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# Calculation of water hammer on the pressure pipeline of modernized irrigation pumping station

# Calculation of water hammer on the pressure pipeline of modernized irrigation pumping station

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**Abstract**. One of the main factors to provide reliable and safe operation of irrigation pump station – prevent possible occurrence of water hammer. In order to determine the magnitude of water hammer's method of characteristics (moc), wave characteristic method (wcm), graphical analytical and simplified methods of calculations are used. During the design for the construction of the new pump station surge analysis should be carried out using accurate calculation methods moc or wcm using special computer software. At the same time, should the modernization of existing pump station is taking place with the installation of the same equipment, then simplified calculations method can be used. But care must be taken to take in to account all the factors that might increase the risk of occurrence and with the higher magnitude of water hammer: reduced inertia of pumping set's moving parts, replacement of shutting valves to different types, replacement of air valves to different types, reduction of hydraulic losses after discharge pipeline repair works and etc. Existing simplified calculation methods to calculate water transients in pump stations was modified to take in to account these factors. Based on the proposed method surge analysis calculations had been carried out at modernized pump station "Kizil-tepa". Comparison of calculation results performed by simplified method and wcm using «KY-Pipe 2018-Surge program-version 9.014» has shown a good similarity in the magnitude of maximal positive pressures.

## 1. Introduction
During the pump station operation it is a common occurrence that pump characteristics are abruptly changed. When pumps start and stop, flow control valves open and close water transients occur along the discharge pipelines. As a result of increased pressures along the pipelines, significant accidents might occur at the pipes, pumping sets, and equipment that are located along the pipelines, if necessary technical measures aren't done based on the surge analysis calculations [1,2,3,4,5].

Other paragraphs are our country currently has undertaken measures to rehabilitate and modernize irrigation equipment of pump stations. During the pump station reconstruction works, major item that is replaced is pumping sets (main and auxiliary pumps). Old equipment isn't replaced with the same models. Many modern pumping sets have significantly reduced inertia values (of rotors and electric motors) and abruptly stop as soon as electric motors are powered off. This might lead to significant water transients, as water inside the discharge pipelines is still continuing to move, and might lead to the separation of the water column (rapid loss of pressure, vacuum). During the pressure wave resonance reverse water flow travels towards the pump impeller at a high speed and low pressure, and

causes the water hammer. In addition, under pump reconstruction shut-valves and pipeline safety devices might also be fully or partially be replaced. Thus, based on the degree of changed goods along the pipeline, hydraulic characteristics of the pipeline system will be changed, along with the shift of pressure waves to different location – leading to significantly high new pressure spikes. That's why, it is a common practice to require new surge analysis calculations during the design stage with taking in to account newly installed equipment [6,7,8 ].

Analytical, graphical, wave and method of characteristics provide detailed and accurate information of pressure spikes during the water hammer [1,9,10,11,12]. These calculations are cumbersome, and utilization of computer software is expensive. That's why simplified water hammer calculations are needed to be done, with taking in to account newly installed major parts, in order to determine if the water hammer is dangerous to the safe operation of the rehabilitated pump station. Calculation accuracy is directly related to the quality of input data.

There are a number of different types of simplified calculation methods to calculate water transients [1]. Current review presents simplified calculation method that takes in to account irrigation pump station specifics. Main requirement to simplified method – water hammer calculated values should be higher than the real values, i.e. there should be some safety margin towards higher pressure spikes. Therefore, during the development of simplified calculation formulas factors that lower positive pressure spikes should be disregarded. The Department of water energy use and pumping stations regularly conducts numerous field studies on the operation modes of pumping units [11,15,16,17,18,19,20].  Particular attention is paid to the issues of safe structures and equipment of irrigation pumping stations, including the prevention of hydraulic shocks

It is clear, that more such factors are removed, simpler the calculations become, and that much higher positive pressures would also be determined to be. For calculations "Kizil-tepa" pump station data after reconstruction were used.

## 2. Methods

Using water hammer calculation method, it is known that magnitude and character of pressure distribution (process) following factors play key role, such as [1,13,14]:

- Rigidity of pipeline material, length, diameter and thickness of the pipeline;
- Rapid closure-opening of closure valves, pump start-stop (rapid velocity change of kinetic parameters of pumped media in the pipeline);
- Initial data: water levels, initial water pressures before water hammer.

Water hammer is also dependent on type, make and size (weight) of pumps, especially it's moving parts and type of pressure characteristics [2,3].

In accordance to a well-known Zhukovsky's formula [3,4] maximal positive pressure increase (m) in the pipeline, under abrupt closure of a valve (direct surge) for the pressure, without causing separation of water column:

$$\Delta H = \frac{v_0 c}{g} \tag{1}$$

Where, $\Delta H$  - is the pressure increase in a pipeline before valve closure (m);

$v_0$ - initial water velocity in a pipe (m/s);

$c$ - pressure wave propagation (increase and decrease pressure) in a pipeline, (m/s);

Magnitude $c$ depended on the pipeline wall material, length and module of elasticity of the liquid. If water's module of elasticity, $2.1 \times 10^4$ kg/cm$^2$, with average water density and gravity, then the formula would be:

$$c = \frac{1425}{\sqrt{1 + \frac{2,10 * 10^4 d}{E\delta}}} \tag{2}$$

Where, E – module of elasticity, kg/cm$^2$;

d – inner diameter, cm;

$\delta$ – pipeline wall thickness, cm.

Maximal wave speed magnitude, that could be, is 1425 m/s. Based on field data [1,2,3,4], this value rarely is higher than 1000 m/s, and sometimes being 500 m/s. Such decrease is described by the presence of dissolved air that should be taken in to account during calculations.

Water hammer analysis will be calculated based on recently renovated pump station "Kiziltepa". For the calculation basis we will take in to account calculation method proposed by "VNII Vodgeo" [3,21,22]:

Pump station has 10 vertical centrifugal pumping sets. Pump Station "Kiziltepa" is the second stage of the second level of "Amu-Bukhara machine canal" (ABMK) [19,20], and had been operational since 1975. Pump Station pumps water to two levels: to "Kharhur" branch, with the flowrate of 45 m$^3$/s and head of 46.0 m., by means of pumping sets 1-4, working in parallel, and with the flowrate of 60.0 m$^3$/s with the head of 71 m  to "Shafirkan" branch (pumping sets  5-10).

Below you can see calculations for "Kharhur" branch of the pump station. Pumping sets that feed "Kharhur" branch take water from an intake channel. Elevation of the bottom of the channel is 214.00 m. Intake pipeline is a squared concrete pipe, with the dimensions of 6x2.8 m, and 8.4 m length, without compensators. Pump impeller axis is 214.00 m. Zero marker for a meter marker is taken as the axis of the pump elevation. Two pumping sets with individual pipelines in the initial section of the pipeline has the diameter of 2440 mm., pipe thickness is 14 mm., and length is 54.87 m., merge in the meter marker (MM) 0+56 via Y-connection, to the discharge pipeline with the diameter of 3240 mm., thickness of from 17 to 10 mm (varying at different sections), and the length of 952 m. Discharge pipeline material is low-carbon steel.

At the MM 0+12 discharge pipeline has hydraulically operated butterfly valve, with the diameter of 2200 mm. Time to fully open the valve can be set at from 20 to 120 seconds. Time for an accelerated closure of the valve is 2.5 seconds to 60$^0$, with the closure of the remaining 30$^0$ takes from 6 to 90 seconds. Fig. 1 shows schematic diagram of the pump station for calculations.
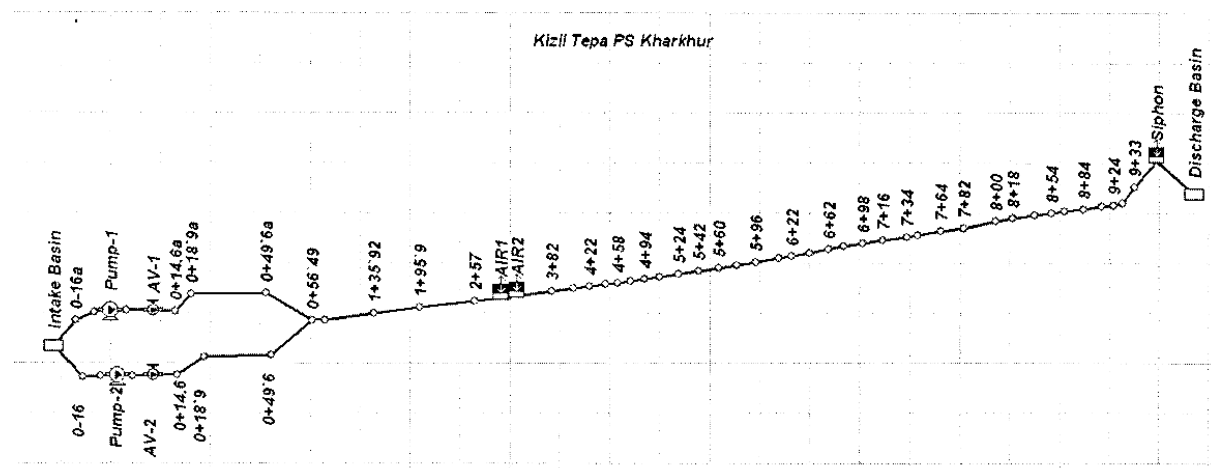


**Figure 1.** Schematic representation of "Kharhur" branch of the "Kiziltepa" pump station.

Initial data for calculations:

- Pipeline length $\ell$= 952 м;
- Pipeline discharge axis at the exit $Z_B$ = 59.33 m;
- Marginally possible vacuum magnitude (under normal conditions and temperatures not exceeding 25-30$^0$C is provisionally taken as 8-9 m. of water head) h = 8.5 m. [3,21].
- Wave propagation velocity c = 806 m/s, based on the formula (2).

- Pipeline material is low-carbon steel.
- At MM 0+12 discharge pipeline has butterfly valve, hydraulically operated, with the diameter of 2200 mm.
- Discharge pipeline has two air inlet valves at MM 3+20 and 3+22, with the dimensions of 1020 mm.
- At an exit, discharge pipeline is equipped with classical type syphon.
- Water velocity at steady-state, with two working pumping sets:

$$v_o = \frac{45.0/2}{3.14 * 3.2^2/4} = 2.79 m/s \; ;$$

- Resistance coefficient for steel pipes with the diameter of d=3200 mm, $\zeta_н$=10,2 [3].

**Wave Characteristic Method:** numerical solution based on the generation and propagation of pressure waves and wave action at all junctions and components. Calculations required at small time steps at nodes only [9].

Pressures under transient moments, and propagation of pressure waves and the wave speed is described by the following formula:

$$\Delta H = \frac{c}{g}(\Delta v), \qquad\qquad (3)$$

Analysis limited to components and junction positions express H and Q in terms of initial values, magnitudes of impinging waves and component characteristics.

Evaluate solutions at intervals of Δt (components and nodes only), and is simplified as:

$$\Delta P = \rho(\frac{c}{g})\Delta v , \qquad\qquad (4)$$

Where, propagation of pressure waves is described as:
- Travel at sonic speed;
- Pressure-flow relation;
- Modified by pipe friction;
- C = wave speed;
- P = pressure;
- V = velocity.

Transient flow in pipes is a result of pressure waves generated at the point of disturbance being propagated throughout the pipe system. The Wave Method analysis is a computational technique for transient flow analysis based on the concept of pressure wave generation and propagation in pipe systems.

## 3. Results and discussions
**Calculation based on simplified method.** Calculation is based on possible water column separation [21,22,23]. At the moment water flow is stopped by the pump, pressure in the pipeline continues to drop, for $\Delta H = z_в = 59.33m$. This leads to the loss of water velocity in a pipe up to

$$v_{up} = v_o - \frac{g}{c}\Delta H = 2.79 - \frac{9,81}{806} 59.33 = 2.05 m/s ,$$

Based on the friction coefficient $\zeta_н$=10.2,

$$К_н = \frac{\zeta_н}{2g} = \frac{10,2}{2*9.81} = 0,52 ,$$

Coefficient of the pipeline is determined by specific friction A of steel pipes, with the diameter of 3200 mm:

A – coefficient of specific friction, dependent on pipe diameter and pipe wall roughness; can be taken from the reference tables or calculated by related formulas [3,20], for steel pipe:

$A = 0,00148(1 + 0.867/v)^{0.3}/d^{5.3}$   when   $v < 1.2$ m/s;

and      $A = 0.001735/d^{5.3}$ when $v > 1.2$ m/s.

$$A = 0.001735/3.2^{5.3} = 0.0000169,$$

Accordingly, coefficient would be:

$$K_{pipe} = AL\frac{\pi^2 d^4}{16} = 0.0000169 * 952 * \frac{3.14^2 3.2^4}{16} = 1.039 ;$$

Thus, head loss in the pipeline after pump stop, when water movement would be

$$Kv_{up}^2 = (K_H + K_{pipe})v_{up}^2 = (0.52 + 1.039)2.05^2 = 1.559 * 4.2025 = 6.551,$$

Under atmospheric pressure water can rise to the elevation of $z = h_{suct} - Kv_{up}^2 = 9 - 6.551 = 3.449 м$,   which is lower than $Z_B = 59.33$ m. Accordingly, pressure pipelines will have water column separation and preventative measures must be taken.

Followed by determining coefficient K, with the diameter of the pipeline d = 32000 mm at the discharge unit, so that the head loss would not be determined by using water movement velocity in it, but water velocity inside a pipe, to simplify calculations.

In accordance to this, coefficients $\zeta_{disch}$, for discharge unit have been determined, and can be calculated using the formula [21]:

$$\zeta_{pipe} = \zeta_{pipe}\left(\frac{d_{pipe}}{d_{disch}}\right)^4 ;$$

$d_{pipe}$ - Diameter of the pipeline;

$d_{disch}$ - Diameter of given discharge unit;

At the MM 0+12 pipeline has butterfly installed with the diameter of 2200 mm. In addition, at MM 3+20 and 3+22 there are two air inlet valves, with the air inlet diameter of 1020 mm. for each.

Aggregate coefficient of discharge unit $\sum\zeta_{disch}$ can be determined by the formula:

$$\sum\zeta_{disch} = \left(\frac{3.2}{2.2}\right)^4 \sum\zeta_{2200} + \left(\frac{3.2}{2.2}\right)^4 * A_{2200} * l_{disch} * \frac{\pi^2 2.2 * g}{8} ;$$

$A_{2200}$ - Specific resistance of steel pipes with the inner diameter of d = 2200 mm;

$l_{disch}$ - Length of discharge pipeline;

$\sum\zeta_{2200}$ - Total local losses at the diameter of 2200 mm.

$$\sum\zeta_{2200} = \zeta_1 + \zeta_2 + \zeta_3 + \zeta_4,$$

$\zeta_1 = 2$ - Resistance coefficient of preventative discharge valve (depending on the type of a valve);

$\zeta_2 = 0.1$ - Fully open valve resistance coefficient;

$\zeta_3 = 0.2$ - The coefficient of resistance in the transition from pipes with a diameter of 2200 mm to pipes with a diameter of 3200 mm;

$\zeta_4 = 0.37$ - Resistance coefficient of the Y-connection.

$$\sum \zeta_{2200} = \zeta_1 + \zeta_2 + \zeta_3 + \zeta_4 = 0.1 + 2 + 0.2 + 0.37 = 2.67m,$$

With taking in to account abovementioned, total coefficient of the discharge unit is equal to:

$$\sum \zeta_{disch} = \left(\frac{3.2}{2.2}\right)^4 2.67 + \left(\frac{3.2}{2.2}\right)^4 *9*22*\frac{3.14^2 *2.2*9.81}{8} = 11.952 + 4.476*5227 = 23410,$$

Thus:

$$K_c = \frac{\sum \zeta_{disch}}{2g} = \frac{23410}{2*9.81} = 1193,$$

Taking in to account that $Z_B$ =59.33 m is larger value, then the maximal pressure rise in the pipeline that have antisurge devices is determined by the following formula:

$$H_{max} = z_\text{в} + h_{suct} = 59.33 + 8.5 = 67.83m,$$

$$A = \frac{g^2}{c^2} H_{макс} (K_c + K_{pipe}) = \frac{9.81^2}{806^2} 67.83(1193 + 1.03) = 0.82m,$$

Then, pressure magnitude needs to be determined, under existing hydraulic resistance of discharge device and the pipeline:

$$H = H_{макс}\left[1 - \frac{1}{2A}(\sqrt{4A+1} - 1)\right] = 67.83\left[1 - \frac{1}{2*0.682}(\sqrt{4*0.682+1} - 1\right] =$$

$$= 67.83*\left[1 - \frac{1}{1.364}*(1.931 - 1)\right] = 67.83*0.317 = 21.50m,$$

Magnitude of the maximal hydraulic head $H_{max}$ are taken by the methodology of not taking in to account changing inertia of moving parts of the pumping set, after pump station rehabilitation works (pump and motor rotors). Under modernization, vertical single-entry pumping units 2000 В–16/63-3 (with the weight of 88700 kg) and vertical 3-phase synchronous electric motor ВДС 375/130-24–УХЛ4 (with the weight of 132000 kg), and the moment of inertia for the pumping set of 670000 Hm$^2$, have been replaced with pumping sets type 1180_SP-ns "Andritz Hydro" (China), with the moment of inertia 164000 Hm$^2$. So, newly installed pumping sets have significantly less inertia and after sudden power loss would stop rather quickly. This could lead to significant surges, in the absence of check valves, surge suppression devices, because water in the pipeline is continuing to move forward, and water column separation would occur. After water column reverses its flow, pressure in the pipeline would continue to decrease and water hammer would occur.

To determine the maximal pressure rise, with taking in to account changed inertia values formula [3]. In this case, pressure surge would be the following:

$$\Delta H = \frac{v_0 c}{g} + 2H_{st} \qquad (5)$$

Where, $\dfrac{v_0 c}{g}$ – maximal pressure rise (m) in the pipeline, after sudden valve closure would be (direct surge), using Zhukovsky's formula (1);

$H_{st}$ - static (geometric) head of the pump station, is equal to difference in water level at the upper and the lower bays of the pump station. In our case $H_{st} = 40.0m$;

$$\Delta H = \frac{v_0 c}{g} + 2H_{cm} = \frac{3.93 * 806}{9.81} + 2 * 40.0 = 402.89m \text{,}$$

Pressure at the pipeline:

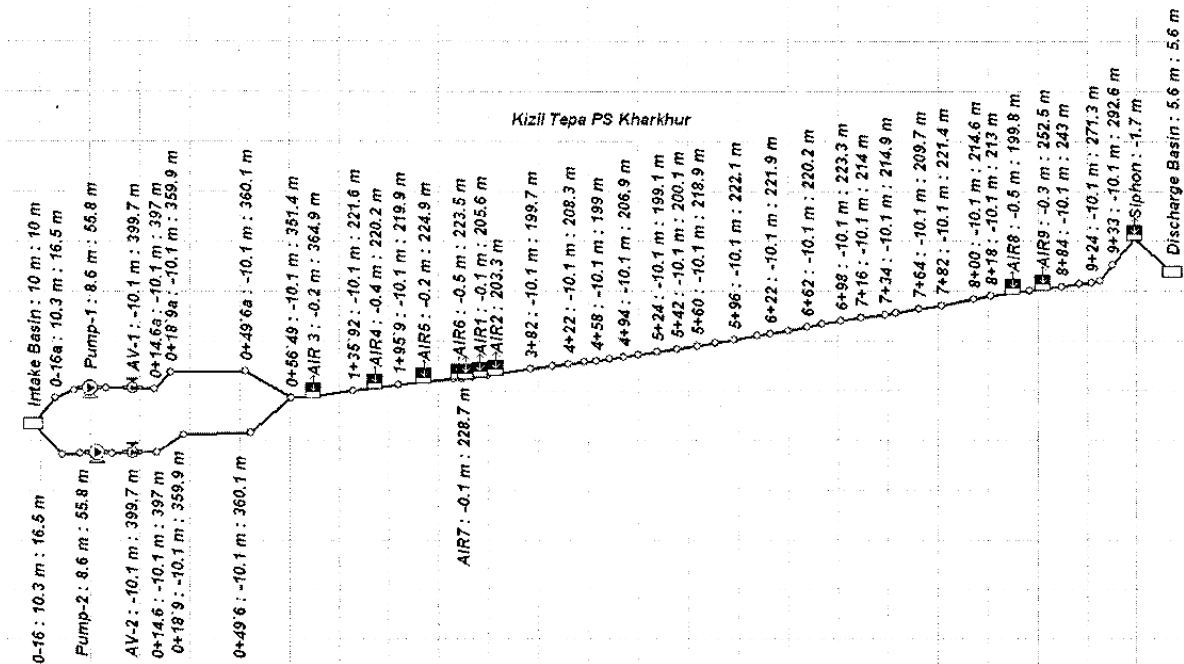$$\Delta H = \frac{v_0 c}{g} + 3H_{cm} = \frac{3.93 * 806}{9.81} + 3 * 40.0 = 442.89m \text{,}$$



**Figure 2.** The surge calculation results of "Kharhur" branch of the "Kiziltepa" pump station, using the software «KY-Pipe 2018-Surge program-version 9.014».

Figure 2 shows results of the surge analysis of the "Kharhur" branch that had been done by "Zarbuloq Injiniring" LLC, using «KY-Pipe 2018-Surge program-version 9.014» software, under the worst-case conditions (without using antisurge devices). Based on the wave characteristics method of calculations, maximal positive pressure of water hammer was determined to be 399.70 m. Based on the simplified calculations, maximal positive pressure was determined to be 402.89 m, and the pressure inside the pipeline 442.89 m. Simplified method also predicts water column separation inside the pipeline.

## 4. Conclusions

1. Simplified surge analysis calculation method has been proposed for irrigation pump station discharge pipelines with taking in to account inertia changes to the pumping sets. Calculation without inertial changes predicts smaller pressure spikes.

2. Maximal predicted positive pressure spike inside the pipeline of the "Kiziltepa" pump station is similar to the one predicted by «KY-Pipe 2018-Surge program-version 9.014» software. But exact locations and time step of pressure spikes cannot be determined.

3. Simplified method lets us determine maximal positive pressure spikes during water hammer, but vacuum magnitudes have been taken conditionally and without pinpointing to a certain location. So, simplified method can only be used during pump station modernization feasibility studies, reconstruction of the irrigation pump stations with the replacement of one type of equipment under provisional surge analysis calculations with taking in to account the worst operating conditions.

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