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Model and protected design of water piping system to minimize the water hammer effect

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Abstract

The effect of the water hammer is investigated to predict the water hammer effect in a wastewater pipeline and to develop the piping system design to overcome the predicted effect. The piping system is sensitive to any effects of the water hammer phenomenon. The sudden change in pressure within pipes or conduits used to transport liquid under pressure may result in serious damage. A modified numerical approach is developed to predict the water hammer effect. The system under study was modified to handle and reduce the effect of water hammer. By calculating the water hammer's effect, the safe piping system design can be developed. A model was developed to predict the effect of water hammer and the expected pressure drop/increase across the piping system. The pipe properties and measured pressure are the model operating parameters. The maximum and minimum pressure envelopes across the piping system were calculated. By simulating the power failure and/or pump shut down, the model showed a good prediction for the effect of piping system design variations. The optimum design for the piping system was developed and presented.

Keywords: the water hammer, surge analysis, piping system, pressure, pipelines

1. Introduction

The water hammer is a serious phenomenon occurring in water supply and wastewater treatment pipeline systems. For piping system safety, the effect of water hammer should be considered while designing the piping system to ensure that the system will handle pressure variations [1]. Water hammer refers to a momentary pressure increase within the piping system as a result of a sudden change in the liquid velocity or direction within the piping system [2-3]. It is important to avoid the water hammer in the piping system to prevent pressure increase, which may result in pipe rupture or equipment damage [2-4]

Analyzing the flow in networks and pipelines has presumed that the flow is at stable conditions. So, the flow does not alter at any place in the pipeline scheme with time. The analysis becomes easier with the idea of uniform flow, and solutions are simple to acquire. A transient condition should be considered while studying the flow as pipeline flows are often unstable as a result of sudden valve opening and closing. All transient flows are either long-term or short-term transitions. Transient flow can be described as a fluctuation of flow when a fluid or gas flow velocity and pressure alter over time as a result of system modifications, specifically pressure-related transients. It is not feasible to prevent pressure transient when operating a piping system, but this situation can be controlled [1-3].

Closing or opening valves in the piping scheme, turning off the energy supply, or a power failure and/or machinery failure are the primary causes of

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transient flow circumstances. The sudden closure of a control valve, the pump shut down, and the variation of the discharge owing to discharge variation due to the pipeline's rupture results in surplus stress in a pipeline. Due to the abrupt closure of the hydraulic valve, the unstable flow is frequently experienced in hydraulic power plants with a lengthy conduit without the surge tank's supply. The speed in the water hammer scenario fluctuates within the pipe from considerably elevated to exceptionally low with a change of direction after a certain time interval [1-4].

During the water hammer, shock waves travel through the piping system back and forth in speed equal to the speed of the sound in the flowing fluid [3-5]. The waves travel back and forth between solid obstacles like valves and pumps until the pressure reaches a steady value. As a result of sudden valve closure, a force is excreted on the valve’s closing element by the liquid column momentum. The liquid column separation will lead to a pressure increase on the valve’s upstream side and a pressure drop on the valve’s downstream side. A vacuum will be created on the downstream side. The liquid will attempt to carry on the flow, which may collapse or implode the pipe. This issue might be riskier if the pipe is mounted on a downhill slope.

Water hammer is a transient phenomenon that takes place when quick valve closure blocks the pipeline flow unexpectedly. It is a function of the fluid compressibility in which sudden pressure changes occur. Understanding water hammer is critical to prevent unnecessary stress in pipelines that may cause harm to the pipeline [3]. The pipeline pressure shift depends on gas speed, valve time closure, and the closing valve arrangement [4]. During the valve closure or at the end of the closure procedure, maximum stress may happen. Therefore, brief times during valve closure, particularly in emergency circumstances, are crucial in decreasing the peak pressure. Since this harm is not always noticeable until long after the case, transient stress is hard to regulate. Valves are always mounted in the pipeline to regulate the flow of gas in the event of harm.

Leishear, R. A. [5] reported that major breaks can trigger the transient stress results from an abrupt shift in the flow velocity. The hydraulic transient is widely known as the water hammer. Leishear [6] conducted an experimental study to evaluate water-hammer wave velocities and pressure increase. The purpose of the study was to determine how well classic hydraulic transient elastic theory can predict the water hammer in polyvinyl chloride (PVC) and strengthened plastic pipes. The results were in good agreement with the theoretical calculations.

The pressure change in pipelines is affected mostly by the following factors: the arrangement of the closing valve, gas velocity, and valve closure time [4]. The pressure could reach a maximum value during valve closure or at the end of the closure operation. Consequently, the maximum pressure can be reduced by employing short valve closure times, especially in emergency conditions. It is difficult to control the pressure transient since the damage is usually not visible instantaneously. To reduce the damage related to the pressure increase, valves are employed to control the gas flow in the pipeline.

Moghaddas [7] defined four different methods to modify the valve action (closure law). The four methods are known as concave, convex, linear, and instantaneous closing law. The four closing valve laws are mathematical functions describing the flow speed variation during the valve closing. Valves are employed to control the gas flow in the pipeline gas flow to reduce the damage related to the pressure increase. The closure rate is an important factor in controlling the water hammer phenomenon [1]. Valve closure time is an important factor affecting the water hammer. Several attempts were made to optimize the closure time of the control valves considering various constraints.

Urbanowicz [8] introduced air chambers and safety valves for controlling water hammers. Heng, Z. [1] established a closing rule curve to control the impact of water hammer on the valves used in pipelines. The developed curve predicts that the valve closing scenario in fluid flow will include an increase in the pressure and pipe discharge. Warda [9] explored the effect of several parameters including viscosity, velocity, and compressibility of the flow on the water hammer. Kaveh Hariri Asli [10] investigated the water hammer effect within hydraulic systems and tested several hydraulic parameters sensitivity and their effect on the water hammer phenomenon.

Vítkovsky [11] discussed the detailed and accurate simulation of pressure Zielke and Vardy-Brown unsteady friction in pipe transients [12]. The authors have developed a model for predicting the friction effect in pipelines under several operating conditions to reduce energy loss due to friction. The least square method was used successfully to develop an exponential model to describe the pressure fluctuation though pipelines [13]. Several models were developed based on the Zielke classic function with a reasonable accuracy [12-14].

The water hammer phenomenon is a significant factor in design in many hydraulic systems due to the extreme pressure difference created. The drastic increase in stress can cause tubes to break. An adverse wave accompanying the elevated pressure wave can trigger very low pressure leading to contaminant intrusion. It is necessary to establish momentum and continuity equations to model the water hammer phenomenon in conduits. The momentum and continuity equations are a set of non-linear, hyperbolic, partial differential which can be solved numerically. The Finite difference method (FDM) and the method of characteristics (MOC) are two common numerical methods used widely to study the discharge and transient pressure in the water hammer phenomenon.

In this article, the water hammer will be studied to develop a model to predict the water/wastewater piping system's pressure changes. The system behavior will be investigated before and after the proposed system protection to check the effectiveness of the proposed protection. The main objective is to develop a modified numerical method to predict the water hammer effect. The mathematical formulation of the model will be deliberated. The model results will be discussed in detail to figure out how to change the process parameters to reduce the impact of the water hammer on the piping system. Based on the model results, the piping system design is improved to overcome the water hammer effects. The piping system specifications and design will be presented. The water piping system under study contains a surge vessel and two air tanks.

This article represents an innovative solution for reducing the water hammer effect on the piping system. The developed model can be used for studying and predicting the water hammer effect on the piping system. The developed model and proposed protection could help in minimizing the maintenance cost and increase the lifetime of the piping system.

2. Model Equations

The dependent model variables are the flow velocity V and pressure P, as shown in Equations (1-3). The partial differential Equations (1-2) are developed based on continuity equations and solved using Transient Flow Modeling Software [15]. The following specifications of the piping system will be considered: the measured pressure surges, and pipe properties required in the pipe strain. The time t and the unrolled reach of pipe x (distance) are independent variables for each pipe in the piping system. The initial conditions were determined as the steady state conditions of the flow inside the pipeline before the commencement of water hammer. The boundary conditions are determined based on the pipeline inlet and outlet conditions. The detailed mathematical model originated from the Continuity Equation is illustrated below:

$$\frac{\partial V}{\partial X} + \frac{1}{\rho . a^2} . \frac{\partial P}{\partial t} = 0 \qquad [1]$$

$$\frac{\partial V}{\partial t} + \frac{1}{\rho} . \frac{\partial P}{dx} - g . \sin(\alpha) + \frac{\lambda}{2.d} . V . |V| = 0 \qquad [2]$$

Where:
V: velocity, m/s
t: time, s
a: Wave propagation velocity through the fluid in the pipeline, m/s
ρ: density, kg/m^3
x: distance/piping system length, m
g: Acceleration of gravity, m/s^2

The mathematical model was applied considering the initial piping system design. The model equations were solved using computer numerical techniques to predict the effect of water hammer on the system under study. The model results were used to improve the piping system design. The regions controlled by water hammer were described by the method of characteristics (MOC). A time-line interpolation scheme was used to find the first occurrence of water hammer at a computational section.

2.1 Surge analysis

Using a computer model (KY Pipe – version 2018), surge analysis was conducted to study the effect of the water hammer on the pipelines and the pump station across the piping system at a pipe distance of 3500 m. The analysis was used to conclude the best solution to protect the system against the water hammer effect. The piping system was designed according to process requirements. The analysis was done initially assuming a regular system design. According to model results, a protection method was developed, and the analysis was performed again for the protected piping system. Once safe protection was developed according to the model results, a final design of the piping system was issued. The developed model was able to provide an excellent prediction of the water hammer effect on the piping system.

The first run was conducted to simulate a power failure or pump shut down assuming an unprotected piping system. The hydraulic gradient and the maximum and minimum pressure envelopes along the line after a power failure are presented in Figures (1-2). Figure (1) shows the change in pressure across the piping system as a function of the pipeline length. The pressure change diminishes as the distance increases when the power failure occurs from 16 to 2 m at a pipe distance of 3500 m. Figure (2) shows the maximum and minimum envelope profile as a function of the pipeline length.

As shown in Figure (2), the maximum pressure envelope profile shows a pressure rise in the pipeline doesn't exceed the permissible pipeline pressure, corresponding to an elevation change= 23.1 m (Safe). The minimum pressure head envelope shows a pressure drop in the pipeline exceeding the permissible pipeline pressure at most nodes, corresponding to an elevation change= -5m (Unsafe). The results indicated that the system will not be handle sharp pressure changes safely. Based on the simulation results, one can conclude that piping system protection is needed.

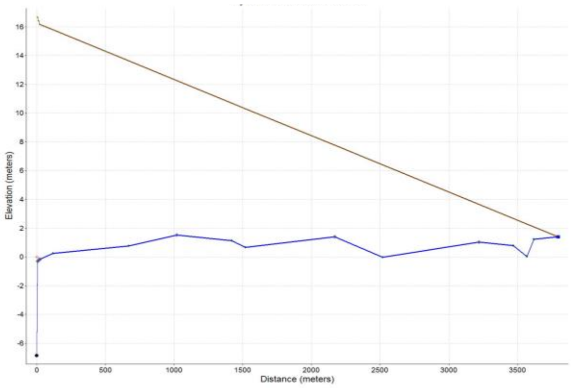


Figure (1) Hydraulic gradient curve before protection

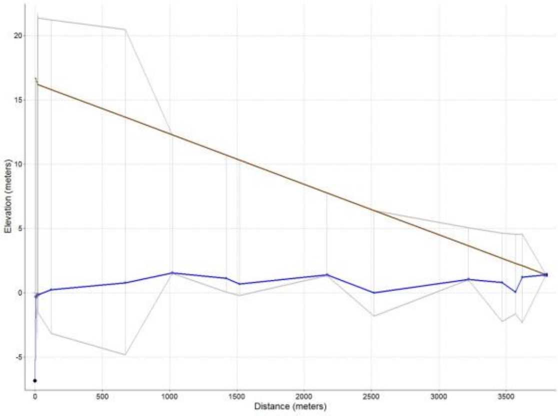


Figure (2) Maximum and minimum envelope profile along the pipeline after power failure

Several system protection methods and designs were applied numerically to optimize the system response and minimize the water hammer effect using the developed model. To study the effect of the protection on the system behavior, a second run is done by simulating a power failure or pump shut down after protection to mimic the system behavior after protection. Figures 3 and 4 show the time dependent volume and pressure gradient.

Figure (3) shows the gas volume after protection in m^3 at the outlet of 3500 m pipeline as a function of time. A closed surge tank of a total volume of 15 m^3 and initial air volume 6 m^3 (air volume at steady state) were implemented in the system design, as shown in Figure (3). Figure (4) shows the maximum and minimum pressure head envelopes along with the line profile after power failure using a protected piping system design at the outlet of 3500 m pipeline as a function of time.

The maximum and minimum line pressure was 2.3 and - 0.5 bar respectively. Maximum and minimum pressure envelopes don't exceed the permissible pressure (pressure increase corresponding to an elevation change =23.1 m (Safe), pressure drop corresponding to an elevation change = - 1.8 m (Safe).

Figures 3 and 4 indicate that the protection system has reduced the variation in pressure to less than 2 m of pressure head after around 1500s.

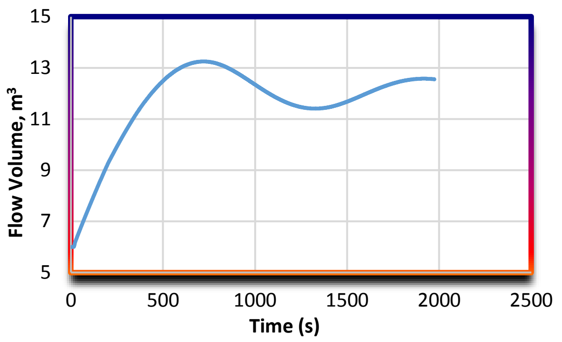


Figure (3) Gas volume after protection at the outlet of 3500 m pipeline

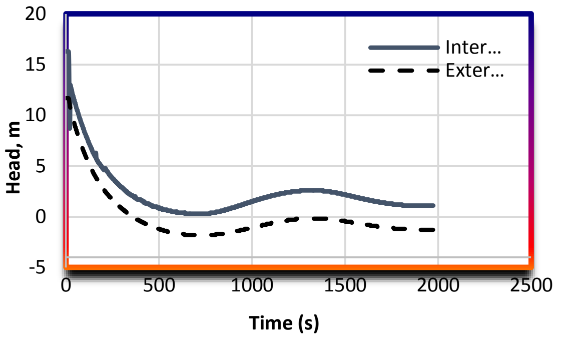


Figure (4) Head Curve at the outlet of 3500 m pipeline

3. Piping System Design

The model results gave a good forecast for optimum protection design that can be applied to protect the piping system. The model results presented in Figures (1- 4) showed expected system performance, which was used to develop suitable protection for the piping system under study. As a part of the protection system, different flow control instruments were used to control the effect of the water hammer. The protected system was studied to ensure a minimum water hammer effect. According to model prediction, a protected piping system was designed. In the following section, the air compressor and the air receiver tank design calculation will be discussed in details:

Air Compressor Calculations:

The compressor required flow rate can be calculated according to the following method:

$$P_1V_1^n = P_2V_2^n \qquad [3]$$

Where:

P_1: *Atmospheric pressure (1 bar),*
V_1: *Required volumetric flow by air compressor(l/m),*
P_2: *Gas pressure inside tank (bar),*
V_2: *Volumetric flow into tank (l/m), and,*
n: Gas constant (= 1.2).
n: Gas constant (= 1.2).

Applying Equation (3) under the following conditions, 15 cm height of dissolved air compensation in 10 minutes. Therefore, the required flow can be calculated as follows:

$$(1)*(V_1)^{1.2} = (2.5)*(425)^{1.2}$$

Then, Required flow (V_1) *= 91.2 LPM*
Compressor used = 580 LPM

The compressor used was able to mainain an air of 580 LPM flowrate

Air Receiver Tank Sizing

The air receiver tank volume is calculated according to the following method:

$$V = (t * C * P_a)/(P_i - P_f) \qquad [4]$$

Where:

V: Volume of the receiver tank (L)
t: Time for the receiver to go from upper to lower pressure limits (min)
C: Free air needed (580 lpm)
P_a: *Atmosphere pressure (1 bar)*
P_i: *Maximum tank pressure (3 bar), and,*
P_f: *Minimum tank pressure (1 bar)*

Calculation is based on 2 bar compensation in 1 minute, therefore:

$$V = (1 * 580 * 1) / (3 - 1)$$

Required receiver tank volume (V) = 290 L
Air receiver tank volume used= 300 L

The standard air receiver tank used was 300L.

Protected system:

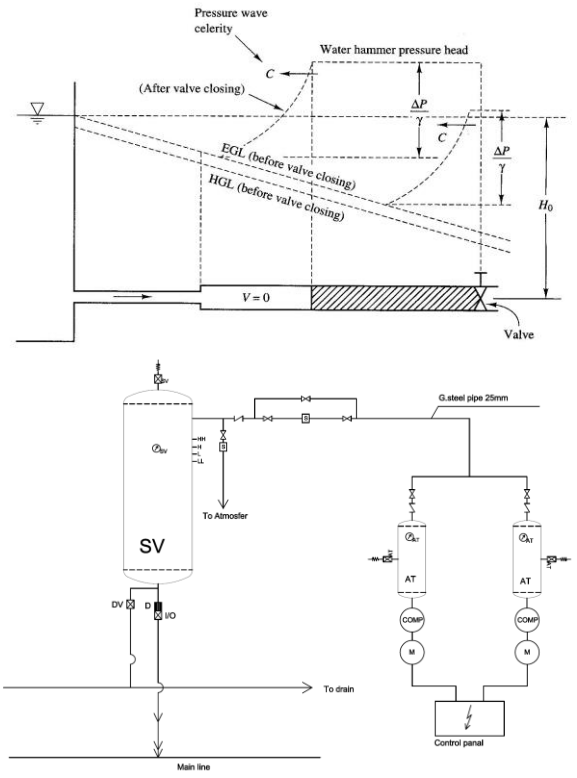
The protected water piping system developed is shown in Figure (5). The system contains a surge vessel and two air tanks. By modifying the system design using valves, pumps, and air compressors, system protection can be achieved. The pumps and piping specifications are listed below.

Pumps characteristics:

- Working pumps: 2
- Discharge per pump: 50 l/sec
- Head: 25 m
- Speed: 1450 rpm

Pipe line:

- Total length: 3777 m
- Pipeline Nominal Diameter:350 mm.
- Material: HDPE
- Roughness coefficient: 150 (Hazen-Williams)
- Wave speed: 300 m/s



Item	Qty	Description
AT	2	Air Tank
SV	1	Surge Vessel
⊘SV	1	Surge Vessel Pressure Gauge
⊘AT	2	Air Tank Pressure Gauge
—/—	3	Non-Return Valve 25mm
S	2	Solenoid Valve 25mm
⊠SV	1	Safety Valve for Surge Vessel 25mm
⊠AT	2	Safety Valve Air Tank
⊠ I/O	1	In/Out Valve
DV⊠	1	Drain Valve 80mm
—⋈—	6	Ball Valve 25mm
D▥	1	Displacement
Comp	2	Air Compressor

P&I Diagram

Figure (5) The water piping system under study

The online measurements and results indicated that the developed protection was efficient and able to handle large pressure variation as a result of water hammer. Figure (6) shows the hydraulic gradient for the pipeline at steady state in relative to pipeline profile. The pipeline is divided into nodes; the nodes are selected in accordance to change in level along with the pipeline profile as drawn in the hydraulic model as shown in Figure (6).

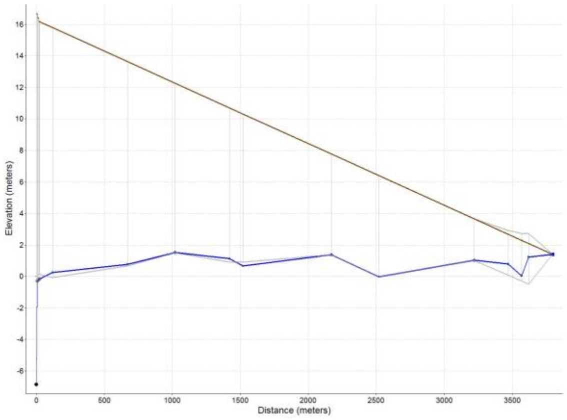


Figure (6) Hydraulic gradient for the pipeline at steady state in relative to pipeline profile after protection

The proposed system for water hammer protection shall be based on accurate hydraulic calculations of pressure variations during all possible flow transient conditions. These include pump start/stop, power failure, pipeline filling, and downstream valve closure. The maximum and minimum pressure expected along the pipeline should be investigated which will indicate the need for a further design modification. The pipeline data shall be used to obtain the steady-state hydraulic gradient line. The water hammer protection system is required to ensure that the maximum up-surge pressure during transients shall not exceed 50% of the operating pressure or the maximum pressure rating of the pipeline.

The water hammer control is significant for protecting and reducing the turbulence in the system significantly. The water hammer protection system shall comprise surge vessels of a suitable size to satisfy the hydraulic requirements. The water level inside the vessel shall be controlled with a suitable control system. A bladder type vessel with a bladder of suitable material for wastewater application shall be used. The test pressure of the vessel shall be 1.5 times its design pressure.

4. Conclusion

A modified numerical approach is developed to calculate the pressure changes resulting from the water hammer effect on the water piping system. The model showed an excellent prediction of the water hammer effect before and after system protection. A mathematical model was developed to simulate the pressure change in the system based on the continuity equations. The model was used to simulate the power failure and/or pump shut down situations. The model can predict the maximum and minimum pressure envelopes and how the pressure changes may affect the piping system. The piping system properties are considered as an essential operating parameter in the model.

The model was used to study a water piping system containing a surge vessel and two air tanks. The model could predict the effect of various protection configurations on the piping system's safe operation. The pressure variation showed a pressure drop in the pipeline exceeding the permissible pipeline pressure at most nodes by examining the water hammer effect on the system under study during a power failure or pump shutdown, Based on the simulation results, one can conclude that protection is needed. The piping system under study was upgraded to withstand the water hammer effect. By adding suitable protection provisions, the maximum and minimum envelopes along did not exceed the permissible pressure.

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