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REVIEW ARTICLE

Water Hammer Analysis in Water Pipelines and Methods for Protection

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Abstract

In water processing industry, pressurised pipeline problems bring dangerous consequences, causing flooding, traffic accidents or death, financial and material losses and the disruption of the water supply. There are some problems in water pressurised pipelines system occur gradually, and some problems occur in very sudden without any warning with massive impacts and harms. Most of the sudden events that affect water system and municipal operation and maintenance centres are the phenomenon of sudden explosions and cracks in water pipes which lead to disaster. The phenomenon of water hammer is as a result of imperfect design or poor operation methods. The transition in the pressurised pipeline from one steady state to another steady state such as from a constant velocity to another velocity without a protection system make huge in pressure change. Any change in velocity leads to a pressure changes in very short time will cause to disaster strikes for the system stabilization. Professional design of liquid pipelines and proper selection of materials prevents the phenomenon of water hammer. Therefore, in this paper, the important issues on water hammer, protection systems and professional planning with special software programmes such as Allievi software was addressed.

Keywords: Water Hammer, Surge Tank, Hydraulic Transient, Pressurised Pipeline

Introduction

Various water hammer events frequently occur in pressurised piping systems. This water hammer can cause serious damage or even lead to the failure of the pumping station. In practise, most pressurised pipelines are subject to strong hydraulic fluctuations. The pipeline network consists of irregularly varying flows, especially when it pressurized. The operations team and researchers in the field are looking for solutions to reduce the occurrence of water hammer. One good strategy is to improve operating procedures (Kubrak et al., 2021)

The phenomenon of water hammer can cause pipes to burst, and there are many examples where the difference in pressure in a pressurised pipe system caused a rupture that led to the collapse of the road. In addition, it also can cause flooding in the streets and houses, can lead to disasters if it is near gas or steam lines or near power cables, and lead to criminal cases resulting in the death of some people.

Fluid or gas pipelines can be subjected to cyclical stresses during operation that could lead to failure. Pipe failure could endanger human lives, which is why manufacturers adhere to very strict safety requirements. However, there is still a risk of catastrophic failure when using welded structures. In most cases, failure is due to the presence of small pits in a place of high stress such as dirt, bulges and welding defects (Pérez-Sánchez & López-Jiménez., 2020). The aim of this article is to provide good understanding on water pipelines issues, good design and right material selection for pipelines to mitigate and control the effects of the water hammer phenomenon.

Water Hammer Phenomenon

In a water supply system, water hammer occurs whenever the steady state changes, e.g. when the pump is stopped, the pump is started or a valve is closed. When the system changes from one stable state to another stable state, there is a difference in flow and pressure, and then the system stabilizes in a fixed state. The magnitude of water hammer and the duration of the transition state depend on the rate of flow change, piping material, and other conditions such as pumps, air valves, tanks, and changes in pipe diameter (Gibson., 1908; Wróbel & Blaut., 2021).

The phenomenon of water hammer is still not clearly understood, due to the change of cases and the difficulty of making a uniform judgment on all cases (Boulus et al., 2005). Water hammer is defined as the pressure created inside the pipes as a result of the change in velocity of the liquid a change in velocity causes a change in pressure. In order to control the phenomenon of water hammer, a protection system must be built, taking into account three important things: Correct design of the protection system, correct installation of the protection system and correct operation of the protection system. A low pressure or negative pressure is no less important than a high pressure. Problems with negative pressure can also cause major damage, such as the collapse or deformation of pipes, which can damage the portable water supply and lead to health-threatening problems from water leaks or mixing with sewage pipes.

One solution to the problem of water hammer is to install a non-return valve, whose job is to keep the flow of liquid in the pipes in one direction. When the flow velocity changes a lot, pressure energy is generated from the kinetic energy. These pressures are variable and rapid in the pipeline, and as a result of the pressure changes, rapid water waves are generated (Chaudhry., 2014).

The most important reasons for the presence of water are fittings, pipes changes, valves and fittings which result in any diameter change, pumps, tanks or vessels, blockages or leaks in pipes, vibrating elbows, entrapped air pockets and wave speed changes due to any reason. In all these cases, there is a serious change in wave propagation upon transition (Kubrak et al., 2021).

Water Hammer Equations

In many cases, designers rely on straightforward mathematical equations to avoid the phenomenon of water hammer. One of the most meaningful and important equations for avoiding water hammer is commonly attributed to Joukowsky and is therefore often referred to as the "Joukowsky" equation (5) (Gibson., 1908).

Joukowsky Equation

Joukowsky equation relates the change in maximum pressure (ΔP) to the change in fluid velocity before and after a sudden valve shift (ΔV) as mentioned in (1). Here (ρ) is the fluid density and (C) the wave propagation velocity:

$$\Delta P = \rho \times c \times \Delta V \tag{1}$$

The above method is a useful description of the water hammer phenomenon in practise, it is simple and easy. Equation (1) allows the estimation of the maximum pressure range due to water hammer for cases of unsteady flow in flexible pipes (Gibson, 1908; Chaudhry., 2014). Transient flow equations can be expressed in the following forms:

$$\frac{\partial Q}{\partial t} + \frac{c2}{gA}.\frac{\partial Q}{\partial x} = 0 \tag{2}$$

$$\frac{\partial Q}{\partial t} + gA.\frac{\partial H}{\partial x} + fQ\ \frac{|Q|}{2DA} = 0 \tag{3}$$

Where, f is the friction factor (-), c is the pressure wave velocity (m/s), H is the metric head (m), Q is the discharge (m^3/s), g is the gravity acceleration (m/s^2), x is the space coordinate (m), t is time (s) and A is the cross-sectional area of the pipe (m^2) (Chaudhry., 2014).

From this equation it can be seen that any change in velocity (ΔV) leads to a change in head (ΔH), pump failure due to power failure: The interruption of the power supply to the pumps leads to a change in the flow rate in the pipeline, i.e. a change in velocity (V), i.e. a change in pressure head (ΔH).

Shutting down or starting a pump, closing or opening a valve will result in a change in V, a change in total flow and a pressure variation, as will a flushing operation, the collapse of a cavity, a rapid change in demand, a rapid change in the level in the reservoir, a rapid change in the level in the tank, a pipe burst, the slamming of an air valve, the slamming of a non-return valve, the shutting down of an elevation valve in the tank or any other event that results in a change in velocity or pressure in the pipeline.

The level of velocity and pressure change should be checked whether it causes damage to the pipeline or otherwise. If so, installation of a protection system need to be addressed because the pipelines that are not adequately protected can cause pipe and element ruptures due to a high pressure surge. If the transient pressure increases as a result of the force in the pipeline, various types of failure may occur. For example, an extreme pressure drop can cause the pipeline to collapse, while pumps and other hydraulic equipment can fail completely if the flow is cavitating. On the other hand, a positive rise above the pipeline's design pressure can cause the pipeline to burst (Chaudhry., 2014).

Close the valve suddenly (Characteristic time)

When the valve is suddenly closed, the waves are compressed before the area of the stopper and stretched after the area of the stopper, i.e. the pressure upstream increases, the pressure downstream decreases.

We need to calculate the wave velocity, the characteristic time and the rate of valve closure. Wave speed A can be calculated using the following equation:

$$A = (\frac{\sqrt{K}}{\rho})/\sqrt{(1 + \left(\frac{K}{E} \times \frac{D}{e}\right))} \tag{4}$$

Where;
D: pipe diameter, e: pipe wall thickness, E: young's modulus, K: bulk modulus, ρ: fluid density.

Characteristic time (Tr) is time wave to go and return to the same place from which it generated:

$$Tr = \frac{2L}{a} \tag{5}$$

Rate of valve closure (Tc) is the time required for the valve to close, the closure of valves are classified as 4 cases of instantaneous closure: when Tc = 0; Rapid closure: when Tc ≤ Tr; gradual closure: when Tr < Tc ≤ 10 Tr and slow closure: when Tc > 10 Tr

Protection System

The control measures taken often involve the use of special equipment, such as surge tanks, air vessels, and air valves. The results of several studies have shown that these devices are significantly capable of alleviating the transient state of water distribution networks (WDNs) Rezaei et al., 2015). Therefore engineers are trying to reduce the impact of the water hammer phenomenon. Protective measures range from installing special devices such as pressure relief valves and air vessels, selecting pipe characteristics and adjusting the operating procedures (Gong., 2018). Each of these solutions has significant drawbacks, including the need to drain the liquid outside the pipeline, the need for large tanks, or the delayed mitigation of the pressure wave (Ramezani & Karney., 2017).

The pressure increases during the occurrence of water hammer with the increase of the velocity of the pressure wave, so it is preferable to reduce the velocity of the wave, and this can be done by placing flexible pipes inside the pipeline (Zhang et al., 2008).

Air Vessels

Air vessels (or air chambers) are installed in areas where water hammer is common and are typically usually located behind tank's valves. They are shaped like a thin, inverted bottle with a small opening connected to the pipe and are filled with air Fig.1. The air is compressed to absorb the shock and protect the fitting and pipework (Stephenson., 2002).

An air vessel is also known as air chamber, pressurized surge tank or pneumatic tank. The volume of water and the volume of air in the air tank determine how the air tank works.

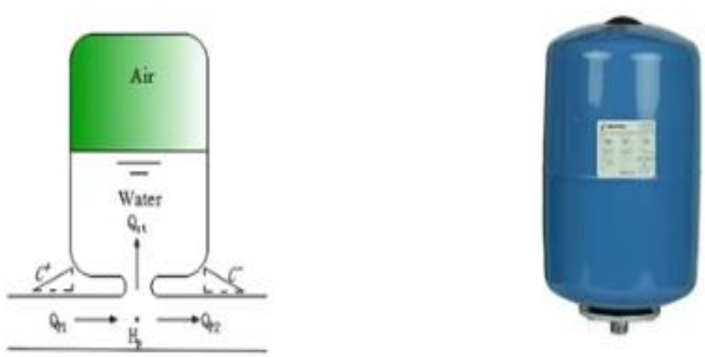

Figure 1. Air Vessel installed in the pipeline

Check Valve

Backflow through the pump when a power failed can be prevented by installing a non-return valve in the pump's discharge pipe. This device serves to keep the pipeline filled with water and prevent air from entering the system (Jones et al., 2008).

When the water flow in the pipes returns as a result of the power cut-off, the non-return valve (CV) starts to close. In this case, the pipes are subjected to a sudden, rapid back pressure by the closing of the CV. Jones et al. Tom suggested reducing the speed of closing CV to mitigate the large hydraulic surge caused by closing CV, but if the closing time is increased, the duration of the pump's rotation in the opposite direction increases (Wahba., 2016).

Authors showed that it is important to establish a reasonable operating time differential in pump-valve systems to prevent backflow, reverse rotation and overpressure (Wan & Li., 2016).

Normally, the water is shocked in the last phase of closing the CV, so the speed of the valve must be reduced. In one of the designs Fig.2, a pin was used to make the valve close gradually in the last phase of closing. Some companies compete in developing special mechanisms to achieve slow closing in the last part of the closing process.

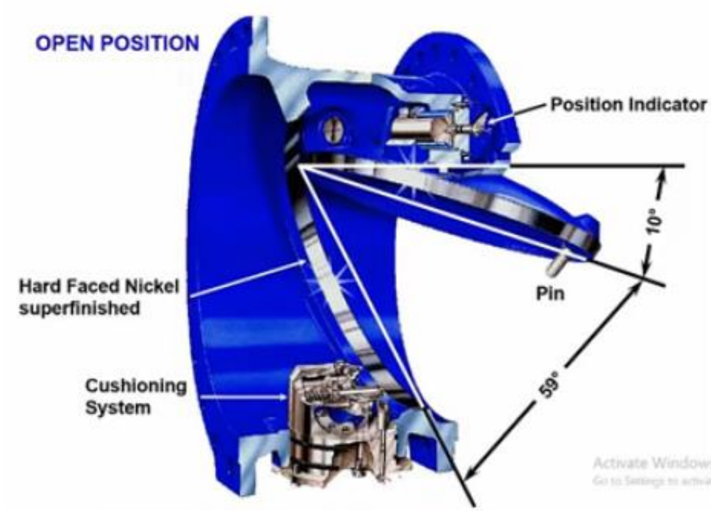

Figure 2. Check valve with special pin mechanism

Air Release Valve

Air release valve (PRV) is installed at the highest point of the pipeline. It opens when the pressure in the pipeline exceeds a certain limit. It ensures the stability of the pipeline pressure. It protects the pipeline from high pressure damages. There are different types depending on the pressure and size of the pipeline. An undersized pressure relief valve is used in special cases, it is not able to provide protection against extreme pressures (Ramos & Beta$_{\chi}$ mio de Almeida., 2002).

Control of Pipes Thickness and Specification

It is necessary to select the specifications of the pipeline metal accurately. The thickness of the pipe plays an important role in protecting the pipeline from sudden pressure differences. Increasing the thickness of the pipe can be more expensive, but it is an important factor in protecting the pipeline and prolonging its life, and reduces the surface cracks on the pipes.

Software applications to protect pipelines from water hammer

In the last three decades, the availability of software applications based on diagrams dealing with the problem of water hammer has increased. This is very helpful in determining the types of protection devices that reduce the effects of sudden high pressures and help make hydraulic water waves more stable.

Allievi software is a free license, it's a research product package developed by the University of Valencia (Spain), which is characterised by the dynamic comparison of scenarios, a large number of elements and a steady-state as well as a transient analysis, also Allievi software can conduct calculations with/without cavitation, The experiments case study in this paper will be applied to the Allievi program.

Analysis of Pump trip-out by Allievi software

The case study in this paper explores ways to prevent water hammer damage when a pump fails. Pump trip-out occurs because the pump is not needed, or unplanned due to a sudden failure, such as a power shutdown. As a result of a pump trip-out, a negative pressure is created which generates air bubbles that grow larger and larger and form an air pocket. This pocket is compressed in the pressurised pipe and there is an impact and knocking on the pipe wall, which is called water hammer.

Allievi software will be used to perform a water hammer analysis in the event of a pump trip out. Allievi is a free license software that can be used to analyse steady as well as transient analysis in transmission pipeline and distribution network, the software is a research product package that is developed by University of Valencia in Spain (Santana., 2018). Allievi software is characterized based on large number of elements, no of notes and including pumps and turbines,dynamic comparison of scenario, steady as will as transient analysis and calculations with/without cavitation.

Experimental Case Study

The pipeline line consists of two tanks, one pump and pipes, the pump will suction water from tank 1 into tank 2 through pipe. The details information on the process operation is given as below:

- Pump specs: Q: 488 L/s, H: 140m, ή: 70%, N: 145 rpm
- Pipe spec: Steel Cast Iron pipe size diameter: 600mm, Sch10: 7mm thick

In the beginning before pump trip out, the pressure is high, when the pump stop, there is a gradual decrease in the hydraulic waves, and eventually it will fall to the pump centre line, and a negative pressure will occur, which leads to the occurrence of cavitation and column separation. It's required to use Allievi package to analyse the effect of pump trips on the pipeline shown below Fig.3.

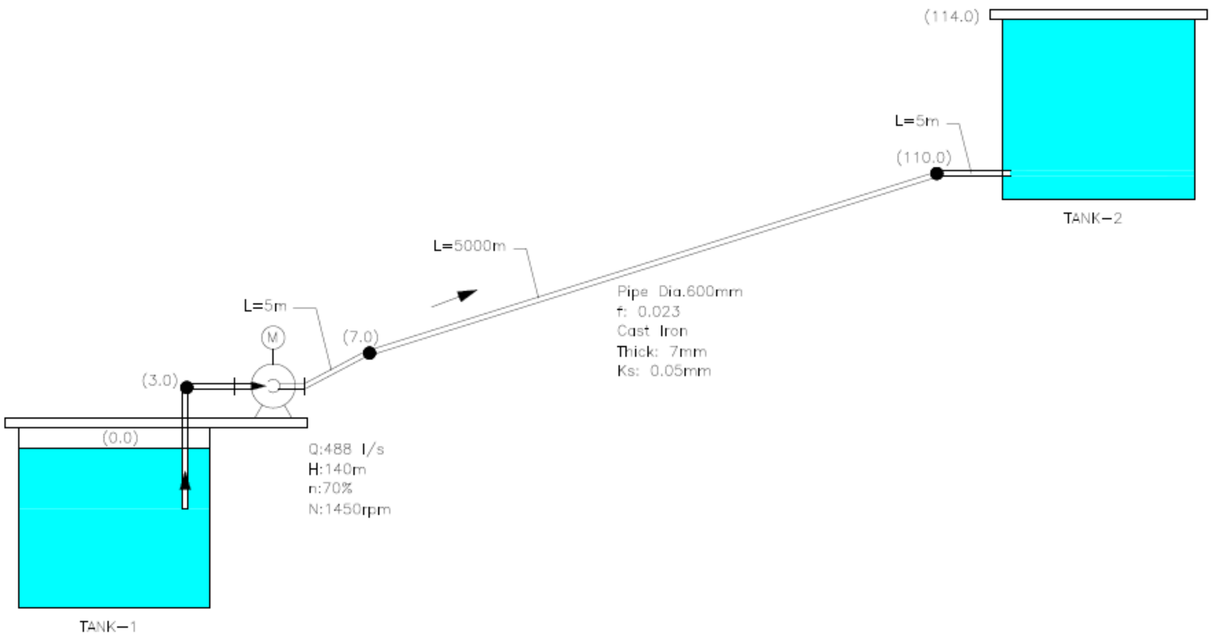

Figure 3. Pipeline 5010 m – 600 mm Dia. With pump and two tanks

First Scenario Pump trip-out without protection

Analyse the effect of pump trips on the pipeline without any protection. By using Allievi and assumed data, the pipeline drawing will be as Fig.4, the pipe line consist of two tanks, pump and pipe (5010 m x 600 mm Dia.)

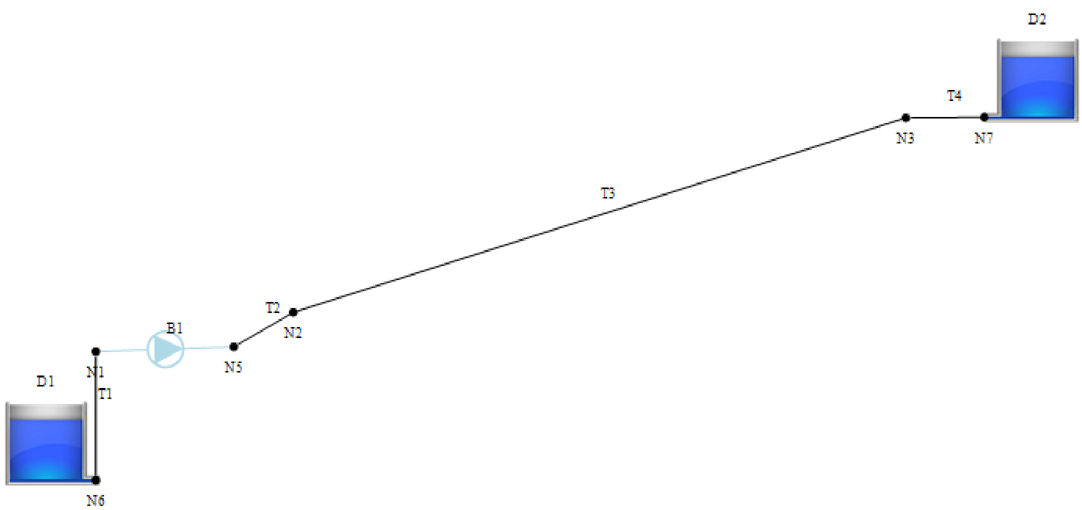

Figure 4. 1st scenario of pipeline without protections

By Allievi, the Envelopes graphs will be as Fig.5, we notice the following. The maximum pressure (red line) reach to 218m, while in the steady state (blue line) is 133m. There is an increase in pressure 85m (8.5 bars) as a result water hammer, which leads to the collapse or explosion of the pipeline.

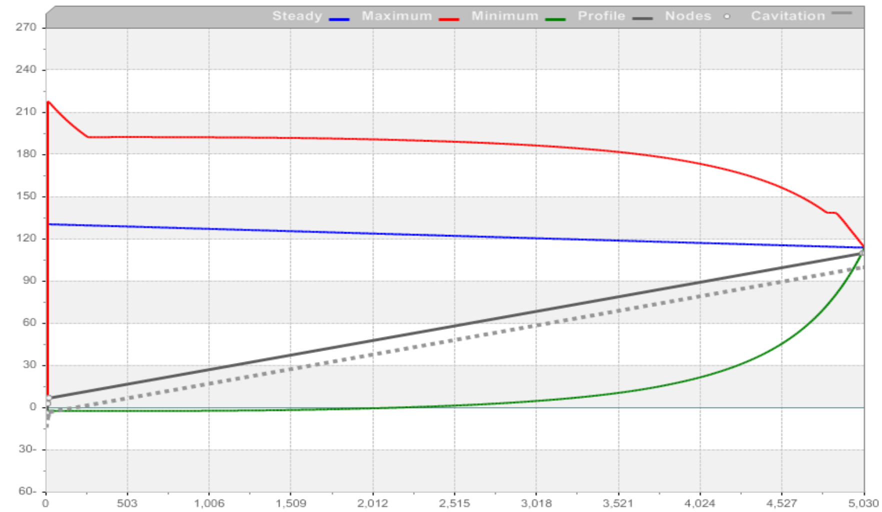

Figure 5. Pump trip-out scenario without protection

Allievi show the animations gradually over time. From Fig.6, when the water wave (blue line) goes under the grey line, this main there is a negative pressure and cavitation along of pipeline.

Figure 6. Negative pressure and cavitation after 10 s

After 26 s the pressure (red line) increased up to 220m, in addition of cavitation as in Fig.7, the big problem need to be solved by install some equipment to protect the pipeline of damage.

Figure 7. Negative pressure, cavitation and high pressure (220m) after 26 s

Second Scenario Pump trip-out with protection (adding one air vessel)
We will install an air vessel C1 in the maximum pressure point (point N10 directly after the pump). The air vessel C1 is a vertical type, with volume 28 m^3 (or 4 x 7m^3) Fig.8.

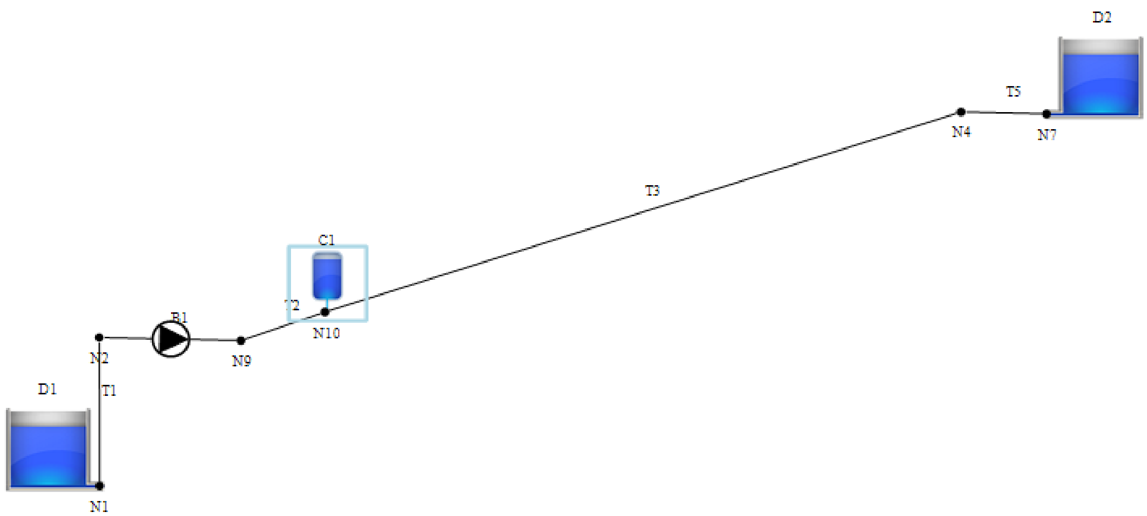

Figure 8. Pipeline without protections

Based on the Allievi software, results in Fig. 9, depicted the following finding of the maximum pressure decrease up to 133m, it's the same of the steady pressure, but still more than the steady pressure in point 4527m, then still we have problem and need to more protection approaches.

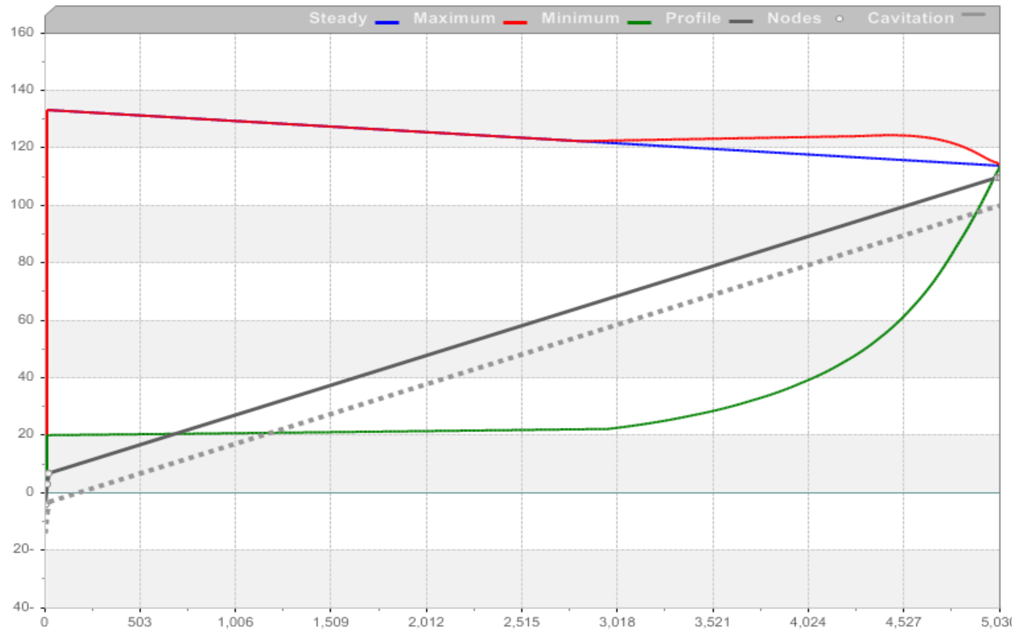

Figure 9. Pump trip-out with one air vessel as protection

By Allievi animations gradually over time as in Fig.10 showed that the cavitation disappeared from point 0 to point 1700 m, but it still available from point 1700 m to 4000 m.

Figure 10. Negative pressure and cavitation at point 1700 m to 4000 m after 10 sec

Third Scenario Pump trip-out with protection (adding two air vessels)

We will install another air vessel C2 in the high pressure area at point N11. The air vessel C2 is a vertical type, with volume 60 m^3 (or 4 x 15m^3) as in Fig.11.

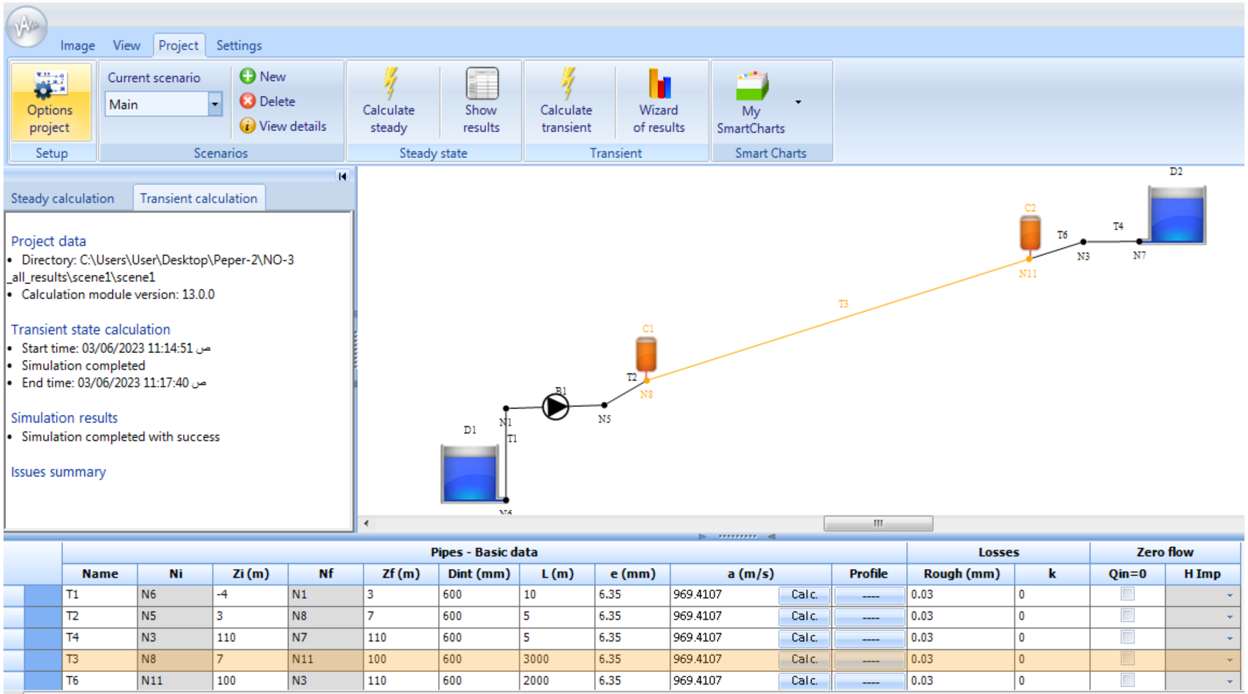

Figure 11. Allievi water hammer simulation with 2 air vessels

By Allievi, the graphs the process will be plotted as in Fig.12, the following phenomena as found that are no more any pressure above the steady state pressure along of pipeline

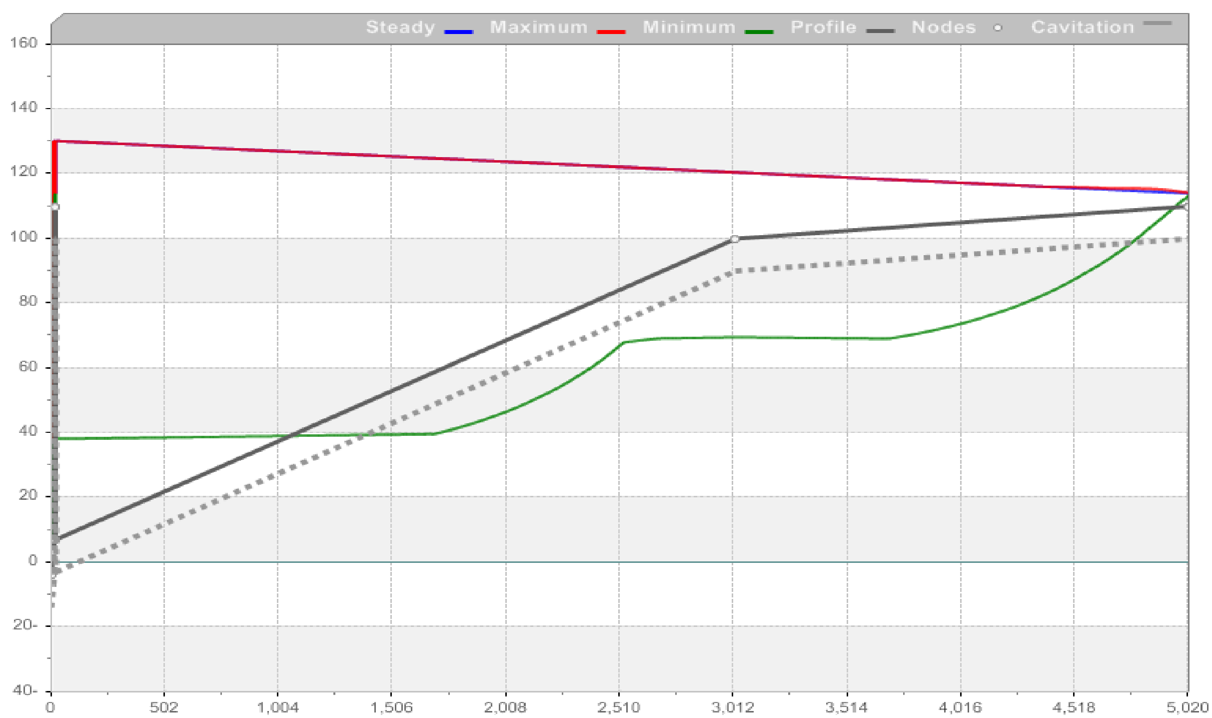

Figure 12. Pump trip-out with two air vessels as protection

Results from Fig.13, revealed that, the used of two air vessel caused the cavitation disappeared permanently.

Figure 13. Result of no negative pressure, no cavitation after 21 s

Conclusion

From the case study analysis, the following steps must be taken into account when design the pipelines to avoid the water hammer problems: a) Pump starting problems can be avoided by increasing flow slowly, or by maintaining low piping speeds. b) Sudden pressure surges in the pipeline can be mitigated by installing a tank directly on the pipeline. It is an air tank or a surge tank. c) The best way to avoid damage from water hammer when the pump is shut down is to install check valves that close automatically.

They should be closed quickly but gradually in the last phase of shutdown. d) The occurrence of a pressure rise or fall at high points in the pipeline requires the installation of an air and vacuum relief valve. e) The result of these experiments is that the air vessel attenuates the hydraulic waves created by the sudden shutdown of the pump. It is important to determine the number of air vessels, the appropriate location, size and all specifications of the vessels. All this was done with the help of the Allievi software, which has flexibility and practical options that enabled somewhat to solve the water hammer problem. And f) The Allievi software is the best tools for water hammer analysis and design simulation verification.

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