UNCONFIRMED FLUID MOVEMENT IN THE PYRAMID-SHAPED WELL OF THE CENTRIFUGAL PUMP

Albert Margaryan[1], Garnik Vermishyan[1], Aram Sahakyan[1]*, Hovsep Hoveyan[1]

[1] *National University of Architecture and Construction of Armenia, Yerevan, RA*

Abstract: *The article touches upon the unconfirmed fluid movement in the prism-shaped receiving basin of a multi-unit pumping station, which is fed from a large-volume basin through a fluid pressure overflow pipe. During the joint operation of the units, a constant fluid level is established in the receiving basin when the total output driven by the pumps equals the output of the overflow pipe. When one (or several) units are shut down or initiated, an unconfirmed movement occurs in the overflow pipe and the receiving basin. The pattern of change of the fluid level in the receiving basin over time and the timeframe for the formation of a new level have been determined. This study is of practical significance from the perspective of excluding the discontinuity of fluid flow in the pump suction pipe as well as in terms of avoiding cavitation.*

Keywords: *unconfirmed movement, cavitation, discontinuity, stationarization period, unit.*

Aram Sahakyan*

E-mail: sahakyan.aram@nuaca.am

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Introduction

The discontinuity of fluid flow in the suction duct of a centrifugal pump is accompanied by cavitation. Cavitation refers to the formation of local bubbles when the absolute pressure drops to the level of the liquid's saturated vapor pressure. The tendency for cavitation to occur increases when the pump operates with a positive suction lift, approaching its calculated limit [1,2], particularly on the inlet part of the pump, such as the sealing ring, front disc, and impulse wheel. With a negative suction lift (self-suction), cavitation can also occur. Therefore, when operating three pumps in parallel, each with a capacity of 1850 l/s, if two pumps are shut down, the operational pump's performance, according to the main characteristic of the pump, should increase to 2500 l/s. However, this hydraulic mode of operation for the pumping unit is not achievable due to the absence of excess pressure between the water level in the discharge tank and the pump axis.

This mode leads, on the one hand, to an overtolerance load on the electric motor and, on the other hand, to pulsating ruptures of the water column in the suction pipe of the pump because the hydraulic resistance of the latter prevents the passage of such a flow rate with a given excess pressure. Secondly, it causes pulsating ruptures of the water column in the pump's suction pipe. The excess pressure can not pass through the pipeline because of resistance. At the Mkhchyan pumping station in Armenia, which consists of nine units, each with a capacity of 1600 kW, the leading edges of the impeller blades experienced an average reduction in length of 20 to 23 mm due to cavitation wear. This wear occurred during the irrigation season. When centrifugal machines enter the cavitation mode of operation, it not only has mechanical consequences but also affects hydraulic parameters and energy indicators. Specifically, pumps experience a decrease in productivity and pressure, while turbines - a significant decrease in efficiency [3].

Therefore, it is crucial to identify and prevent the initiation and development of cavitation in centrifugal machines. There are several methods available for preventing cavitation, and in our opinion, the most simple and reliable methods are acoustic [4,5] and vibrational [6,7]. It has been observed that high-frequency implosions of vapor bubbles interact with the low-frequency passing of the rotating blades. Detection of semiopen impellers cavitation at initial and intermediate stages of cavitation development, it is found that the high frequency implosions of vapor bubbles interact with the low frequency passing of the rotating blades and compose part of the vibration signal under initial cavitation conditions [8].

Materials and Methods

The calculations related to the studies were performed by the following well-known hydraulic principles and laws. The experimental studies were conducted directly on the water supply network under production conditions.

The effect of transient phenomena on the pump suction process in the pump suction pipe

Let us consider the non-stationary fluid movement in a prism-shaped well of limited volume (receiving basin) of a small pumping station, which is fed from a large-volume basin by the q and from which a Q constant output is pumped out.

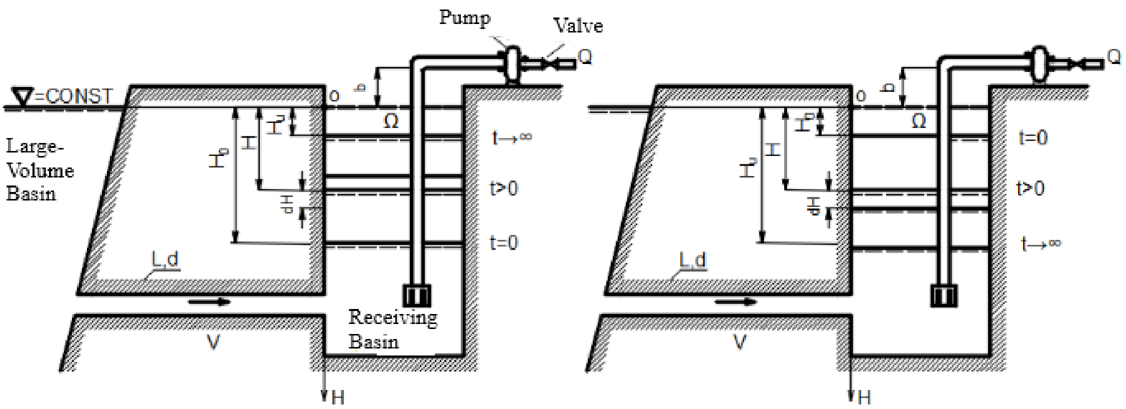

Fig. 1. *Side view diagram of the hydraulic system*

Fig. 1 shows a side view diagram of the hydraulic system. The well is connected by a pipe to a large-volume basin in which a constant fluid level is maintained. The basin feeds the well at the q output variable depending on the varying fluid level in the well over time.

Let us assume that at the initial $t = 0$ moment of time the fluid level in the well is lower than the fluid level in the basin in H_0 amount and $Q = const$ output is pumped out of the well. Since there is a H_0 difference in fluid levels between the basin and the well, the basin feeds the well through a pipe. The output feeding the well is determined using Bernoulli's equation written for the cross-sections of the basin and fluid levels of the well [9,10]:

$$H_0 = \sum h_W, \tag{1}$$

where $\sum h_W$ is the total energy loss in the feeding pipe [11].

$$\sum h_W = h_1 + h_L + h_2 = \frac{V^2}{2g}\left(\varsigma_1 + \lambda\frac{L}{d} + \varsigma_2\right), \tag{2}$$

V is the average velocity of fluid movement, ς_1 and ς_2 are the local resistance coefficients of the pipe input and output, λ is the coefficient of frictional resistance of the pipe, while L and d are the length and diameter of the pipe.

Let us insert (2) into (1) and determine the average V_0 velocity of the fluid flow in the pipe at the $t = 0$ moment of time:

$$V_0 = \sqrt{\frac{2gH_0}{\varsigma_1 + \lambda\frac{L}{d} + \varsigma_2}}.$$

Therefore, the initial q_0 output feeding the well will be [12]

$$q_0 = \frac{\pi}{4} d^2 \sqrt{\frac{2gH_0}{\varsigma_1 + \lambda \frac{L}{d} + \varsigma_2}} \quad \text{or} \quad q_0 = \mu A \sqrt{2gH_0}, \quad \left(\mu = \frac{1}{\sqrt{\varsigma_1 + \lambda \frac{L}{d} + \varsigma_2}} \right). \tag{3}$$

It is obvious that in the established hydraulic regime, the q_0 output feeding the well will equal to the Q output pumped out of the well: $q_0 = Q$.

In case one of the pumps is decommissioned at the $t = 0$ moment of time, the output feeding the well exceeds the output from the well, which leads to an increase in the fluid level in the well.

Let there be the z increase in the level at the $t > 0$ moment of time, and the pressure difference between the ends of the pipe feeding the well becomes $H_0 - z$, as a result of which the output issued through the pipe becomes

$$q = \frac{\pi}{4} d^2 \mu \sqrt{2g(H_0 - z)} = k\sqrt{(H_0 - z)}, \ k = \frac{\pi}{4} d^2 \mu \sqrt{2g}\,. \tag{4}$$

At dt timeframe the level will increase in dz. The fluid level in the well continues to increase until the feeding output has not equaled the $Q - \Delta Q$ output from the well, when the hydraulic established regime is reestablished, where the ΔQ is the output of the decommissioned pump.

At dt timeframe the volumes of liquid filling the well and withdrawing from the well will correspondingly be as follows:

$$qdt \quad \text{and} \quad (Q - \Delta Q)dt.$$

Since the output feeding the well exceeds the output withdrawing from the well: $q > Q - \Delta Q$, an increase emerges in the Ωdz fluid volume in the well, where the Ω is the cross-sectional area of the prism-shaped well.

Therefore:

$$qdt - (Q - \Delta Q)dt = \Omega dz \Rightarrow dt = \frac{\Omega dz}{q - (Q - \Delta Q)}\,.$$

A differential equation with separable variables (z, t) has been obtained. Inserting q from (4) into the above equation, we obtain

$$dt = \frac{\Omega dz}{k\sqrt{H_0 - z} - (Q - \Delta Q)} = \frac{\Omega}{k} \frac{dz}{\sqrt{H_0 - z} - \frac{Q - \Delta Q}{k}}\,.$$

Let us denote:

$$\frac{Q - \Delta Q}{k} = \sqrt{H_U} \ \Rightarrow k\sqrt{H_U} = Q - \Delta Q\,. \tag{5}$$

The left side of equation (5) represents the q feeding the well and the right side represents the output withdrawn from the well. Therefore the H_U is the boundary depth of the fluid level in the well below the fluid level in the basin at which these outputs equalize.

After the given notation, the differential equation takes the following form:

$$dt = \frac{\Omega}{k} \frac{dz}{\sqrt{H_0 - z} - \sqrt{H_U}}\,.$$

Let us integrate the differential equation under the following initial condition:

$$t = 0, \qquad z = z_0.$$

$$\int_0^t dt = \frac{\Omega}{k} \int_{z_0}^{z} \frac{dz}{\sqrt{H_0 - z} - \sqrt{H_U}}.$$

Let us denote $\sqrt{H_0 - z} = x \Rightarrow x^2 = H_0 - z \Rightarrow dz = -2xdx$.

Let us calculate the integral with the new variable:

$$\int_{Z_o}^{z}\frac{dz}{\sqrt{H_0-z}-\sqrt{H_U}}=2\int_{\sqrt{H}}^{\sqrt{H_U}}\frac{xdx}{x-\sqrt{H_U}}=2\int_{\sqrt{H}}^{\sqrt{H_U}}\frac{x-\sqrt{H_U}+\sqrt{H_U}}{x-\sqrt{H_U}}dx=$$

$$=2\int_{\sqrt{H}}^{\sqrt{H_U}}dx+2\sqrt{H_U}\int_{\sqrt{H}}^{\sqrt{H_U}}\frac{dx}{x-\sqrt{H_U}}=2\left(\sqrt{H_0}-\sqrt{H}+\sqrt{H_U}\,ln\frac{\sqrt{H_U}-\sqrt{H_0}}{\sqrt{H_U}-\sqrt{H}}\right).$$

Inserting the expression of k from (4), we finally obtain

$$t=\frac{2\Omega}{\mu A\sqrt{2g}}\left(\sqrt{H_0}-\sqrt{H}+\sqrt{H_U}\,ln\frac{\sqrt{H_U}-\sqrt{H_0}}{\sqrt{H_U}-\sqrt{H}}\right). \quad (6)$$

This solution result coincides with the case of discharge from a prism-shaped basin under variable pressure, when the basin is fed from above by a constant output.

The difference between the problem under discussion lies in the fact that a constant output is withdrawn from the well, while the well is fed from a large-volume basin with a variable output.

It follows from solution (6), that

a) in order for the logarithm to exist, it is necessary for the initial H_0 and variable H depths of the fluid to be simultaneously greater or less than the H_U boundary level,

b) when the variable level tends to reach the boundary level $H \to H_U$, then $t \to \infty$, i.e. transition to an established regime is a seamless process.

c) if the H_0 initial level in the well is lower than the H_U boundary level, the H variable level increases asymptotically towards the H_U boundary level, and if it is high, it tends to the same boundary level by decreasing.

Fig. 2 shows the curves of the change in the fluid level in the well.

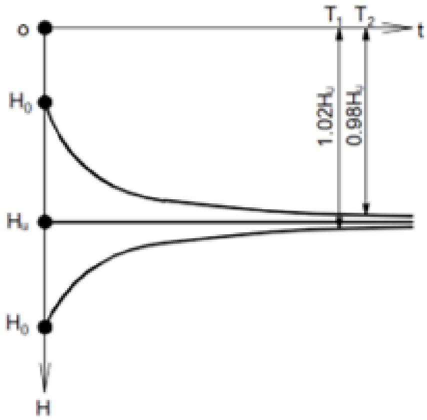

Fig. 2. *Change in fluid level over time*

Results and Discussion

The determination of the period for the generation (stationarization) of the established hydraulic regime has an applied significance. In practice, it can be determined with any accuracy. For example, to determine the T timeframe of stationarization with a 2% accuracy, we accept that $H = 1.02H_U$ in case of increasing the level in the well and $H = 0.98H_U$ in case of decreasing the level in it.

If all the pumps are decommissioned, i.e. $Q = 0$, according to (5), $H_U = 0$ and the solution (6) will take the following form:

$$t=\frac{2\Omega}{\mu A\sqrt{2g}}\left(\sqrt{H_0}-\sqrt{H}\right),$$

which will determine the T_0 timeframe, during which the fluid levels in the well and the basin are equalized $H = 0$ over time, in case of variable (decreasing) pressure feeding the well from the basin, i.e.:

$$T_0=\frac{2\Omega\sqrt{H_0}}{\mu A\sqrt{2g}}.$$

Example: Two identical centrifugal pumps with parallel connection pump out an output of $Q = 0.17$ m³/s from the prism-shaped well. Determine the timeframe for the stationarization of the hydraulic regime, if one of the pumps is decommissioned. The values of the geometric dimensions and hydraulic quantities of the system given in Fig. 1 are:

$H_0 = 3$ m, $d = 300$ mm, $L = 100$ m, $\Omega = 10$ m², $\varsigma_1 = 0.5$, $\lambda = 0.025$, $\varsigma_2 = 1$.

Solution: In case of established movement during the operation of both pumps, the H_0 initial fluid depth in the well from the level of the basin, according to (4), will be

$$H_0 = \frac{Q^2}{2g\mu^2 A^2} = \frac{0.17^2}{19.62 \cdot 0.32^2 \cdot 0.071^2} = 2.88 \text{ m},$$

where

$$\mu = \frac{1}{\sqrt{0.5 + 0.0247\frac{100}{0.3} + 1}} = 0.32\,, \quad A = \frac{3.14}{4}0.3^2 \approx 0.071\text{m}^2.$$

The productivity of the pump in operation increases from its productivity in case of joint operation to 0.085 m^3/s. Let us consider it $Q_1 = 0.1$ m^3/s and determine the depth of the H_U boundary level from the fluid level of the basin:

$$H_U = \frac{Q_1^2}{2g\mu^2 A^2} = \frac{0.1^2}{19.62 \cdot 0.32^2 \cdot 0.07065^2} = 1.0\text{m}.$$

Inserting $H = 1.02H_U$ in (6), we obtain the T timeframe of the stationarization of the fluid flow movement in the well with a 2% accuracy:

$$T = \frac{2 \cdot 10}{0.32 \cdot 0.07065 \cdot \sqrt{2 \cdot 9.81}}\left(\sqrt{2.88} - \sqrt{1.02 \cdot 1} + \sqrt{1}\, ln\frac{\sqrt{1} - \sqrt{2.88}}{\sqrt{1} - \sqrt{1.02 \cdot 1}}\right) = 988\text{s} \approx 17\text{min}.$$

It is obvious that the increase of the fluid level in the limited-volume receiving basin by 2.88-1 = 1.88 m within the T timeframe leads to the improvement of the suction process of the operating pump, because the suction height of the pump gradually decreases.

Now let us assume that two pumps are in operation and another is being started. In this case, the fluid level will decrease in the receiving basin, and after some time, a lower fluid level will be established, i.e., a greater suction height will be established, as a result of which the suction process of the pumps will deteriorate.

The number of pumps with parallel connections is reasonable to implement with three identical pumps, which have a relatively large permissible vacuum gauge height due to the significant variation in pump suction height.

Conclusion

1. The variation in liquid level within the well, in response to changes in the number of units in operation, remains independent of the well's cross-sectional area.
2. The time needed for the well to achieve stationary motion is directly proportional to its cross-sectional area.
3. Selecting a pipe with higher roughness can decrease the time required for the fluid flow in the well's feeding pipe to establish a consistent movement.

Therefore, to mitigate the effect of the transient phenomenon on the pump suction process in the suction pipe of operating pumps, it is necessary to take the following measures:

1. Before shutting down one of the operating pumps, first the output of the operating pump needs to be reduced by throttling its discharge valve to closing, then the pump should be shut down, and the discharge valve of the operating pump should be opened.
2. Before operating a new pump, it is necessary to reduce the initial output first by throttling its discharge valve to the closed position, then start the pump operation, and after a short time open the valve.

It should be noted that the degree of throttling of the valve is determined experimentally. The present experiment has been performed by us on the discharge conduit of the Khor Virap pumping station. The noise (like a shot) that can be heard from the body of the pump, as well as soft vibrations of the suction pipe, can be considered a signal. During the transition from one established hydraulic regime to another, the inertial pressure, which is equal to zero when the established regime of fluid flow occurs, conditions the mentioned actions (valve throttling).

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Albert Margaryan, Doctor of Science (Engineering) *(RA, Yerevan) - National University of Architecture and Construction of Armenia, Professor at the Chair of Water Systems, Hydraulic Engineering and Hydropowe, mark-as@mail.ru*

Garnik Vermishyan, Doctor of Philosophy (PhD) in Engineering *(RA, Yerevan) - National University of Architecture and Construction of Armenia, Associate Professor at the Chair of Higher Mathematics and Physics, vermishyan.garnik@gmail.com*

Aram Sahakyan, Doctor of Philosoph (Ph.D) in Engineering *(RA, Yerevan) - National University of Architecture and Construction of Armenia, Dean of the Construction Faculty, sahakyan.aram@nuaca.am*

Hovsep Hoveyan, Doctor of Philosophy (PhD) in Engineering *(RA,Yerevan) - National University of Architecture and Construction of Armenia, Chief of the Staff, Assistant at the Chair of Technology and Organization of Construction Production, hoveyan@nuaca.am*