



Optimizing Control Device Placement to Mitigate Hydraulic Transient Effects in Water Transmission Pipeline Networks

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ABSTRACT

Hydraulic transient, commonly known as 'water hammer,' occurs in hydraulic fluid network systems due to rapid pressure variations caused by sudden changes in fluid momentum from transient events. This phenomenon poses significant challenges, particularly in high-pressure transmission networks, where it is crucial to model and analyze transient conditions to identify vulnerabilities and predict potential adverse effects. This research introduces a hydraulic transient and optimization model for determining the optimal placement of control devices in a water transmission pipeline network, considering transient events such as pump start. The study focuses on the 50MLD Zaria waterworks transmission pipeline network as a case study. The methodology involves transient modeling and iterative problem solving using a meta-heuristic (PSO) optimization technique. The goal is to maximize the minimum transient pressure head and minimize the maximum transient pressure head resulting from transient conditions under various worst-case scenarios. The results of the case study demonstrate that optimizing the locations of control devices leads to a significant improvement, with a 2.98% increase in the minimum transient pressure and a 0.72% decrease in the maximum transient pressure for one pump start scenario with one running pump. It is noteworthy that the optimized control device placement effectively mitigates the impact of transient pressures, ensuring that they remain within the pressure rating of the pipeline material (Steel ANSI) used throughout the system. This research underscores the importance of proactive measures in managing hydraulic transient effects, ultimately enhancing the reliability and performance of water transmission networks.

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INTRODUCTION

Hydraulic transient, commonly known as "water hammer," is a critical issue that plagues hydraulic fluid network systems, especially in high-pressure transmission pipelines. This phenomenon occurs when there are sudden changes in fluid momentum within the system, leading to rapid pressure fluctuations. These fluctuations can result in significant pressure surges, posing risks such as pipeline damage,

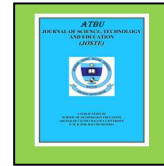
system inefficiency, and operational disruptions (EL-Turki, 2013). Thus, understanding and addressing hydraulic transient effects are essential for ensuring the reliability, safety, and longevity of water transmission pipeline networks. To tackle the challenges posed by hydraulic transient, this paper introduces a comprehensive approach to modeling, analyzing, and optimizing control device placement in water transmission pipeline networks. The study focuses on the

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50MLD Zaria waterworks transmission pipeline network as a case study, utilizing advanced transient modeling techniques and iterative optimization methodologies. By harnessing meta-heuristic optimization techniques, such as Particle Swarm Optimization (PSO), the research aims to identify the most effective locations for control devices. These devices play a crucial role in managing hydraulic transient effects by maximizing the minimum transient pressure head while minimizing the maximum transient pressure head. In essence, this paper presents a proactive strategy to mitigate the adverse impacts of hydraulic transient in water transmission pipeline networks (EL-Turki, 2013). By employing cutting-edge modeling and optimization techniques, the study seeks to enhance the resilience and efficiency of these critical infrastructure systems, ultimately contributing to the overall reliability and sustainability of water supply networks. The major contribution of this paper are as follows Walski and Barnard (2004):

1. Ascertained the transient pressure values arising from flow control operations within the current 50MLD Zaria waterworks transmission pipeline system.
2. Pinpointed the optimal positions for control devices along the transmission pipeline system utilizing the PSO algorithm.
3. Assessed the effects and impacts of the optimized control device placements in the system by comparing their performance with that of the existing control device locations.

The paper is structured as follows: Section 2 provides an overview of hydraulic transient phenomena and its implications for water transmission pipeline networks. Section 3 outlines the methodology employed, including transient modeling techniques and optimization algorithms.

Section 4 presents the results of the case study, highlighting the effectiveness of optimized control device placement in mitigating hydraulic transient effects. Section 5 presents the conclusion of the study.

LITERATURE REVIEW

Concept of Hydraulic Transient

When pressurized water flows through a closed conduit, the principles governing pressure and velocity changes along the pipe depend on the flow conditions. If we assume the water is incompressible and the discharge remains constant, we can use the steady flow energy equation to analyze the flow's energetics at different points in the conduit. However, when the flow is unsteady, meaning it changes rapidly from one moment to the next at a specific location in the conduit, sudden pressure fluctuations can occur, rendering the steady flow energy equation invalid. These rapid pressure fluctuations are known as "hydraulic transients," often referred to as "water hammer" due to the audible hammering sound associated with the phenomenon. The transient state of water flow, or water hammer, from the moment of valve closure until a new steady-state condition is established, is complex because of the pressure surges that propagate away from the valve. When a valve closes rapidly, it converts the fluid's kinetic energy into strain energy in the pipe walls. This results in a "pulse wave" of abnormal pressure traveling from the point of disturbance into the pipeline system. The hammering sound often heard is a result of a significant portion of the fluid's kinetic energy being transformed into pressure waves, causing noise and vibrations in the pipe. Energy losses, primarily due to friction, cause the transient pressure waves to diminish until a new steady state is reached. Figure 1 depicts water hammer in a pipeline caused by the rapid closure of a gate valve for fluid flowing along the pipeline (Osman, 1992).

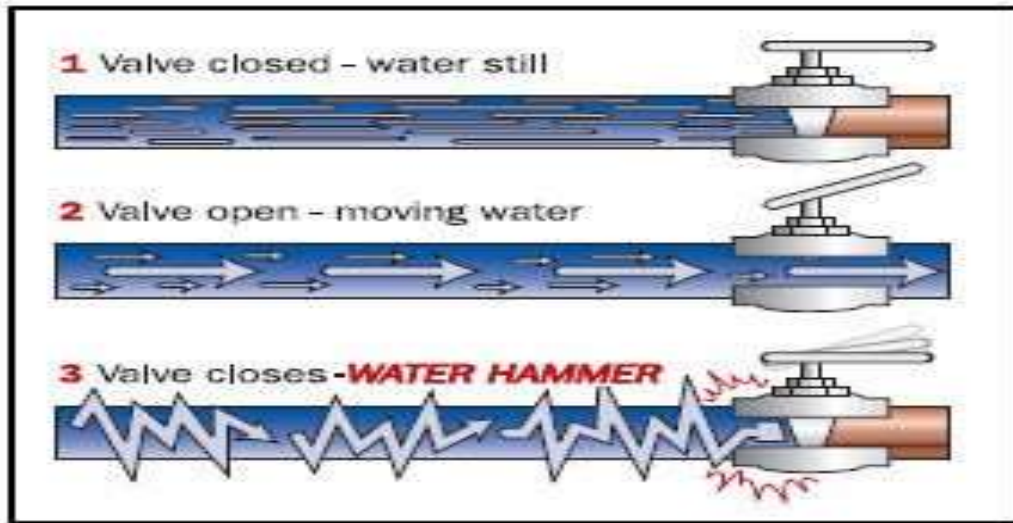


Figure 1: Water Hammer Description (Osman, 1992)

Table 1 gives a brief description of the causes and effects of hydraulic transient events in water pipeline systems. It outlines how these events occur due to operational changes such as pump start-up or shutdown, valve opening and closing, demand fluctuations, and changes in boundary conditions. The description column also highlights the potential consequences of hydraulic

transient, including damage to equipment, system disruption, and environmental risks. It emphasizes the importance of hydraulic engineers and designers in mitigating these effects to ensure system safety and operational efficiency (EL-Turki, 2013).

Table 1: Brief Description of the Causes and Effects of Hydraulic Transient (EL-Turki, 2013).

Aspect	Summary of Description
Causes of Hydraulic Transient	<ul style="list-style-type: none"> Hydraulic transient events result from operational changes in a system, such as pump start-up or shutdown, valve operation, demand fluctuations, and changes in boundary conditions. These events create rapid pressure changes that propagate as pressure waves throughout the distribution system, leading to transient adjustments until a new steady state is reached. Pump trip events typically initiate the most severe water hammer conditions.
Effects of Hydraulic Transient	<ul style="list-style-type: none"> Hydraulic transient events in water pipeline systems can cause significant damage, system disruption, and environmental risks. They occur at various points in the system and can result from a range of operational and unforeseen factors. The consequences include overpressures, erosion, cavitation, vibration, and contaminant intrusion, posing challenges for system safety and operational efficiency.

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Flow Control Operation Classification Based on Characteristic Time

In flow control operations, a pressure wave is generated, propagating at a speed represented by 'a', and traveling across the pipeline within a time interval of 'L/a' seconds to reach the opposite end. The same time interval is required for the reflected wave to return to its origin, resulting in a total time of '2L/a' seconds, known as the characteristic time of the pipeline. This characteristic time plays a pivotal role in classifying the speed of maneuvers that trigger water hammer phenomena (Díaz, 2009). If a flow control operation induces a velocity change (dv)

within a time interval (T_m) equal to or less than the pipeline's characteristic time, it is labeled as "rapid." Conversely, operations occurring over an interval longer than the characteristic time are categorized as "gradual" or "slow," depending on the extent of the difference (Abubakar et al., 2022). The characteristic time holds significance in transient flow analysis as it determines the applicable method for evaluating specific flow control operations within a given system (Walski & Barnard, 2004). Table 2 gives the characteristics time operations of the pipeline.

Table 2: Characteristics Time Operations

Operation Time	Operation Classification	Method of Analysis
$T_M = 0$	Instantaneous	Elastic Model
$T_M \leq 2L/a$	Rapid	Elastic Model
$T_M > 2L/a$	Gradual	Elastic Model
$T_M \gg 2L/a$	Slow	Rigid Model

Understanding the Dynamics of Transient Flow

Hydraulic transients arise when the flow momentum undergoes a change due to the rapid operation of flow control devices within a hydraulic system, leading to fluid acceleration. Mathematically, hydraulic transients are analyzed by solving equations for velocity ($V(x, t)$) and pressure ($P(x, t)$) over a defined elevation profile of the system, considering specific initial and boundary conditions determined by the system's flow control operations. Essentially, the objective is to solve a problem with two unknowns, velocity (V) and pressure (P), with respect to the independent variables of position (x) and time (t). Alternatively, the equations may be solved for flow (Q) and head (H).

The continuity equation and momentum equation are essential for determining velocity (V) and pressure (P) in a one-dimensional flow system. The solution of these equations yields theoretical results that generally mirror actual system measurements if the data and assumptions used in constructing the numerical model are accurate. Discrepancies between

transient analysis results and actual system measurements often stem from inappropriate system data, particularly boundary conditions, and unfounded assumptions (EL-Turki, 2013).

Evaluating Transient Effects

Transient analysis is vital for pipeline systems, especially those operating under high pressure. Velocity-dependent systems, including service connections and system loops, may amplify transient effects, necessitating a comprehensive analysis during the initial design phase of the project. It's crucial to consider all factors, including predictable emergency operations and abnormal flow control activities that may occur during system operation (Walski & Barnard, 2004). Assessing potential transient effects involves determining the maximum (P_{max}) and minimum (P_{min}) pressures of the transient pressure wave, corresponding to the maximum (H_{max}) and minimum (H_{min}) pressure heads at critical positions in the system, as illustrated in Figure 1.2 above. The hydraulic grade lines for the maximum and minimum hydraulic grades resulting from the transients are determined by estimating

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these head values in the system. If the elevation (z) along the pipeline is known, the pipeline profile can be plotted along with the hydraulic grades to examine the range of possible pressures throughout the system (Ore-Ofe et al., 2023). In

Figure 2, a pump system experiencing an emergency pump stopping scenario is depicted, showcasing the extreme values indicated by the hydraulic grade lines over time along the pipeline.

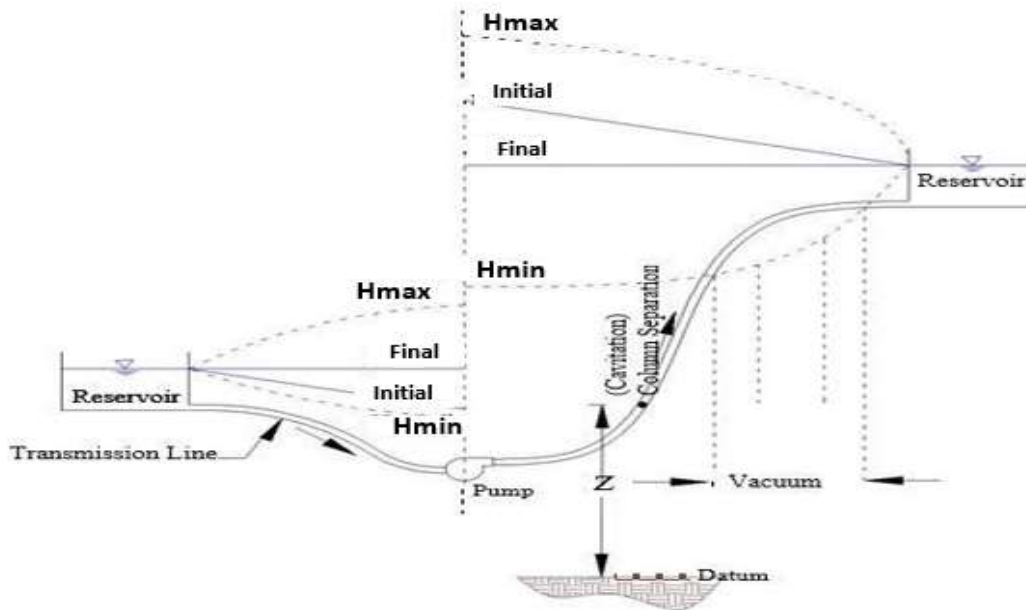


Figure 2: Pumping System during an Emergency Shutdown (Díaz, 2009).

These grade lines provide foundational insights for hydraulic system design. A significant drop of the minimum head (H_{min}) grade line below the pipeline elevation suggests a vacuum pressure condition, potentially leading to column separation and pipeline collapse. Therefore, if transient pressure exceeds the pipe's pressure rating, pipe failure may occur. The maximum and minimum transient pressures at any point in the pipeline system can be determined by subtracting the pipe elevation (z) from the maximum and minimum heads (H_{max} and H_{min}), and converting the resulting pressure head values to appropriate pressure units (Díaz, 2009).

MODELS FOR ANALYZING HYDRAULIC TRANSIENTS

Two primary models are utilized for analyzing hydraulic transients:

1. Rigid Model

In the rigid model, the pipeline is assumed to be non-deformable, while the fluid is considered incompressible. Flow control operations influence only the frictional and inertial aspects of transient flow. Accordingly, any flow control operation causes instantaneous flow changes throughout the system, with the fluid moving as a single mass inside the pipeline, resulting in mass oscillation. The governing equations transform into ordinary differential equations, simplifying the analysis considerably. However, this model is limited to surge analysis and is not suitable for rapid flow changes due to its inability to accurately interpret pressure wave propagation caused by flow control operations. The maximum transient head envelope calculated by the rigid water column theory typically follows a straight line. The rigid model is given as (Díaz, 2009):

$$H_1 - H_2 = fLQ + gLAdQ \quad dt \quad H_1 - H_2 = QfL + dtgLA dQ \quad (1)$$

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Where: H_1 is the total head at position 1 (m, ft), H_2 is the total head at position 2 (m, ft), f is the difference between Darcy and Weisbach friction factor, L is the length of pipe (m, ft), Q is the flow (m^3/s , cfs), g is the gravitational acceleration (m/s^2 , ft/s^2), A is the area (m^2 , ft^2) and dQ/dt is the derivative of flow with respect to time.

Elastic Model

The elastic model assumes the pipeline and fluid to be deformable and compressible, respectively, due to changes in fluid momentum. The fluid experiences slight density changes during the propagation of a transient pressure wave (Díaz, 2009). The elasticity of the fluid, described by the modulus of elasticity, determines the wave speed, representing the speed at which a disturbance moves through the fluid. Wave propagation analysis considers the propagation of pressure waves in the fluid and the effects of pipe elasticity. Equations for wave speed in the pipeline are developed based on the pipeline's elasticity and fluid compressibility (Gençoğlu & Merzi, 2017). The constraint condition of the pipeline affects the wave speed, with different coefficients used for various scenarios, such as anchored pipelines and those with expansion joints. The elastic model equations for pipeline is given as (Gençoğlu & Merzi, 2017):

$$P = \rho a V P = \rho a V \quad \text{or} \quad H = -a V g H = g - a V \quad (2)$$

Where: PP is the change in pressure (Pa, psi), ρ is the fluid density (kg/m^3 , slugs/ ft^3), a is the characteristic wave speed of the fluid (m/s , ft/s), V is the change in fluid velocity (m/s , ft/s), H is the change in head (m, ft) and g is the gravitational acceleration constant (m/s^2 , ft/s^2).

Overall, both models offer valuable insights into hydraulic transients, with the rigid model simplifying analysis for surge events and the elastic model providing a more comprehensive understanding of wave propagation phenomena.

Basic Concept of PSO Algorithm

The Particle Swarm Optimization (PSO) algorithm is a nature-inspired optimization

technique that mimics the social behavior of bird flocking or fish schooling. In PSO, a population of candidate solutions, represented as particles, move through the search space with the aim of finding the optimal solution to a given problem. Each particle adjusts its position based on its own experience (local best) and the experience of the entire swarm (global best) (Jain *et al.*, 2022).

Now, let's discuss PSO algorithm in the context of the model equations provided for the optimization of control device placement in a water transmission pipeline network (Jain *et al.*, 2022).
PSO Algorithm Steps:

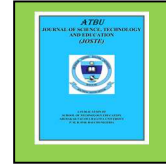
1. **Initialization:**
 1. Initialize a swarm of particles with random positions within the search space.
 2. Assign random velocities to each particle.
2. **Objective Function Evaluation:**
 1. Evaluate the fitness of each particle's position using the objective function. In this case, the objective function could be based on the model equations related to the hydraulic transient and optimization model.
3. **Update Particle's Best Position:**
 1. Update the best position (local best) for each particle based on its current position and the objective function value.
4. **Update Global Best Position:**
 1. Determine the global best position among all particles based on their fitness values.
5. **Update Particle Velocity and Position:**
 1. Update the velocity of each particle using the following equation:

$$v_i(t+1) = w \cdot v_i(t) + c_1 \cdot \text{rand}_1 \cdot (pbest_i - x_i(t)) + c_2 \cdot \text{rand}_2 \cdot (gbest - x_i(t))$$

$$v_i(t+1) = w \cdot v_i(t) + c_1 \cdot \text{rand}_1 \cdot (pbest_i - x_i(t)) + c_2 \cdot \text{rand}_2 \cdot (gbest - x_i(t)) \quad (3)$$

where:

$v_i(t)$ is the velocity of particle ii at time tt ,
 w is the inertia weight,



c_1 and c_2 are acceleration coefficients,
 $rand_1$ and $rand_2$ are random values between 0 and 1,
 $pbest_i$ is the best position of particle i ,
 $gbest$ is the global best position,
 $x_i(t)$ is the current position of particle i at time t .
Update the position of each particle using the new velocity.

6. Stopping Criteria:

1. Terminate the algorithm if a stopping criterion is met (e.g., maximum number of iterations reached, satisfactory solution found).

7. Optimal Solution:

1. The global best position found by the swarm represents the optimal solution to the optimization problem.

PSO optimizes the placement of control devices by iteratively adjusting the positions of particles in the search space, aiming to minimize/maximize the objective function based on the model equations. The model equations are used to evaluate the fitness of each particle's position, guiding the swarm towards regions of the search space where the objective function is optimized (Yu *et al.*, 2021). By updating particle velocities and positions according to the PSO algorithm, the swarm collectively converges towards the optimal solution for the placement of control devices in the water transmission pipeline network. In summary, PSO is a powerful optimization technique that can effectively address complex optimization problems such as control device placement in hydraulic systems, leveraging mathematical models and iterative improvement to find near-optimal solutions (Seguini *et al.*, 2021).

Review of Similar Works

Akpan *et al.*, (2015) conducted modeling of both a miniature (Graze's laboratory set-up) and a simple main water riser pipe systems under various flow conditions,

encompassing steady and transient states. Utilizing WANDA transient simulation software, the model accounted for sudden valve closure as the transient initiator for the Graze laboratory set-up and a pump trip transient event for the simple water main riser pipe system. Validation of the model involved comparing experimental data with transient data obtained from the simulation software. The results demonstrated high accuracy of the model, suggesting its effectiveness in approximating air behavior in an air vessel used for controlling transient conditions in a pipeline system.

Saldarriaga & Salcedo, (2015) developed a multi-objective optimization model aimed at determining the optimal location and settings of pressure relief valves to tackle water leakage issues in pipeline water distribution network systems. They employed a non-sorting genetic metaheuristic algorithm (NSGA-II) aligned with relevant hydraulic criteria. Testing the model on two different water distribution networks with varying leakage configurations and hydraulic parameters yielded superior results compared to those achieved by other researchers using the same case studies.

Ateş, (2017) developed a hybridized model integrating newton-raphson and hardy-cross techniques to control nodes (such as PRV's, check valves, safety valves, and pumping stations). Employing an iterative numerical algorithm, the model solved loop equations for the linearized energy equation using the newton-raphson technique and adjusted flow rates of loops containing closed conduit pipes locally using the hardy-cross method. The hybridized technique exhibited robust and fast converging behavior suitable for real-world distance pipe network applications.

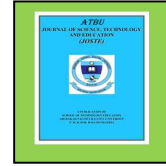
Moghaddas *et al.*, (2017) utilized an air chamber and air-inlet valves as protection devices and developed a single objective optimization model applied to a 4m³/s flow capacity real transmission pipeline network. The model addressed a pump trip transient scenario, minimizing total cost while ensuring all pressures along the pipeline network remained within allowable range. Employing a metaheuristic self-

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adaptive real genetic algorithm, the model determined the optimal number, types, and locations of air-inlet valves, thereby reducing total costs by 30% while ensuring design safety against water hammer conditions.

Gençoğlu & Merzi, (2017) developed a heuristic optimization model based on genetic algorithm (GA) to minimize excess nodal pressures and leakages in a water distribution network. By optimizing the location and setting of control valves, the model demonstrated considerable excess pressure minimization in an 89-nodes water distribution network system used as a case study

METHODOLOGY

Within this chapter, we looked into the techniques, resources, and steps utilized to accomplish the research objectives. We conducted hydraulic transient analysis through the method of characteristics and simulated the optimization of control devices using AFT Impulse 6 and MATLAB R2015b within a simulation environment.

Case Study

50MLD Zaria Waterworks Transmission Pipeline (from 50MLD Zaria water treatment plant to Hanwa reservoirs). The system comprises 7.581 km (24,865.98 feet) of ANSI steel pipe material throughout its length, with three different diameters (750mm, 500mm, and 400mm). It

includes a 10,000 cubic meter capacity suction reservoir made of concrete at the upstream end, three high-lift pumps with an operational discharge capacity of 1300 cubic meters per hour each at 82 meters pressure head, and two overhead concrete reservoirs downstream, each with a capacity of 7500 cubic meters, distributing water to end users by gravity. The pipeline incorporates various conform devices such as elbows, gate valves, pressure reducing valves, and air chambers. Additionally, it utilizes two types of joints along its path: mechanical and flanged.

Geometry and Alignment of the Pipeline

The geometry and alignment of the transmission pipeline and its conform devices were manually obtained using handheld GPS, a handheld laser meter, Google Earth, and ArcGIS in the field, with the assistance and permission of the Kaduna State Water Corporation authority. With the field data and information provided by the authority, it was possible to identify the pipeline alignment and critical locations where accidents could occur. This information is crucial as the pipeline traverses areas including roads, pedestrian zones, areas with light and heavy traffic, water bodies, and residential areas located near roads. The model considered only changes in the vertical axis throughout the route for steady-state simulation. The Zaria waterworks transmission pipeline network is given in Figure 3.

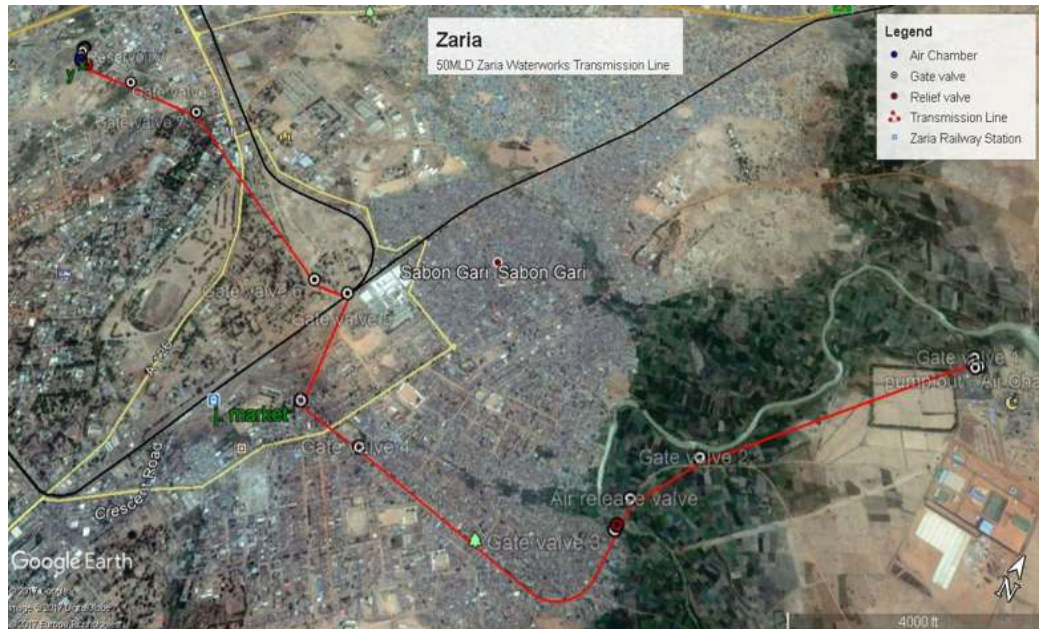


Figure 3: Zaria waterworks transmission pipeline network (sources: Google Earth pro)

METHODOLOGY

The following methodology were adopted in carrying out the research work.

Steady State Analysis in AFT

In the context of hydraulic engineering, steady-state analysis refers to the examination of a system under conditions where flow rates, pressures, and other hydraulic parameters remain constant over time. In the case of AFT Impulse, a transient analysis software widely used in hydraulic engineering, steady-state analysis plays a crucial role in understanding the baseline behavior of a hydraulic system before any transient events occur. When conducting steady-state analysis in AFT Impulse, engineers input the system's geometry, including pipe lengths, diameters, elevations, and other components such as pumps, valves, and reservoirs. The software then calculates the steady-state flow

distribution, pressure profiles, and other hydraulic parameters throughout the system. The steady-state analysis provides valuable insights into the normal operating conditions of the hydraulic system. Engineers can assess factors such as flow velocities, pressure drops, and head losses to ensure that the system operates efficiently and within design specifications. It also serves as a basis for comparison when evaluating the effects of transient events. Moreover, steady-state analysis helps identify potential issues or inefficiencies in the system design. By analyzing pressure variations, flow distribution, and other parameters, engineers can optimize the system layout, component sizing, and operational settings to improve performance and reliability. Overall, steady-state analysis in AFT Impulse forms the foundation for comprehensive hydraulic system modeling and transient analysis. It allows engineers to understand the system's behavior under normal conditions and provides valuable insights for design optimization and troubleshooting. The model workflow is given in Figure 4.

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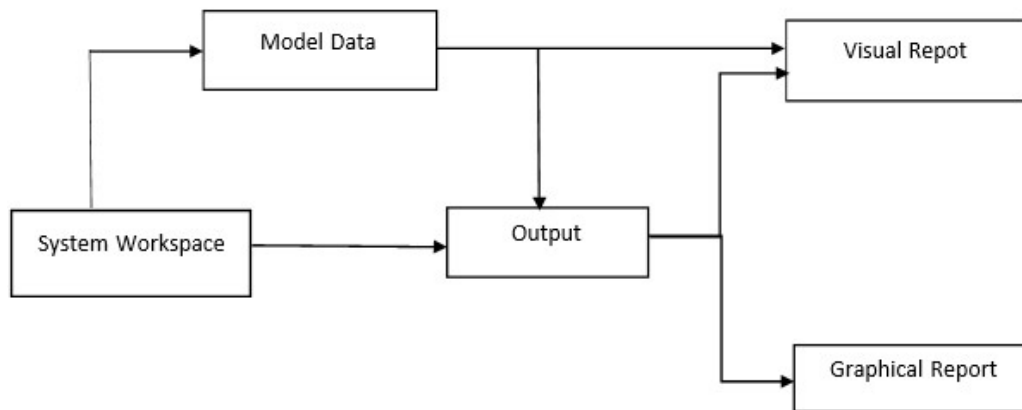


Figure 4: AFT Impulse Model Workflow Chart

In order to carry out both steady and transient state analysis of the case study (50MLD zaria waterworks transmission pipeline) an AFT Impulse model software application was installed on a digital computer and simulation was carried out based on characteristics method as follows:

1. AFT Impulse 6 software application in a computer was started and "Start building model" option was selected
2. The model lay out was drawn in the workspace window using the toolbox tools.

Also, the first step in the model checklist involved specifying steady-state solution control by accessing the steady solution control window from the analysis menu. This item is automatically checked when starting the AFT Impulse software, as the application assigns solution control parameters for the steady-state section of the analysis based on several engineering assumptions:

1. The system operates with liquid flow.
2. Flow is one-dimensional.
3. No chemical reactions occur within the system.
4. The wave speed remains constant during transients.
5. Negligible release of non-condensable gas.

6. Bubbles formed during transient cavitation remain stationary.

Next, system properties were defined by accessing the "System properties" window from the analysis menu. The following fluid properties were entered:

1. Selected the "AFT Standard" option on the fluid data tab.
2. Specified a temperature of 60°F.
3. Selected "Water at 1 atm" from the list of available fluids in the database.
4. Chose the "Constant fluid properties" option.
5. The solver determined the density, dynamic viscosity, bulk modulus, and vapor pressure properties of the water system by selecting the "Calculate properties" option.
6. Selected the "Add to model" option to incorporate water into the model.

Finally, the model components (links and nodes) were defined by double-clicking on each component and entering the following input data: Links input data: Link 1 – 35 (suction1 – pipe 37) are Steel ANSI, STD friction data set, Thick-wall anchored upstream, with a roughness of 0.0018 inches, and an initial flow rate of 1300m³/hr. The pipeline input data is given in table 3. And the branch node input data is given in

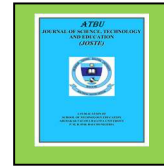


table 4. Also, table 5, 6, 7, 8, 9,10, 11 and 12 gives the pump input data, Reservoir input data, Pressure relief valve input data, Air chamber input data, Gate valve input data, Dead end input data,

Tee input data and pump event transient input respectively.

Table 3: Pipeline Input Data

Link	Name	Length (feet)	Hydraulic Diameter (inches)	Wave speed (m/s)
1	Suction 1	10	15.25	1214
2	Suction 2	10	15.25	1214
3	Suction 3	10	15.25	1214
4	Pipe4	10.5	15.25	1214
5	Pipe5	10.5	15.25	1214
6	Pipe6	10.5	15.25	1214
7	Pipe7	11.5	29.25	1094.847
8	Pipe8	11.5	29.25	1094.847
9	Pipe9	79	29.25	1094.847
10	Pipe10	173	29.25	1094.847
11	Pipe11	5253	29.25	1094.847
12	Pipe12	1351	29.25	1094.847
13	Pipe13	3.2	29.25	1094.847
14	Pipe14	464	29.25	1094.847
15	Pipe15	3.2	29.25	1094.847
16	Pipe16	78	29.25	1094.847
17	Pipe17	5412	29.25	1094.847
18	Pipe18	1325	29.25	1094.847
19	Pipe19	2062	29.25	1094.847
20	Pipe20	680	29.25	1094.847
21	Pipe21	4632	29.25	1094.847
22	Pipe22	1687	29.25	1094.847
23	Pipe23	1079	29.25	1094.847
24	Pipe24	39	29.25	1094.847
25	Pipe25	78	29.25	1094.847
26	Pipe27	8	29.25	1094.847
27	Pipe28	8	29.25	1094.847
28	Pipe29	9	29.25	1094.847
29	Pipe30	99.7	19.25	1176.059
30	Pipe31	139.6	19.25	1176.059
31	Pipe32	3.5	19.25	1176.059
32	Pipe33	52.5	19.25	1176.059
33	Pipe34	4.92	19.25	1176.059
34	Pipe36	54.86	19.25	1176.059
35	Pipe37	3	29.25	1176.059

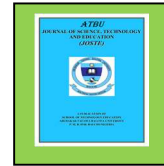
Table 4: Branch Node Input Data

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Node	Name	Inlet elevation (feet)	Outlet elevation (feet)
11	Branch 4	2021	2021
13	Branch 5	2023	2023
14	Branch 6	2021	2021
17	Market branch	2100	2100
22	Down hill	2163	2163
23	Up hill	2193	2193
25	B	2210	2210
27	D	2213	2213
28	E	2209	2209

Table 5: Pump input data

Node	Name	Elevation (feet)	Pump type	Design flow rate (m ³ /hr)
2	Pump 1	2029	Vol. flow	1300
3	Pump 2	2029	Vol. flow	1300
4	Pump 3	2029	Vol. flow	1300

Table 6: Reservoir input data

Node	Name	Liquid surface elevation (feet)	Liquid surface pressure (psig)	Pipe depth (feet)
1	Clear water tank	2044	0	"(P1)2029", "(P2)2029", "(P3)2029"
31	Hanwa reservoir 1	2207	0	"(P32)2187"
35	Hanwa reservoir 2	2221	0	"(36)2201"

Table 7: Pressure relief valve input data

Node	Name	Elevation (feet)	Valve type	Opening type	Over pressure (feet)	Set pressure (feet)	Loss model
12	Relief	2023	Relief-	Instant	6000	5000	Cv
	v.1		inline				
26	Relief	2211	Relief-	Instant	6000	5000	Cv
	v.2		inline				
32	Relief v.3	2205	Relief- inline	Instant	6000	5000	Cv

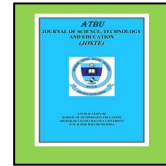
Table 8: Air chamber input data

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Node Name	Inlet elevation (feet)	Tank height (feet)	Tank area (mm ²)	Surface pressure (psia)	Connector pipe diameter (mm)	Connector pipe length (m)
8 Surge 2030 tank		7	33912	0	360	0.4

Table 9: Gate valve input data

Node	Name	Inlet elevation (feet)	Loss model
9	Fence valve	2033	Cv
10	Obasanjo farm	2023	Cv
15	Rafi mosque	2024	Cv
16	Dogon Bauchi	2080	Cv
18	Railway gate	2106	Cv
19	Railway farm	2104	Cv
20	Bitmas junction	2150	Cv
21	Namadi farm	2139	Cv

Table 10: Dead end input data

Node	Name	Elevation (feet)
39	Dead end	2029

Table 11: Tee input data

Node	Name	Inlet elevation (feet)	Tee type	Pipes A, B, C
36	Tee or wye 1	2029	Round straight	"4, 8, 9"
37	Tee or wye 2	2029	Round straight	"5, 8, 7"
38	Tee or wye 3	2187	Round straight	"31, 33, 32"
40	Tee or wye 4	2029	Round straight	"6, 7, 37"

Table 12: Pump Event Transient Input

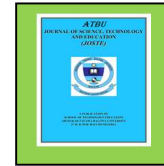
J2 - Pump 1		J3 - Pump 2	
Time (seconds)	Vol. flow rate (m ³ /hr)	Time (seconds)	Vol. flow rate (m ³ /hr)
0	0	0	0

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2	1300	2	1300
10	1300	10	1300

Generate the Set Scenarios

This model aims to assess pump starting condition with one running scenario

Configure Scenarios

The child scenario inherits data from its parent, ensuring consistency in parameter values. The setup for the scenario considered is as follows:

- One pump start with one running:
 1. Activate the "One pump start with one running" scenario on the workspace. In this setup, pump 1 runs at 100% speed during both steady-state and transient conditions, while pump 2 is started.
 2. Open the pump 1 window and set the special condition to "None" on the optional tab. Then, select "Ignore transient data" on the transient tab.

Steady and Transient State Analysis of the Optimized System in AFT Impulse

The following steps were used on the analysis of the optimized system.

1. Rearrange Control Device Positions: Using the toolbox tools, adjust the positions of the control devices in the developed layout model (Figure 3.2) to match the optimized locations from the base scenario.
2. Verify Model Inputs: Thoroughly review all inputs in the model data window to ensure accuracy and completeness.
3. Execute Steady State Solver: Run the optimized model using the steady-state solver to analyze its behavior under stable conditions.
4. Define Pipe Sectioning: Specify pipe sectioning for the optimized model to segment the system into manageable sections for analysis.

5. Configure Transient Control: Set up transient control for the optimized model by defining start and stop times as 0 (zero) and 10 (ten) seconds, respectively.
6. Review Transient Data for All Scenarios: Examine all scenarios' transient data to ensure consistency and reliability.
7. Perform Transient Analysis: Run the three scenarios from the scenario manager using the transient solver to assess the system's behavior during dynamic conditions.

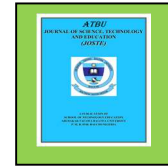
RESULTS

In this section, we report the transient pressure values resulting from flow control operations, specifically the pump start event transient, in the 50MLD Zaria Waterworks transmission pipeline. We utilize an AFT Impulse model to simulate and optimize the performance of control devices along the system, employing a particle swarm optimization algorithm. The scenario considered here is the "One pump start with one running" scenario.

One Pump Start Scenario Maximum and Minimum Transient Pressures

Table 4.13 and 4.14 shows the result of 'one pump start scenario' simulations under existing and optimized locations of the control devices above which indicates that the maximum and minimum steady-state static pressure is 95.44 psia at pipe 12 outlet and 11.64 psia at pipe 34 inlet respectively. Whereas the maximum and minimum transient pressures are 120.1 psia at pipe 6 (link 6), station 0 and -152.0 psia at pipe 31 (link 30), station 0 under both existing and

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optimized locations of the control devices in the system, as shown in Figure 4.5 and Figure 4.6 respectively, while the maximum and minimum velocity during the transient event under the two scenarios in question are 9.72 m/s at pipe 32 (link 31), station 0 and -9.03E-10 m/s at pipe 2 & 3 (link

2 & 3), station 0 respectively. This means that the locations of the control devices has no effect in the system under both steady-state condition and transient-state condition for one pump start with event transient scenario under existing locations of the control devices.

Table 4.13: One pump start scenario maximum and minimum transient pressures and HGL under existing locations of the control devices

Link	Name	Max. Pressure (pascals)	StaticMax. Pressure Station	StaticMin. Pressure (pascals)	StaticMin. Pressure Station	StaticMax. HGL (m)	Min. HGL (m)
1	Suction 1	148,436	6	132,022	6	623.2	621.6
2	Suction 2	146,121	0	146,121	0	623	623
3	Suction 3	146,121	0	146,121	0	623	623
4	Pipe4	725,134	0	-809,887	0	682.1	525.4
5	Pipe5	802,522	0	-753,708	0	690	531.2
6	Pipe6	828,295	0	-749,572	0	692.6	531.6
7	Pipe7	738,249	0	-660,982	0	683.4	540.6
8	Pipe8	707,873	0	-635,621	0	680.3	543.2
9	Pipe9	683,633	7	-627,599	12	677.9	544.1
10	Pipe10	631,181	0	-200,049	111	672.8	588.8
11	Pipe11	652,086	3377	-200,049	0	672.8	588.9
12	Pipe12	658,059	868	-166,541	0	672.8	589
13	Pipe13	658,059	0	-165,689	2	672.8	589.3
14	Pipe14	652,086	0	-168,557	225	672.8	589.1
15	Pipe15	658,059	2	-166,164	0	672.8	589.3
16	Pipe16	658,059	0	-167,888	50	672.8	589.4
17	Pipe17	649,099	0	-348,973	3479	672.8	589.4
18	Pipe18	463,943	0	-532,811	800	672.8	575.1
19	Pipe19	481,683	605	-557,125	1280	680.1	574.6
20	Pipe20	482,694	316	-557,081	102	680.4	574.4
21	Pipe21	484,055	25	-700,642	2914	682.7	573.2
22	Pipe22	408,867	1057	-700,808	81	683.4	571.3
23	Pipe23	401,097	122	-827,378	638	685.6	563.9
24	Pipe24	337,533	0	-896,741	25	686.6	566.6
25	Pipe25	263,715	0	-973,089	50	685	564
26	Pipe27	136,922	0	-974,130	1	677.2	563.9
27	Pipe28	119,851	0	-1,010,497	5	675.8	561
28	Pipe29	118,973	6	-1,047,880	6	675.1	556
29	Pipe30	379,805	60	-1,048,269	0	701.7	556
30	Pipe31	568,102	18	-1,048,084	0	719.5	556
31	Pipe32	237,864	0	-130,231	0	680.5	643
32	Pipe33	382,558	9	-180,887	31	697.4	642.2
33	Pipe34	348,967	0	-180,887	0	697.4	643.3
34	Pipe36	406,104	19	-174,774	11	702	642.7
35	Pipe37	739,448	0	-661,919	0	683.6	540.5

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Figure 4.5: Maximum and minimum static pressures vs. length graph for one pump start scenario

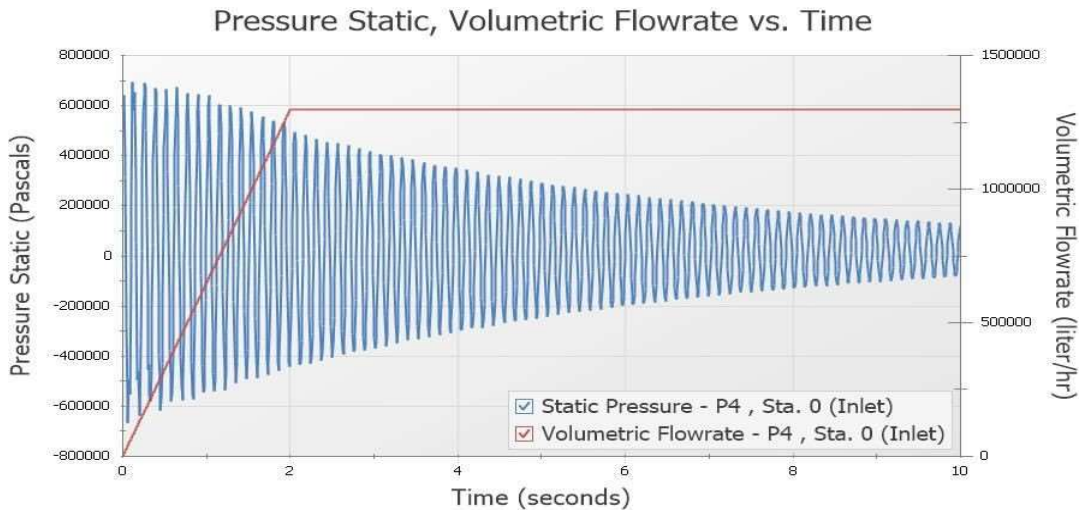


Figure 4.6: Static pressures, volumetric flow rate vs. time graph for two pump start scenario under existing locations of the control devices

Furthermore, the one pump start scenario maximum and minimum transient pressures and HGL for the optimal design is shown in table 4.14.

Table 4.14: One pump start scenario maximum and minimum transient pressures and HGL for the optimal design

Link	Name	Max. Static Pressure (pascals)	Max. Static Pressure Station	Min. Static Pressure (pascals)	Min. Static Pressure Station	Max. HGL (m)	Min. HGL (m)
1	Suction 1	148,436	6	132,022	6	623.2	621.6
2	Suction 2	146,121	0	146,121	0	623	623
3	Suction 3	146,121	0	146,121	0	623	623
4	Pipe4	725,134	0	-809,887	0	682.1	525.4
5	Pipe5	802,522	0	-753,708	0	690	531.2
6	Pipe6	828,295	0	-749,572	0	692.6	531.6
7	Pipe7	738,249	0	-660,982	0	683.4	540.6
8	Pipe8	707,873	0	-635,621	0	680.3	543.2
9	Pipe9	683,633	7	-627,599	12	677.9	544.1
10	Pipe10	631,181	0	-200,049	111	672.8	588.8
11	Pipe11	652,086	3377	-200,049	0	672.8	588.9

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Link	Name	Max. Static Pressure (pascals)	Max. Static Pressure Station	Min. Static Pressure (pascals)	Min. Static Pressure Station	Max. HGL (m)	Min. HGL (m)
12	Pipe12	658,059	868	-166,541	0	672.8	589
13	Pipe13	658,059	0	-165,689	2	672.8	589.3
14	Pipe14	652,086	0	-168,557	225	672.8	589.1
15	Pipe15	658,059	2	-166,164	0	672.8	589.3
16	Pipe16	658,059	0	-167,888	50	672.8	589.4
17	Pipe17	649,099	0	-348,973	3479	672.8	589.4
18	Pipe18	463,943	0	-532,811	800	672.8	575.1
19	Pipe19	481,683	605	-557,125	1280	680.1	574.6
20	Pipe20	482,694	316	-557,081	102	680.4	574.4
21	Pipe21	484,055	25	-700,642	2914	682.7	573.2
22	Pipe22	408,867	1057	-700,808	81	683.4	571.3
23	Pipe23	401,097	122	-827,378	638	685.6	563.9
24	Pipe24	337,533	0	-896,741	25	686.6	566.6
25	Pipe25	263,715	0	-973,089	50	685	564
26	Pipe27	136,922	0	-974,130	1	677.2	563.9
27	Pipe28	119,851	0	-1,010,497	5	675.8	561
28	Pipe29	118,973	6	-1,047,880	6	675.1	556
29	Pipe30	379,805	60	-1,048,269	0	701.7	556
30	Pipe31	568,102	18	-1,048,084	0	719.5	556
31	Pipe32	237,864	0	-130,231	0	680.5	643
32	Pipe33	382,558	9	-180,887	31	697.4	642.2
33	Pipe34	348,967	0	-180,887	0	697.4	643.3
34	Pipe36	406,104	19	-174,774	11	702	642.7
35	Pipe37	739,448	0	-661,919	0	683.6	540.5

Maximum / Minimum Pressure Static vs. Length, Pipe 1 - 36

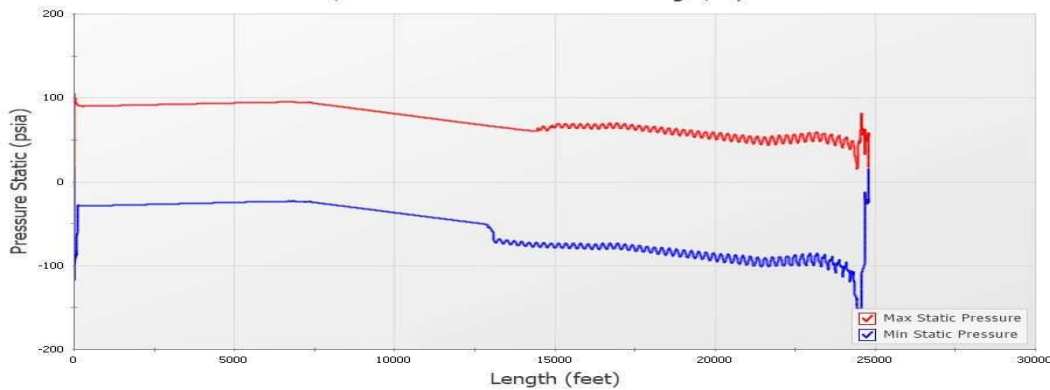


Figure 4.7: Maximum and minimum static pressures vs. length graph for one pump start scenario (with optimized locations of control devices)

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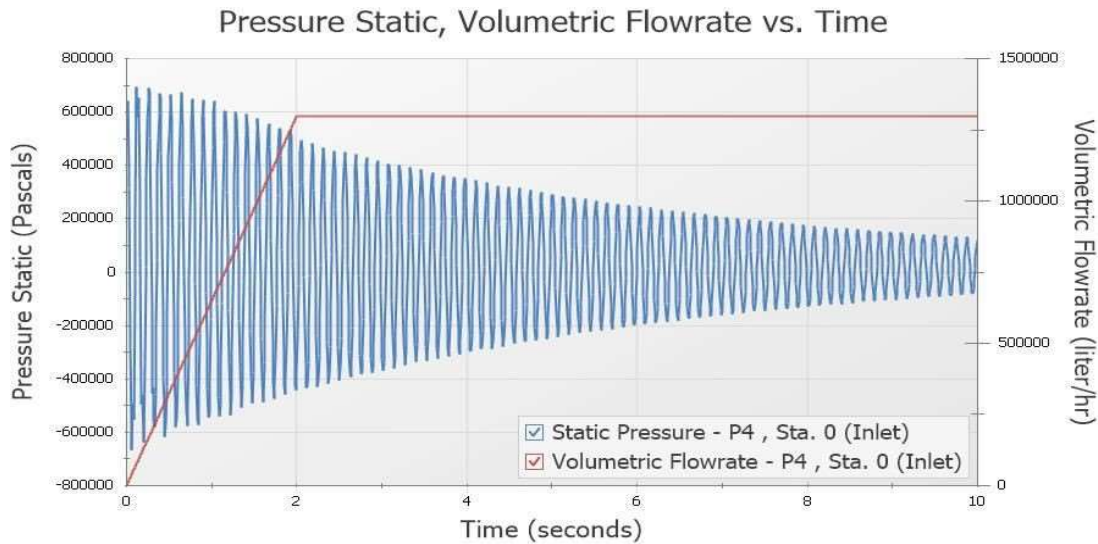


Figure 4.8: Static pressures, volumetric flow rate vs. time graph for one pump start scenario (with optimized locations of control devices)

One Pump Start with One Running Scenario under Existing Locations of the Control Devices

The simulations result for ‘one pump start with one running scenario’ under existing and optimized locations of the control devices shown in Table 4.15 and Table 4.16 above respectively, which indicates that the maximum and minimum steady-state static pressure is 152.6 psia at Pipe 5 inlet and 6.465 psia at Pipe 32 outlet respectively (which means the locations of the control devices has no effect in the system under steady-state condition for the one pump start with one running scenario). Whereas the maximum and minimum transient pressures under existing locations of the control devices are 203.1 psia at pipe 6 (link 6), station 0 and -242.9 psia at pipe 30

(link 29), station 60 respectively, while the maximum and minimum transient pressures under optimized locations of the control devices are 189.5 psia at pipe 6 (link 6), station 0 and -231.4 psia at pipe 30 (link 29), station 60 as shown in figure 4.9 and figure 4.11 above respectively. Also the maximum velocity during transient varies from 15.2698 m/s at pipe 32 (link 31), station 0 to 9.81 m/s at pipe 4 (link 4), station 6, and the minimum velocity during the transient event varies from -10.1914 m/s at pipe 36 (link 34), station 33 to -9.03E-10 m/s at pipe 3 (link 3), station 0 for the existing and optimized locations of the control devices respectively.

Table 4.15: One pump start with one running scenario maximum and minimum transient pressures and HGL under existing locations of the control devices

Link	Name	Max. Static Pressure (pascals)	Max. Static Pressure Station	Min. Static Pressure (pascals)	Min. Static Pressure Station	Max. HGL (m)	Min. HGL (m)
2	Suction 1	103,902	0	99,701	6	618.7	618.3
	Suction 2	148,483	6	132,040	6	623.3	621.6

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Link	Name	Max. Static Pressure (pascals)	Max. Static Pressure Station	Min. Static Pressure (pascals)	Min. Static Pressure Station	Max. HGL (m)	Min. HGL (m)
3	Suction 3	148,483	6	132,040	6	623.3	621.6
4	Pipe4	1,152,412	0	-1,423,646	0	725.7	462.8
5	Pipe5	1,338,234	0	-1,272,792	0	744.7	478.2
6	Pipe6	1,386,690	0	-1,258,232	0	749.6	479.7
7	Pipe7	1,225,310	0	-1,110,054	0	733.2	494.8
8	Pipe8	1,171,779	0	-1,071,669	0	727.7	498.7
9	Pipe9	1,129,219	7	-1,072,847	12	723.4	498.7
10	Pipe10	1,044,674	0	-349,906	111	715	573.6
11	Pipe11	1,032,751	0	-372,779	3377	714.7	568.2
12	Pipe12	980,001	0	-384,772	795	706.3	566.4
13	Pipe13	964,791	0	-386,551	2	704.1	566.7
14	Pipe14	958,768	0	-395,169	225	704.1	565.9
15	Pipe15	957,415	2	-392,641	0	703.4	566.2
16	Pipe16	957,415	0	-394,484	50	703.4	566.3
17	Pipe17	946,982	0	-634,019	3479	703.2	560.8
18	Pipe18	676,719	0	-877,455	800	694.5	539.9
19	Pipe19	643,778	605	-932,397	1280	696.3	536.3
20	Pipe20	630,638	316	-940,155	400	695.7	535.1
21	Pipe21	629,950	27	-1,157,455	2914	695.4	526.5
22	Pipe22	504,435	1053	-1,182,859	990	693.9	521.2
23	Pipe23	496,484	122	-1,378,204	638	695.5	507.7
24	Pipe24	418,034	0	-1,433,616	25	696.9	511.8
25	Pipe25	355,924	0	-1,526,745	50	694.4	507.4
26	Pipe27	180,912	0	-1,527,973	1	681.7	507.4
27	Pipe28	155,464	0	-1,581,728	5	679.4	502.7
28	Pipe29	150,822	6	-1,650,060	6	678.4	494.6
29	Pipe30	562,481	60	-1,667,498	60	720.4	492.8
30	Pipe31	851,146	18	-1,667,498	0	748.4	492.6
31	Pipe32	247,544	0	-316,919	0	681.5	623.9
32	Pipe33	543,945	9	-326,753	31	713.6	627.5
33	Pipe34	504,296	0	-326,753	0	713.2	628.4
34	Pipe36	580,400	19	-328,983	22	719.8	626.9
35	Pipe37	1,227,365	0	-1,111,557	0	733.4	494.6

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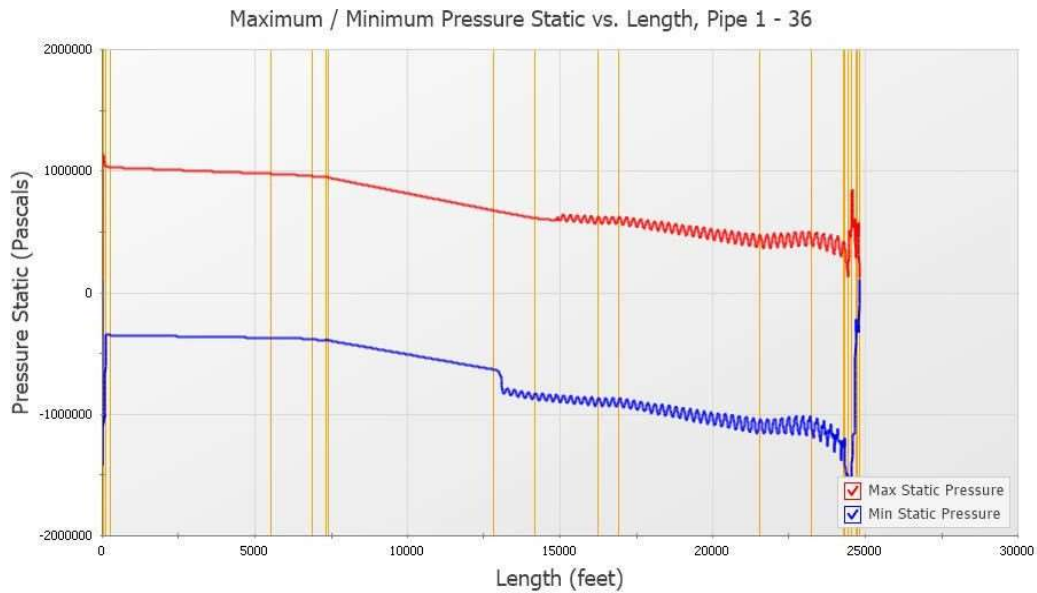


Figure 4.9: Maximum and minimum static pressures vs. length graph for one pump start with one running scenario under existing locations of the control devices

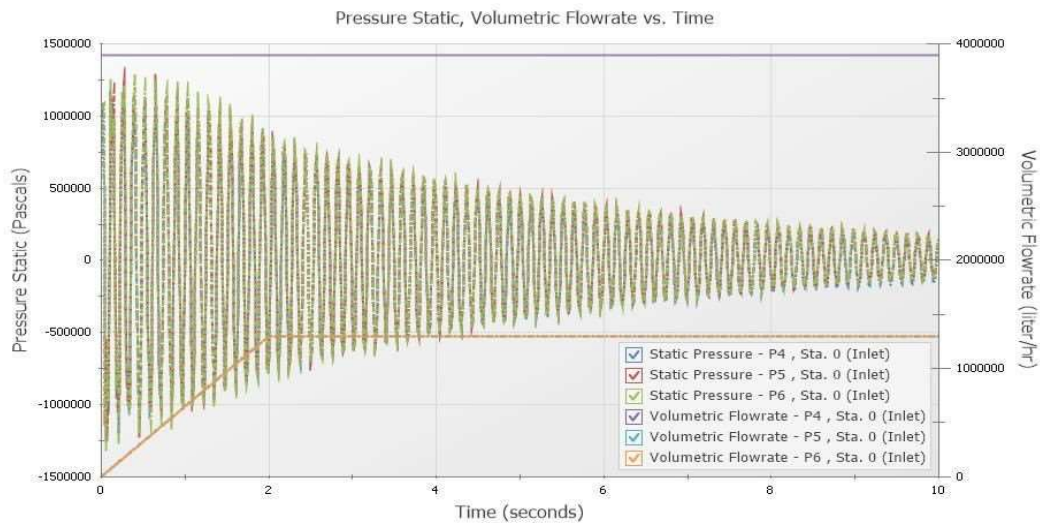


Figure 4.10: Static pressures, volumetric flow rate vs. time graph for one pump start with one running scenario under existing locations of the control devices

Also, the one pump start with one running scenario (with optimized locations of control devices) is given in table 4.16.



Table 4.16: One pump start with one running scenario maximum and minimum transient pressures and HGL for the optimal design

Link	Name	Max. Pressure (pascals)	StaticMax. Pressure Station	StaticMin. Pressure (pascals)	StaticMin. Pressure Station	StaticMax. HGL (m)	Min. HGL (m)
1	Suction 1	103,902	0	99,701	6	618.7	618.3
2	Suction 2	148,436	6	132,022	6	623.2	621.6
3	Suction 3	146,121	0	146,121	0	623	623
4	Pipe4	1,151,874	0	-1,441,036	0	725.7	461
5	Pipe5	1,333,403	0	-1,291,686	0	744.2	476.3
6	Pipe6	1,375,375	0	-1,290,534	0	748.5	476.4
7	Pipe7	1,219,425	0	-1,132,605	0	732.6	492.5
8	Pipe8	1,168,556	0	-1,092,680	0	727.4	496.6
9	Pipe9	1,129,318	7	-1,089,538	12	723.4	497
10	Pipe10	1,044,674	0	-351,162	111	715	573.5
11	Pipe11	1,032,751	0	-373,285	3377	714.7	568.2
12	Pipe12	980,001	0	-385,096	795	706.3	566.4
13	Pipe13	964,791	0	-386,865	2	704.1	566.6
14	Pipe14	958,768	0	-395,427	225	704.1	565.9
15	Pipe15	957,415	2	-392,889	0	703.4	566.2
16	Pipe16	957,415	0	-394,721	50	703.4	566.3
17	Pipe17	946,982	0	-633,494	3479	703.2	560.8
18	Pipe18	676,719	0	-875,317	800	694.5	540.1
19	Pipe19	644,893	605	-930,217	1280	696.4	536.6
20	Pipe20	632,019	316	-937,946	399	695.8	535.3
21	Pipe21	631,380	25	-1,154,932	2914	695.5	526.8
22	Pipe22	505,322	1053	-1,180,082	990	694	521.5
23	Pipe23	497,315	122	-1,375,289	638	695.6	508
24	Pipe24	418,980	0	-1,430,173	25	697	512.1
25	Pipe25	356,754	0	-1,523,904	50	694.5	507.7
26	Pipe27	180,764	0	-1,525,115	1	681.7	507.7
27	Pipe28	155,286	0	-1,578,821	5	679.4	503
28	Pipe29	150,554	6	-1,647,047	6	678.3	494.9
29	Pipe30	565,228	60	-1,664,438	60	720.7	493.1
30	Pipe31	852,891	18	-1,664,438	0	748.6	492.9
31	Pipe32	247,056	0	-315,120	0	681.5	624.1
32	Pipe33	543,076	9	-325,032	31	713.5	627.6
33	Pipe34	503,071	0	-325,032	0	713.1	628.6
34	Pipe36	579,223	19	-328,103	22	719.6	627
35	Pipe37	1,221,384	0	-1,134,200	0	732.8	492.3

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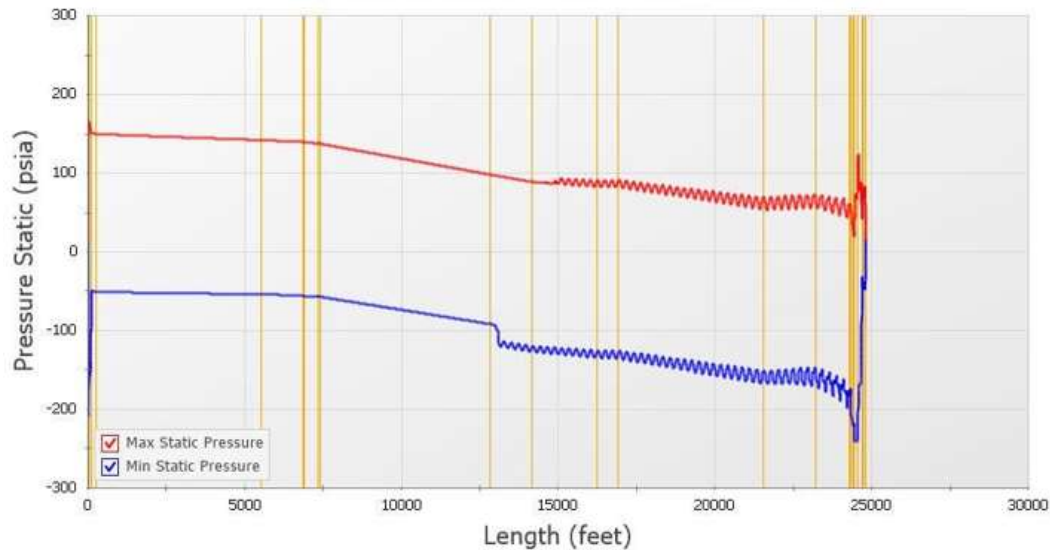


Figure 4.11: Maximum and minimum static pressures vs. length graph for one pump start with one running scenario (with optimized locations of control devices)

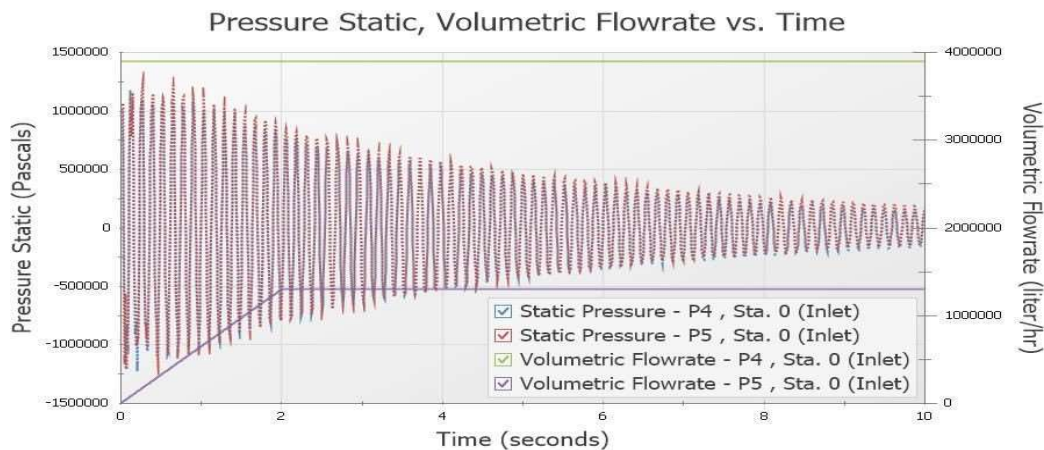


Figure 4.12: Static pressures, volumetric flow rate vs. time graph for one pump start scenario (with optimized locations of control device)

CONCLUSION

This dissertation undertook hydraulic transient analysis and optimization of control devices using the PSO algorithm and AFT Impulse model, employing the characteristics method. The 50MLD Zaria Waterworks transmission pipeline network served as the case study. Performance

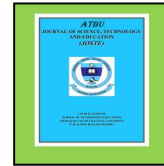
evaluation of the optimized model was conducted using maximum and minimum transient pressure metrics generated in the network system due to pump start event transients across various scenarios. Results indicated improved maximum and minimum transient pressure values of (124.4, 203.1) and (-150.9, -242.9) for the one-pump start with one running scenarios. Consequently, the optimized control device locations in the network

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system yielded a significant improvement of 2.98% and 1.39% for the one-pump start with one running scenario, in terms of maximizing the minimum transient and minimizing the maximum transient pressures.

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