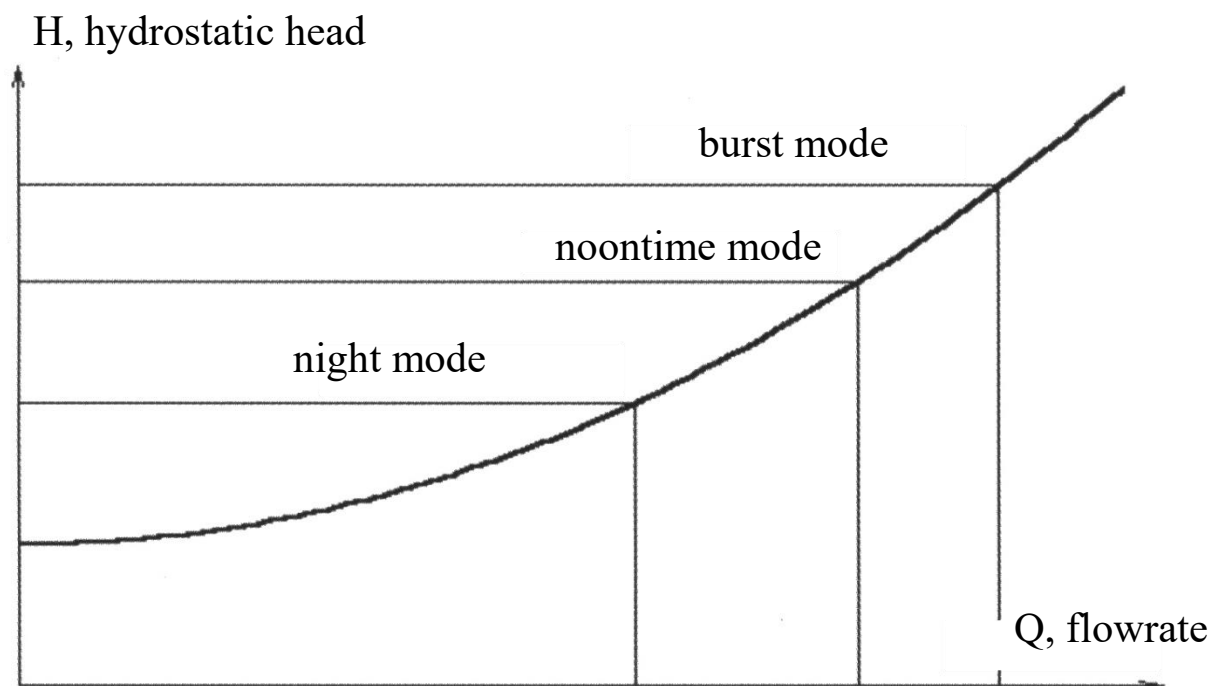

Figure 1. Pump characteristic and specific energy consumption dependence.
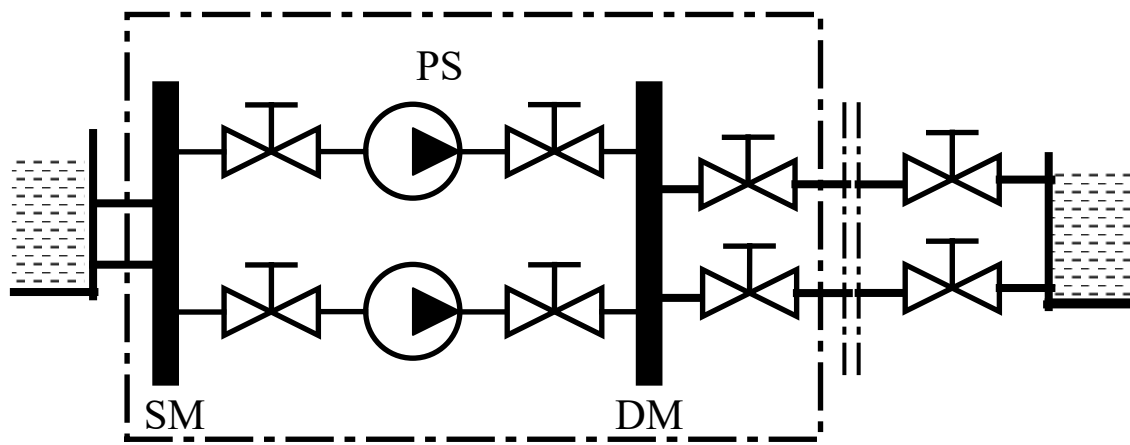
PS — pumping station; SM and DM — suction and discharge manifolds

Figure 2. Diagram of PS and hydraulic system.

Figure 3. Qualitative head characteristic of the city water supply network and its typical modes of operation.
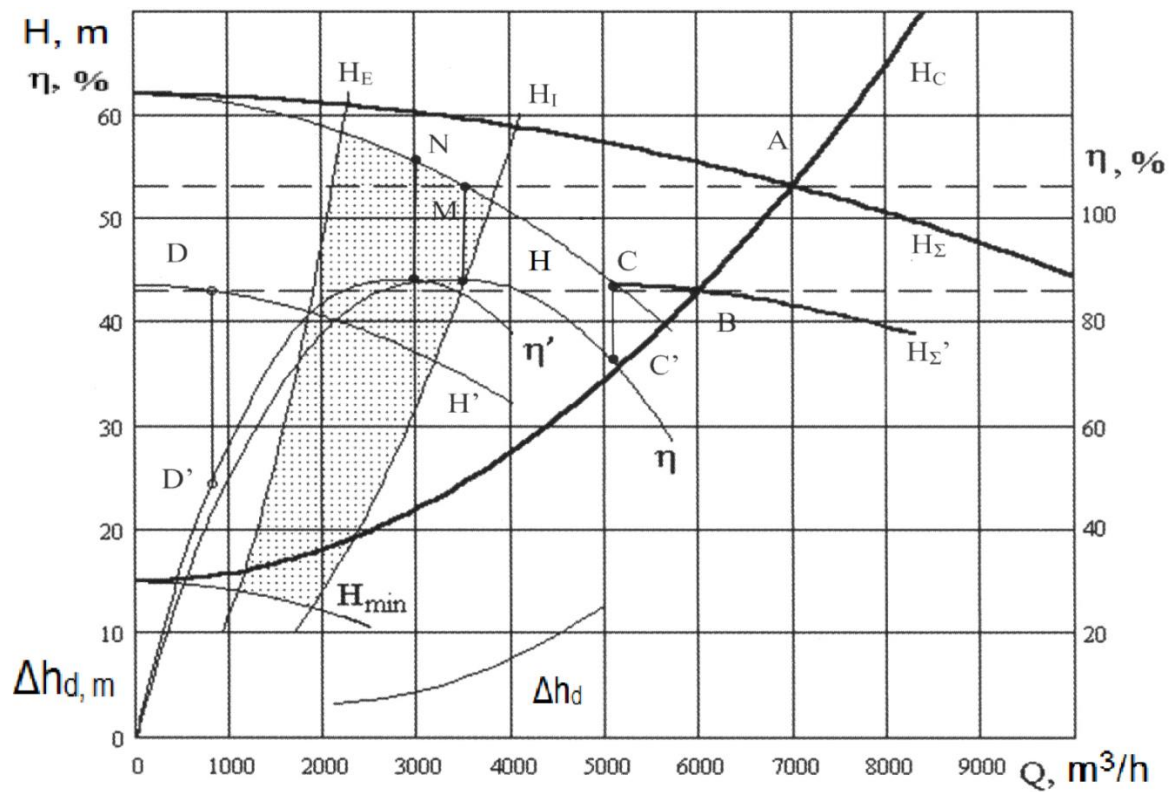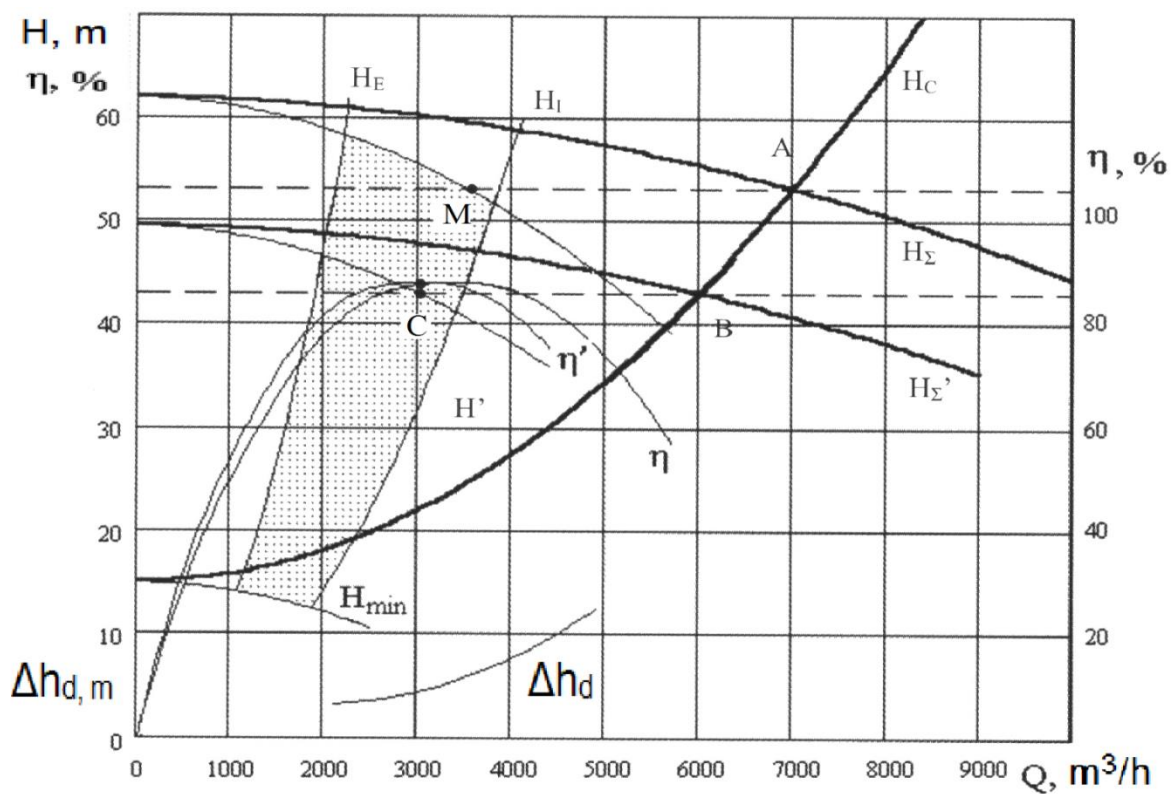
Figure 4.PS with adjustable drive, variant 1.

Figure 5.PS with adjustable drive, variant 2.

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