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Analysis of Water Hammer problems in Low Head Pumping Stations and the Need for Water Hammer Protection Devices

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Abstract—Detailed analysis of low head sewerage pumping stations system in operation, raised up different shortcomings on the design and implementation, especially in relation to the safety operation under the water hammer conditions. It was confirmed that because of low pump head and long pipeline, pump stops cause water hammer separation and cavity-closure chock in reversal flow, both leading to extreme pressure values such as absolute vacuum condition and heavy over pressure, several times higher than the designed pump head. By modelling and simulations for different scenarios of water hammer in the system with and without water hammer protection equipment have been proposed the proper measures to avoid the absolute vacuum condition and heavy over pressure in the pipeline. While the proposed pressure vessel will attenuate pressure oscillation during transients, the Variable Frequency Drives (VFDs) will eliminate any pressure oscillation during normal operation (pump stop and start) by extending the pumps ramping time to at least 120 s. The analysis presented in the paper is a "lesson to learn" for future design of low head pumping stations.

Index Terms—water hammer, pumping station, rising main, wastewater, transient, pipeline, wave velocity, column separation, unsteady state, low head, penstock, vacuum vessel, Variable Frequency Drives (VFD).

1 Introduction

The Kune sewerage pumping station (PS), in the town of Shengjin, north of Albania, is a low head pumping station equipped with two submersible wastewater pumps. Pumps are installed in a pump wet sump with a 1+1 operation mode (one in operation and one stand-by). Pumps. The pump discharge pipes and the associated valves (check valves, gate valves, dismantling joints and discharge header) are installed in a dry valve chamber that is adjoined to the pumps pit. The pumping station rising main (main pipeline) is made of ductile cast iron (DCI). The size of the main pipeline is DN300 and total length is approximately 2,274 m and the rising main terminates in an open sewage manhole. Due to some pumping station rising main failures in other low head sewerage pumping stations of a similar design, it was deemed necessary to undertake a detailed analysis of water hammer problems in other pumping stations. This included Kune sewerage pumping station, in order to analyse the operating regimes and provide recommendations for improving the system performance and operation reliability. While, the analysis was performed for both steady and unsteady states, this paper will focus on the unsteady state analysis.

2 System Data

1. No. of pumps in the PS: 2
2. Operating regime: 1 in operation + 1 standby
3. Motor rated power: 30 kW
4. Pressure pipe in PS: Stainless Steel, L = 7.0 m, DN250
5. Check valve at discharge inside PS: Ball check valve, DN250, PN10
6. Valve at discharge pipe inside PS: Knife Gate valve, DN250, PN10
7. PS Raising Main: DCI, DN300 (profile in the following figure)

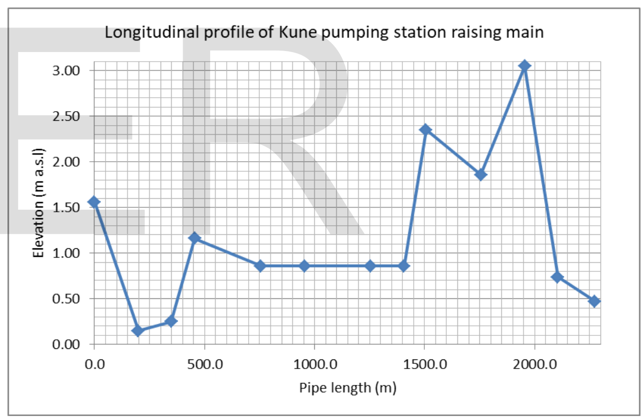

Fig. 1. Longitudinal profile of Kune PS raising main.

3 Unsteady State Analysis

During transient flow, which can be defined as the state with rapidly changed flow in hydraulic systems, velocity, pressure and other hydraulic variables change rapidly over time. Water hammer, as an example of transient flow in hydraulic systems occurs in the following cases:

1. Sudden flow stoppage (for example: valve closure, pump failure, turbine load rejection, main turbine inlet valve closure, Pelton turbine needle closure, turbine guide vanes closure, etc.)
2. Sudden flow start/start-up procedures (valve opening, pump start, turbine start - opening of guide vanes, main inlet valve, etc.)

Any sudden change in flow leads to pressure fluctuations in the system; the unsteady state of a hydraulic system

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generally occurs for many reasons that can be grouped as follows:

1. Uncontrolled and by accident, without control of the operation staff (e.g. pumping station failure)
2. Controlled by operation staff (e.g. pumping station pump start/stoppage, valve opening or closure)

Generally, water hammer causes pressure rise or drop in penstocks-pipelines of pumping stations/hydropower plants, rotational speed change of pump/turbine units and level/pressure variations in surge tanks. Thus, specific protective measures are generally used for protecting mechanical equipment and the pipeline from harmful water hammer effects.

If the system response is not appropriate, due to the maximum and minimum pressures not within the acceptable limits, then either the system layout or parameters have to be changed, or various control devices provided, and the system has to be analysed again. This procedure has to be repeated until a desired response is obtained. The purpose of water hammer control is to stop the kinetic energy from being converted into elastic deformation energy. This can be done by one or a combination of the following basic methods:

1. Energy storage;
2. Optimization of valve closure characteristics;
3. One-way surge and venting facilities; and
4. Optimization of the pipe system control strategy

With pressure (air) vessels and surge tanks, energy is stored as pressure energy; when a flywheel is installed, the energy stored takes the form of rotational energy. Suitable actuation schedules for the opening and closing of valves are calculated and verified by means of a surge analysis on the basis of the valve characteristic. Generally, air valves should not be used until every other solution has been ruled out. Their drawbacks are:

1. They require regular maintenance.
2. If arranged in the wrong place or mounted incorrectly, they can aggravate pressure variations instead of alleviating them.
3. Under certain circumstances, operation of the plant may be limited, as the air drawn into the system has to be removed again.
4. The handling of wastewater calls for special designs.

The water hammer phenomenon is traditionally described by one-dimensional unsteady pipe flow equations and equations describing boundary elements (i.e. in reservoir, valve, surge tank, pump/turbine) and constitutes the transmission of pressure waves along the pipeline resulting from a change in flow velocity. The simplified continuity and momentum equations, appropriate for most engineering applications for unsteady pipe flow, shown in (1) and (2) [2]:

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \qquad (1)$$

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \qquad (2)$$

where:

H = Piezometric head (m)
Q = Discharge (m^3/s)
A = Pressure wave speed (m/s)
D = Pipe diameter (m)
A = Pipe area (m^2)
G = Gravitational acceleration (m/s^2)
f = Darcy-Weisbach friction factor
x = Distance along the pipe (m)
t = Time (s)

3.1 Wave Velocity

Wylie and Streeter (1993) [8] showed that the equation for wave velocity a can be conveniently expressed in the general form:

$$a = \frac{\sqrt{K/\rho}}{\sqrt{1+\frac{K}{E}\frac{D}{e}(1-\mu^2)}} \qquad (3)$$

Based on recommendations from literature for the above parameters the wave velocity can be calculated to range between 203-226 m/s, as shown in the following table.

TABLE 1
WAVE VELOCITY CALCULATION FOR THE OD450 PN6 HDPE100 RISING MAIN PIPE

Parameter	Units	Values
Internal pipe diameter D	mm	300.0
Pipe wall thickness	mm	5.6
Young Modulus of pipe wall E	N/m^2	1.70E+11
Fluid bulk modulus K	N/m^2	2.19E+09
Fluid density (water) ρ	kg/m^3	1,000.0
Poisson's ratio for the pipe μ	-	0.28
Transverse contraction number	-	0.92
Wave velocity	m/s	1,157.0

3.2 Unsteady Analysis: PS Stoppage or Failure

Here are presented the results of transient calculation for the case where the operating pump stops or power supply fails, assuming that there are no water hammer control devices provided for protection of the system, which is the case in Kune pumping station.

If power is cut off from the pump motor suddenly, either accidentally or deliberately, significant water hammer problems may appear.

Generally, a pressure drop which follows pumps trip rapidly propagates upstream from the pumping station up to the end of the system with the wave speed which is equal to the speed of sound through the pumped fluid.

This drop in pressure can lead to column separation. Consequences of cavity-closure shock which follows such an occurrence could be severe. In addition, reversal flow in the system, if not properly handled, can lead to significant overpressure in the system.

Once separation occurs, the above calculation is no longer valid. According to the "Joukowsky equation" [5] sometimes referred to as either the "Joukowsky-Frizell" [4] or the "Allievi" equation [1], the maximum overpressure (Δp) due to a sudden change in velocity can be calculated according to (4):

$$\Delta p = a \times \Delta V / g \qquad (4)$$

where:

a = Wave velocity (m/s)
g = Gravitational acceleration (m/s^2)
ΔV = Change in velocity (m/s)

The following table shows the calculation of overpressures due to water hammer.

TABLE 2
CALCULATION OF WAVE SPEED AND OVERPRESSURE DUE TO WATER HAMMER IN THE RISING MAIN PIPE

Parameters	Units	Values
Pumping Station flow rate	l/s	98.0
Internal Pipe Diameter	mm	300
Wave Speed for Transient Analysis (a)	m/s	1,157.0
Max. velocity of water in the pipeline (V)	m/s	1.386
The acceleration due to gravity	m/s²	9.81
Water hammer pressure increase	mWC	163.5

In that case the maximum pressure at the lowest points of the pipeline will reach the value of app 181 mWC (stationary pressure before water hammer happens is approx. 17.5m and increase of pressure due to water hammer is 163.5m]

This situation summarizes the most common cause of water hammer problems. The result of calculation indicates that water hammer will happen following normal pump stoppage as well as power supply failure.

1. **One pump in operation (capacity approx. 98 l/s), power supply failure**

The following diagram shows the pressure wave time-dependent propagation of pressure waves through the pipeline after the pump has been tripped. As can be seen from the diagram, the envelope of negative pressure intersects the pipeline profile after approximately 0.4 seconds after the start of the event.

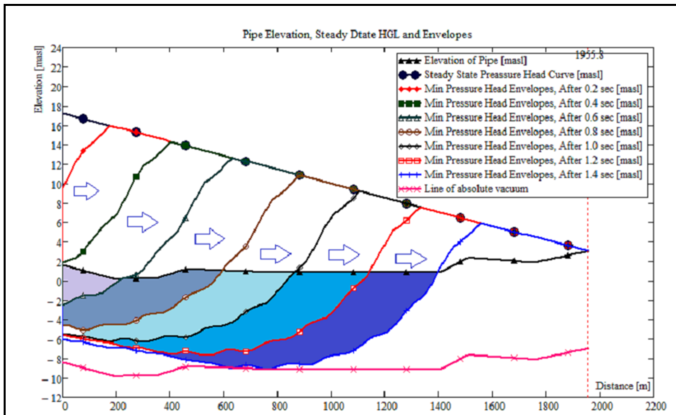


Fig. 2. Pipe Elevation, Steady state HGL and Envelopes.

3.3 PS Start/Stopping time control

The operation conditions of the PS are summarized in the following table:

TABLE 3
PS OPERATING CONDITIONS

Operation conditions	Units	Value
Pump capacity in steady regimes	l/s	98.0
Air valve at distance 1955 m upstream	m a.s.l	3.05
Wave Speed for Transient Analysis (a)	m/s	1,157.0
A. Pump starting/stopping time	sec	30
B. Pump starting/stopping time	sec	60
C. Pump starting/stopping time	sec	90
D. Pump starting/stopping time	sec	120
E. Pump starting/stopping time	sec	150
Water hammer protection equipment		None

Further to the above operation conditions it is assumed that the main discharge pipeline (rising main) is fully de-aerated and free of air pockets.

If pump starting time is too short significant water hammer problems can be developed. If air is present in the rising main in the form of air pocket the system may face different operational and hydraulic problems such as reduction in pump capacity, difficulty in opening non-return valve (if air is entrained through the pumps and accumulated upstream of the non-return valves), drifting of the air bubbles back and forward along the pipeline which can cause pressure oscillations. Based on the conducted analysis prolonged/controlled start of the pumps is much better option. Controlled pumps start can be achieved in the following ways:

1. By installing an Electrically Operated Valve on the pumps discharge
2. By starting pumps via a soft starter
3. By starting pumps over a VFD

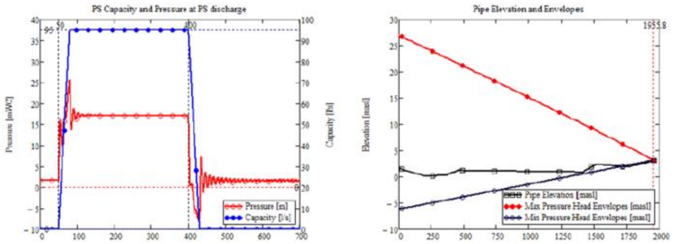
The purpose of controlling pumps by any of the above method is to provide controlled/moderate acceleration of flow in the system.

Throttling the system curve by a valve is not a good option for a sewage PS which by default starts frequently.

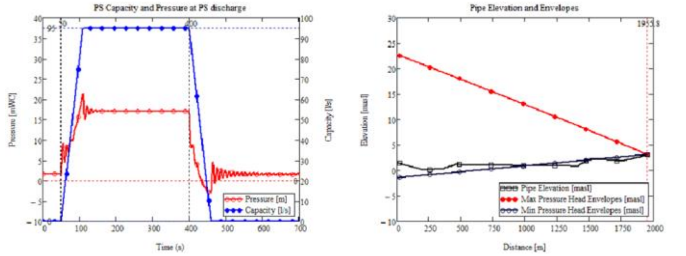
Both, soft starter and VFD, may provide controlled acceleration time. However, a VFD offers one advantage over soft starter because it enables a pump to constantly run with reduced speed. On the basis of the performed analysis, it is recommended that starting/stopping time for existing system and equipment should be longer than 120 seconds.

The results of the simulation for the PS capacities and pressure at the PS discharge and max. and min. pressure envelopes along the raising main are presented below for each case staring/stopping time of the pumps.

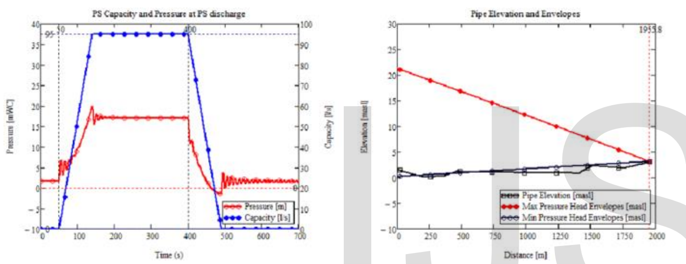
Case A: Starting from 50 to 80 s / Stopping time from 400 to 430 s



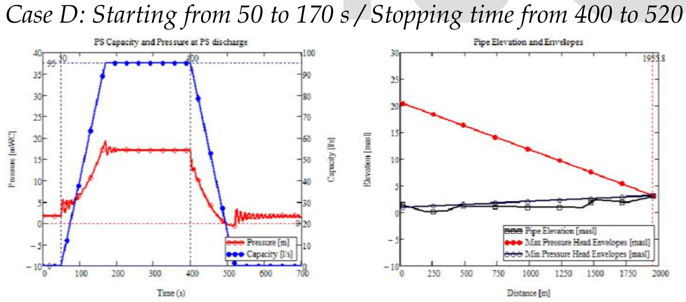
Case B: Starting from 50 to 110 s / Stopping time from 400 to 460 s



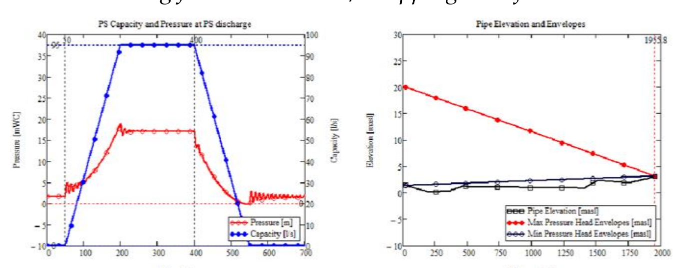
Case C: Starting from 50 to 140 s /Stopping time from 400 to 490 s



Case D: Starting from 50 to 170 s / Stopping time from 400 to 520 s



Case E: Starting from 50 to 200 s / Stopping time from 400 to 550 s



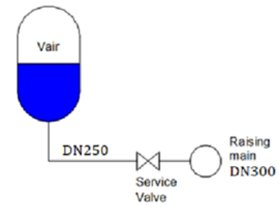
3.4 PS Failure – Pressure Vessel Design

The operation conditions of the PS considered in this analysis are as following:

No. of pumps in operation: 1

PS capacity: approx. 98 l/s
Wave speed: 1,157 m/s
Scenario: Trip/Power failure
Water Hammer protection equipment: Pressure Vessel at PS discharge

Integration scheme of the air Vessel in the discharge system of the PS:



Initial Air Volume in the Pressure Vessel VAir = 1, 2, 3 and 4 m^3.

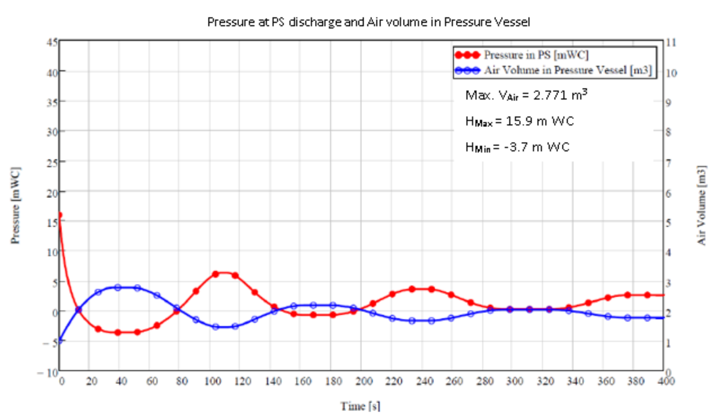
Analyses presented hereinafter deal with transients that happen after the pumps has been stopped working due to malfunction or failure in electrical supply. Non-controlled pumps cut out, no mater of possible cause, is followed with pressure oscillation in a piping system. The capability of a pressure vessel (or an air chamber) to attenuate pressure oscillations is proportional to initial volume of air in a vessel.

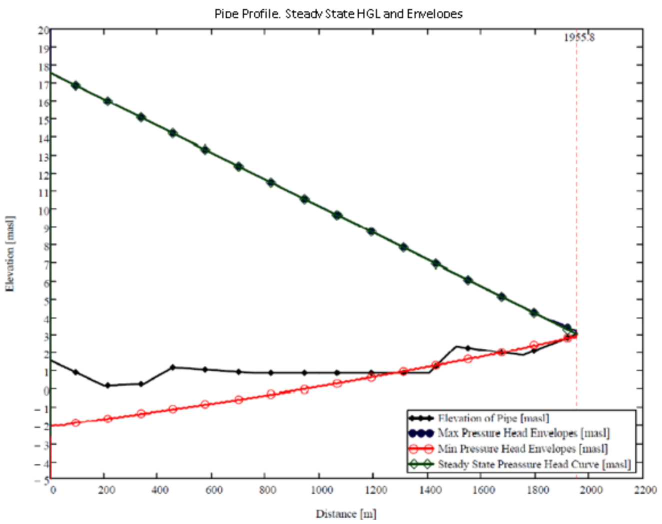
Generally, after pumps suddenly shut down pressure drop downstream of the pump and negative pressure wave start propagating along the pipeline from the pumping station to end of the pipeline with the speed of sound (wave speed). A properly designed pressure vessel provides that minimum pressure line (minimum pressure envelope) does not intersect with profile of a pipeline; otherwise negative pressure will occur.

Load imposed to the pipeline by negative pressure must be added to dead and live load to check for pipe deflection, critical buckling pressure, wall crushing performance and bending stress-strain (where necessary).

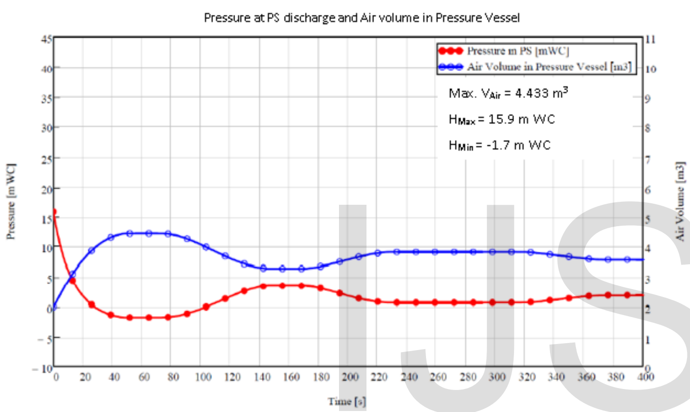
The results of performed calculations are presented in the following figures:

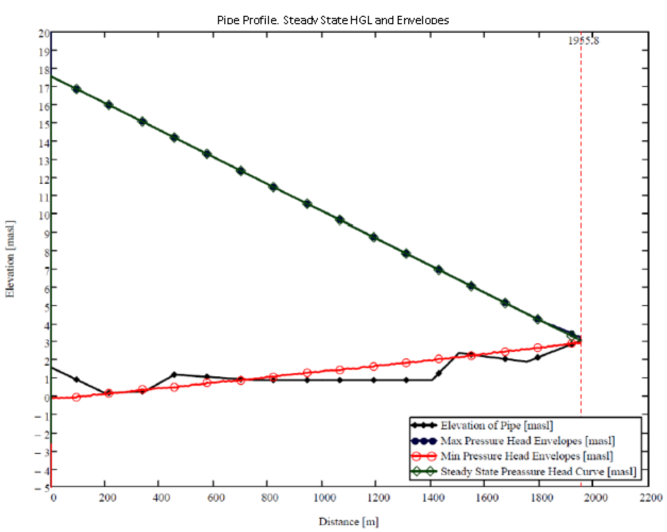
CASE A: Initial Air Volume V = 1 m^3



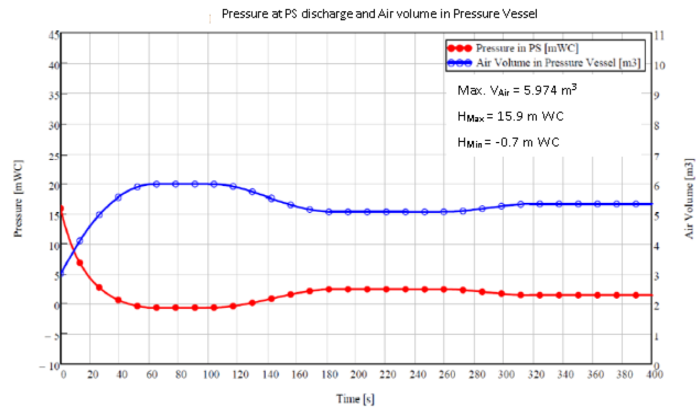


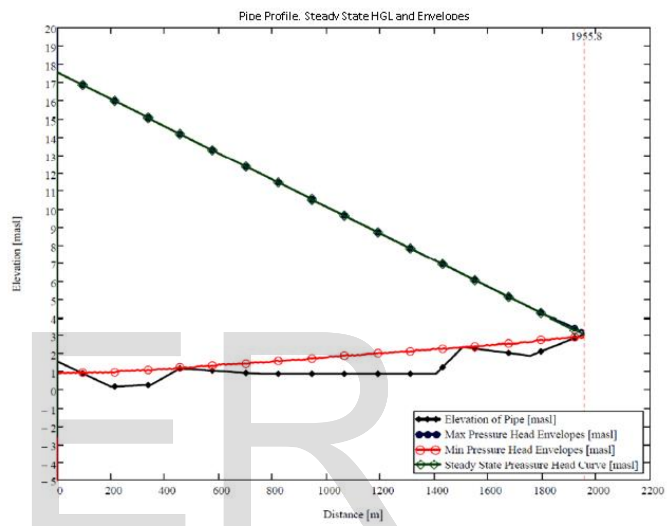
CASE B: Initial Air Volume V = 2 m^3



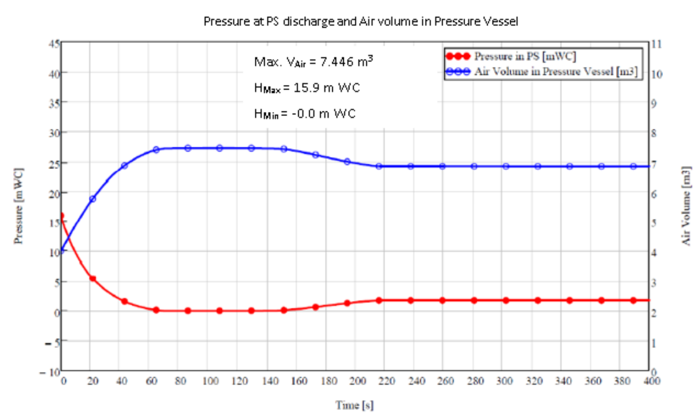


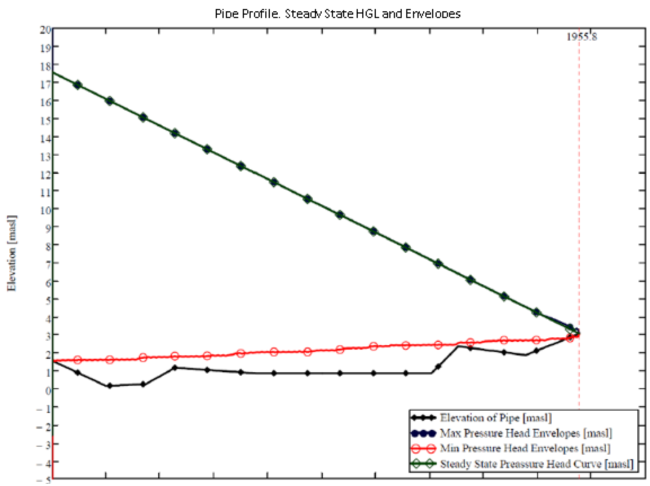
CASE C: Initial Air Volume V = 3 m^3





CASE D: Initial Air Volume V = 4 m^3





Results of unsteady state analyses define the size of the pressure vessel with the following characteristics:

1. Pressure Vessel Type: Membrane Pressure Vessel
2. Gross Volume: 10.0 m^3
3. Air volume: 4.0 m^3
4. Nominal Pressure: PN10
5. Pressure Vessel Connecting Pipe: DN250 with service valve DN250

4 Conclusions

Performed analysis shows that:

1. Each pump cut-off causes water hammer in the system. It happens in normal operation when the pumps stop and start as well as when the pumps fail from the electrical network. Because of low pump head and long pipeline, stops of the pumps cause water hammer separation and cavity-closure chock in reversal flow, both leading to extreme pressure values such as absolute vacuum condition and heavy over pressure of an approximate value of 16 bar.
2. The complex problem of water hammer shall be solved by dual-action which includes deploying of a bladder type pressure vessel to be connected to the rising main, and deploying a VFD to each pump. While the proposed pressure vessel will attenuate pressure oscillation during transients, the VFDs will eliminate any pressure oscillation during normal operation (pump stop and start) by extending the pumps ramping time to at least 120 s.
3. Another function of the VFDs would be reducing the pumps number of starting per hour, hence decreasing the loads imposed to the equipment and electrical network. The goal will be achieved with keeping constant level in the sump wherever it is possible.
4. Existing ball type check valves shall be replaced with flex type check valves. Although ball valves are suitable for sewage they have extremely unfavourable dynamic characteristics (very high reverse velocity) and are subject to slam. Flex valves are design for sewage services (high operational cycles) and have very good response to reversal flow. The valves shall be equipped with a damper for controlled closing.
5. A triple-functioning air valve shall be installed on the top of the discharge header, or at the top of the rising main, as close to the discharge header as possible. The role of the valve is to enable expelling of the air that is withdrawn through the pumps and collected at the top of the discharge header. Proper functioning of the valve is the key element in eliminating air pockets to be form and travel along the rising main.

References

[1] Joukowsky, N., 1900, "Über den hydraulischen Stoss in Wasserleitungsröhren. (On the hydraulic hammer in water supply pipes)", Me´moires de l'Acade´mie Impe´riale des Sciences de St.-Petersbourg, Series 8, Vol. 9, No. 5 (in German, English translation, partly, by Simin, 1904).
[2] Frizell, J.P. (1898). "Pressures resulting from changes of velocity of water in pipes." Transactions of the ASCE 39, Paper 819, 1-18 (presented 6 October 1897).
[3] Allievi, L., (1913). "Teoria del colpod'ariete"Atti Collegio Ing. Arch. (English translation by Halmos EE 1929) "The Theory of Water hammer", Trans. ASME
[4] Chaudhry, M. H. (1987). Applied Hydraulic Transients, Second ed. Van Nostrand Reinhold Co., New York, N. Y.
[5] Duc J. Negative pressure phenomena in pump pipelines. AS ME International Symposium on Water Hammer in Pumped Storage Projects. Chicago, (1965).
[6] Simpson A.R. Large water hammer pressure due to column separation in sloping pipes. Ph.D. Thesis, Dept. of Civil Engineering, the University of Michigan, Ann Arbor, Michigan. (1986).
[7] Wylie, E.B.; Streeter, V.L. Fluid transients. McGraw-Hill International Book Co.: New York, NY, USA, 1978.
[8] Wylie, E. B., and Streeter, V. L. (1993). Fluid Transients in Systems. Prentice-Hall, Englewood Cliffs, New Jersey.
[9] Wylie E. B. and Streeter V. L. Fluid Transients (Republished with minor corrections by FEB Press, Ann Arbor, Michigan, 1983). McGraw-Hill, New York, (1978).
[10] Zaruba, Josef Water hammer in pipe-line systems, ISBN 0-444-98722-3, 1993