SIMULATION OF FLOW TRANSIENTS IN LIQUID PIPELINE SYSTEMS

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ABSTRACT

SIMULATION OF FLOW TRANSIENTS IN LIQUID PIPELINE SYSTEMS

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In liquid pipeline systems, transient flow is the major cause of pipeline damages. Transient flow is a situation where the pressure and flow rate in the pipeline rapidly changes with time. Flow transients are also known as surge and Waterhammer which originates from the hammering sound of the water in the taps or valves. In liquid pipelines, preliminary design parameters are chosen for steady state operations, but a transient check is always necessary. There are various types of transient flow situations such as valve closures, pump trips and flow oscillations. During a transient flow, pressure inside the pipe may increase or decrease in an unexpected way that cannot be foreseen by a steady state analysis. Flow transients should be considered by a complete procedure that simulates possible transient flow scenarios and by the obtained results, precautions should be taken.

There are different computational methods that can be used to solve and simulate flow transients in computer environment. All computational methods utilize basic flow equations which are continuity and momentum equations. These equations are nonlinear differential equations and some mathematical tools are necessary to make these equations linear. In this thesis a computer program is coded that utilizes "Method of Characteristics" which is a numerical method in solving partial differential equations. In pipeline hydraulics, two partial differential equations, continuity and momentum equations are solved together, in order to obtain the pressure and flow rate values in the pipeline, during transient flow. In this thesis, MATLAB 7.1 is used as the programming language and obtained code is converted to a C# language to be able to integrate the core of the program with a user friendly Graphical User Interface (GUI).

The Computer program is verified for different scenarios with the available real pipeline data and results of various reputable agencies. The output of the computer program is the tabulated pressure and flow rate values according to time indexes and graphical representations of these values. There are also prompts for users warning about possible dangerous operation modes of the pipeline components.

Keywords: Pipeline, Computational Fluid Dynamics, Transients, Waterhammer, Surge, Method of Characteristics.

ÖZ

SIVI BORU HATTI SİSTEMLERİNDE ZAMANA BAĞLI AKIŞ SİMÜLASYONU

Koç, Gençer
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Boru hattı sistemlerinde, hatların zarar görmesine sebep olan asıl unsur zamana bağlı akış durumlarıdır. Zamana bağlı akışta, durağan akışın aksine, boru içi sıvı basıncı ve debi zamanla hızlı değişiklikler göstermektedir. Zamana bağlı akış su darbesi olarak ta bilinmektedir ve bu ismi ani kapatılan vana ve musluklarda çıkardığı çekiç sesinden almaktadır.

Sıvı boru hatlarında tasarım durağan akış parametreleri gözönünde bulundurularak yapılmaktadır ancak zamana bağlı akış durumları mutlaka incelenmelidir. Vana kapanmaları, pompa kapanmaları ya da akıştaki dalgalanmalar gibi zamana bağlı akışa ve su darbesine sebep olan bir çok sebep vardır. Zaman bağlı akış ile tahmin edilemeyen basınç yükselmeleri ve alçalmaları söz konusudur. Bu sebepten zamana bağlı akış, değişik akış senaryolarının simüle edilebildiği tam bir prosedürle incelenmelidir. Bununla beraber elde edilen sonuçlarla önlemlerin alınması gerekmektedir.

Zamana bağlı akışı simule etmek ve çözmek için çeşitli hesaplamalı yöntemler bulunmaktadır. Bütün bu yöntemler temel akış denklemleri olan süreklilik ve

momentum denklemlerini kullanmaktadır. Bu denklemler doğrusal olmayan diferansiyel denklemlerdir ve doğrusal denklemlere dönüştürülmeleri için bir takım matematik araçlara ihtiyaç duyulmaktadır. Bu tezde, yine bu matematik araçlardan biri olan “Karakteristik Methodu” kullanılarak bir bilgisayar programı kodlanmıştır. Akışın iki temel denklemi olan süreklilik ve momentum denklemleri boru içi basınç ve debi değerlerinin hesaplanması için çözülmüş ve simüle edilmiştir. Tezde MATLAB 7.1, programlama dili olarak kullanılmıştır. Elde edilen kod, daha sonra C# koduna çevrilerek, kullanıcı dostu bir arayüzle entegre edilmesi sağlanmıştır.

Yazılan bilgisayar programı, literatürdeki bazı örnek soru ve çözümleri için doğrulanmıştır. Programın çıktısı olarak ise, tabule haldeki basınç ve debi değerleri verilebilir. Bu değerlerin grafiksel gösterimleri de program çıktıları arasında sayılabilir. Program aynı zamanda kullanıcıyı tasarıma dair kritik ve hatalı durumlarda uyarabilecek bir yapıya sahiptir.

Anahtar Kelimeler: Boru hatları, Hesaplamalı Akışkanlar Dinamiği, Zamana bağlı akış, Su darbesi, Method of Characteristics

To My Family

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A	Cross Sectional Area of the Pipe
A_G	Valve Opening Area
A	Speed of Sound
B	Pipeline Constant
C_D	Discharge Coefficient
C_M	Negative Characteristics Constant
C_P	Positive Characteristics Constant
C^+	Positive Characteristics Line
C^-	Negative Characteristics Line
C_1	Constant for Defining Pipe Constraint
D	Diameter of the Pipe
E	Modulus of Elasticity
T_f	Circumferential Tensile Stress
F_S	Safety Factor
f	Friction Factor
g	Gravitational Acceleration
H	Piezometric Head
H_R	Rated Head
h	Nondimensional Head
h_f	Head Loss due to Friction
h_p	Pump Head
L	Pipeline Length
$L1$	Name for Momentum Equation
$L2$	Name for Continuity Equation

$\dot{m}$	Mass Flow Rate
N	Number of Meshes
N_R	Rated Rotational Speed
N_{SQ}	Specific Speed of the Pump
P	Pressure
P_d	Discharge Pressure
P_S	Suction Pressure
Q	Volumetric Flow Rate
Q_R	Rated Discharge
R_G	Radius of Gyration of Rotating Masses
Re_D	Reynolds Number Based on Diameter
S_Y	Minimum Yield Strength
T	Torque
T_R	Rated Torque
t	Time
t	Thickness
u	Relative Velocity of Pipe Wall
V	Velocity
V_D	Discharge Velocity
V_0	Initial Velocity
V_S	Suction Velocity
$\forall$	Control Volume
W	Total Weight of the Rotating Parts
WB	Nondimensional Torque Characteristics
WH	Nondimensional Head Characteristics
Δx	Reach Length
Z	Elevation
α	Nondimensional Speed Ratio
β	Nondimensional Torque Ratio
ε_S	Roughness
ε_T	Total Circumferential Strain

γ	Specific Weight
κ	Bulk Modulus of Elasticity
λ	Linear Multiplier of Characteristics Equations
μ	Absolute Viscosity
η	Overall Efficiency
η_R	Rated Efficiency
ρ	Density
Ψ	Permissible Variation in the Wave Speed
σ_1	Circumferential Stress
σ_2	Radial Stress
τ	Nondimensional Valve Opening
ν	Nondimensional Discharge
υ	Poisson's Ratio
ω	Angular Speed

CHAPTER 1

INTRODUCTION

1.1 General

World of 21st century suffers from global warming, hunger, lack of natural resources and wars. Energy and transportation of energy sources are of great importance for the sake of survival of the countries. Countries keep using sorts of cold war instruments in determining their international policies. Some countries play the role of suppliers while the others play the role of demanders thus assets become the bridging concern between countries. Demanders desire the values that they pay for and suppliers desire the payment that they sign for. These commitments require the reliability of payment, service and transportation of the assets.

One of the most important concerns about "wealth" and its sharing is transportation of this wealth. People have always considered different means for transportation of assets in different industries. Companies, countries and even individuals always seek for the most reliable, economic, effective and reasonable transportation means.

For centuries people had to transport water and other natural sources. Water transportation has been done by pipes for about 5000 years and today there are thousands of kilometers of pipelines [14]. These pipelines supply transportation of water, natural gas and petroleum and petroleum products.

Hydraulics of these pipelines can be considered in three main phases, Design of the Line, Construction of the Line and Operation of the Line. For a safe operation of the pipeline and for an accurate design of the line, all operational situations should be considered during design phases.

In steady operation of a pipeline, there is no change in the flow variables like pressure head and discharge.

If a disturbance causes a sudden change in the state of the system, flow parameters start changing with time and flow goes through transients. The time until another steady state is adopted by the system is called Transient Flow or Surge.

Transient flow or Surge is on of the biggest interests of fluid and civil engineers as it can cause great damages to environment and to people. Engineers keep trying to understand the underlying phenomena and dynamics of transient events and they seek for the best way for preventing surge and its effects.

There are significantly important accidents in the history that led to catastrophic results. One of them is the accident in Oigawa Hydropower station in Japan in 1950 [7] and one recent event, took place in December 1997, resulted with a flood of whole power house, in Lapino Hydropower plant in Poland. Investigations showed that the reason for the rapture of the penstock was again a surge situation initiated by a fast valve closure. [21]

In this thesis, a computer program is developed and different possible transient scenarios are considered by using actual data on actual pipeline systems.

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1.2 Review of Literature

There are too many studies on flow transients in closed conduits, especially on liquid pipeline system transients. Predicting the transient scenarios and setting precautions are becoming the main concern of pipeline industry and engineers.

There are some basic definitions that should be stated here in order to have some deeper understanding of the terminology set for transient flow. First term to define is the *steady flow* which stands for the flow with no changes in any condition of flow at any point with time. In *unsteady flow,* conditions may change at any point under consideration with time. This can be also derived from the definitions of steady and unsteady flows that, steady flow is a special case of unsteady flow for which the unsteady flow equations must satisfy. *Uniform flow* means that the average velocity does not change across the cross section of the pipe while *non-uniform flow* stands for the variable average velocity at the cross-section. *Water hammer*, the most common phrase for transient flow, has the same meaning with unsteady flow but generally restricted for water flow. [1]

After defining some basic concepts, the physical facts lying behind should be defined. The main parameter that governs the transient flow is the wave speed at which the information about any change of flow properties is carried through the pipe. Although the value of wave speed may change at different circumstances, for a single line pipe, it won't create a large amount of error to assume a constant wave speed in many applications. The information said to be carried at the wave speed is in fact nothing but the pressure and flow rate variations because of instantaneous or periodic events that causes transients. Former studies about transient flow stated many details relating wave speed, pressure heads and flow rates.

Taieb *et al.* [2] considered the flow of a homogenous liquid-gas mixture through a pipe assuming a rigid and a quasi-rigid pipe segment where they coupled the effect of pressure on the area or vice versa through the elastic modulus of pipe material. They assumed steady state Darcy-Weisbach friction for wall shear and proposed a two-step finite difference scheme in favor to method of characteristics because of variable wave speed. They neglect the effect of pipe elasticity and fluid compressibility in their rigid model.

Streeter and Wylie [1] considered a control volume containing a pipe section and derived the unsteady momentum equation for this control volume. Then they write the continuity equation for the control volume. They introduced Poisson's ratio effects on the pipe elongation which also brings the necessity of defining the pipe supporting means. They used the definitions of axial and radial stresses together with strain in order to couple the area changes to pressure variation and they exclude the area term from their set of equations by defining the wave speed. They also include the effect of air entrainment by slightly modifying the fluid density thus modifying the wave speed.

They considered different upstream and downstream boundary conditions and initial values in their examples and they proposed method of characteristics for the solution to their linearized set of equations.

Chaudry [3] applied the continuity principle to a control volume of an elastic pipe segment and a compressible fluid. By conservation of mass for the selected control volume he ended up with an equation including pipe cross-sectional area, flow velocity and fluid density as the variables. He also got rid of the area term in his equations because he selects the pressure and flow rate as the variables of interest. He rearranged his equations such that strain related pressure terms came into picture, which is then written in terms of wave speed. He also utilized momentum equation for his control volume. After obtaining simplified continuity and momentum equations, he considered many different pipe materials in their effects on the wave speed and did modifications on wave speed equations accordingly. He also proposes the method of characteristics as a solution and alternatively he derives the basic finite difference equations for both implicit and explicit methods.

Parmakian [4] on the other hand, uses the graphical methods for water hammer analysis. He utilizes Elastic water column theory for his derivations and he ends up with different graphical solution schemes set up with dimensional and non-dimensional parameters especially in flow velocity and pressure head.

Adamkowski [5], dealt with the analysis of flow transients in closed conduits with expending and contracting sections. He used the well known simplified continuity and momentum equations with a slight difference in continuity equation that he included an additional term that takes the variable cross-section into account. As he assumed predefined cross-section variation i.e. an analytical relation of the area with the pipe extend, he simply ended up with a slight modified characteristics equations. He also compared the validity and accuracy of both equivalent pipe segment assumption and using analytical relation between pipe length and cross section.

Air molecules in the pipelines considerable change the dynamics of transients and surge pressures. Presence of air bubbles changes the speed of sound and causes local pressure variations throughout the transients. Wang *et al*. [6] considered the propagation of surges with the formation of air pockets in a sewer pipe. They considered two different scenarios for observing air pocket formation. One of the scenarios has two surge pressures, one negative and one positive. The other scenario is considered with two positive surges bracketing the air pocket and for both scenarios they compared the speed of formation of air pocket and effects of the pocket on the flow parameters.

Joukowsky, in 1900s conducted experiments on water hammer situations when he derived his well known instantaneous water hammer pressure. Although Carpenter was first to record sub-atmospheric pressures, Joukowsky became the first to see and understand the column separation phenomena.[7]

One well known example of column separation event is the accident in Oigawa Hydropower station in Japan in 1950. In the accident which killed three workers, a fast closure of a valve caused extremely high pressures in the plant and split the penstock which then caused a negative pressure in a considerable large part of the connected pipe.[7]

Yang [8] presented a practical method to prevent liquid column separation in a pipeline by increasing the moment of inertia of rotating parts in a pump. He compared the method with the conventional methods like air vessels and surge tanks. He concluded that increasing the moment of inertia of pumping units have advantages of reliability, safety, being independent of the conveyed media and requiring no additional maintenance. He stated the applicability of the method for all kinds of pumping units as long as there are no limitations in manufacture.

Tijsseling [9] considered water hammer with FSI (Fluid-Structure interaction) in thick walled cylinders. He coupled basic fluid equations with pipe equations by the help of boundary conditions defined on the pipe walls. By coupling liquid axial and radial motion equations with the solid radial and axial motion equations, he ended up with FSI Four Equation Model for Thick-walled Cylinders. He concluded the applicability of thin-wall assumption for long waves in fairly thick walled pipes.

One of the possible transient flow situations in liquid pipelines is due to the leaks in the pipeline. Abhulimen *et al* [10] developed a model for leak detection in pipelines and generated a numerical solution pattern. Developed model uses the concept of instability and deviations of flow parameters from no leak situation. They used implicit finite difference schemes to solve nonlinear second order partial differential equations. They concluded that pressure measurement is a more sensitive way for leak detection then the flow rate measurement.

Aksel [11] simulated transient flow in liquid pipelines by using method of characteristics. She used specified time intervals for time discretization of the governing equations and developed a computer program simulating transients with different components like pumps, relief valves, check valves and different types of reservoirs.

Shimada *et al* [12] considered possible errors that arouses while evaluating friction terms in Method of Characteristics analysis. They studied on the possible error sources and listed three main sources. They stated the first error as the simplification of real physical system by using passive boundaries and neglecting many physical phenomena underlying in dynamic boundaries like pumps and valves. Second error source is identified as the underestimating of two and three dimensional effects and neglecting the skin friction dependency on rates of changes of flow state. And final error source is described as the deviations of numerical solutions from the analytical exact solution due to methods of integration. They concluded that Courant number is well a criterion for frictionless flow while a second stability criterion should be defined for frictional cases in order to assure stability.

With the emerging details of unsteady flow theory, computer software packages become more reliable and feasible for end users and engineers. There are commercial packages that simulate steady and unsteady flows in complex piping systems.

Oakleigh Software [13] develops computer software for different pipe flow analysis including transient flow solvers. *Pipe Flow Expert,* developed by the company, has the capability of creating complex networks and analysis. *Pipe Flow 3D* is a three dimensional pipe network designer and analyzer.

In this study, a control volume with moving boundaries is considered and continuity and momentum equations are derived meaning that instead of deduction, an individual approach is accepted. System is considered in 1-D domain because of the negligible or no radial flow velocities. After obtaining the final differential equations, Method of

Characteristic, a numerical method that captures the wave due to transients at each predefined time increment, is used for solution of partial differential equations. A complete computer code is developed and integrated with a graphical user interface that can operate stand alone in windows platforms.

1.3 Aim of the Thesis

In this thesis a computer program is coded which constructs transient scenarios, solves, and simulates these scenarios and presents results in means of graphics and tabular output data. Developed computer code utilizes two nonlinear partial differential equations. Method for solving these equations is chosen to be method of characteristics. Computer code stores output values for every time step and every reach decided by the user. Coded computer program is intended to simulate different transient events with different boundary conditions. Capabilities of the computer program are listed below with brief explanations.

- Setup a steady state or transient scenario with graphical and schematic visuals through a user friendly graphical user interface.
- Ease user operations by drag and drop capability of the program.
- Simulate steady state flow in a pipeline with given topographical data, pipe material and fluid properties.
- Compute necessary parameters like wave speed, Reynolds number, friction factor, mesh size and mesh number with the input data provided by the user.
- Read external data representing the dynamics of pipeline components as complete pump characteristics, topographical data, and pipe and fluid properties.
- Compute and plot the limit values of operational parameters like pressure and flow rate.
- Compute and plot pressure and flow rate values at every time step and every pipe reach through pipe extend and at boundaries defined by the user.
- Simulate and solve precaution scenarios against surge situations with surge tanks, air vessels and valves closing with function of times.
- Make parametric studies on pipe friction with the ability of no friction selection.
- Simulate pump trip scenarios accompanying valves.

- Plot maximum pressure values at every mesh thus plot the pressure envelope of the pipeline going through transients.

Beyond the capabilities of the program, this thesis has great influence on questioning time dependent flow situations in a pipeline system with different system components. Comparison of numerical methods and finding out advantages together with their individual drawbacks is also another outcome of the thesis.

CHAPTER 2

PIPELINE HYDRAULICS

2.1 Steady State Flow

2.1.1 General

In liquid distribution systems, flow conditions may be divided into two groups, namely steady and transient flows. Before dealing with the details of the transient flow, it is necessary to derive the steady state flow equations. For a transient flow, steady state properties of the flow plays an important role in being the initial condition values of nonlinear partial differential equations of transients.

It is better to start with some important definitions which are also used in transient flow terminology.

Energy Grade Line (EGL) is the line showing total energy of the fluid flowing in the pipeline system. On the other hand, *Hydraulic Grade Line* (HGL) is the line connecting point of elevation plus pressure head inside the pipeline. [10]

Total head is the height of the EGL above datum. The height above *piezometric head* (HGL) is the dynamic head. Following are the mathematical representations of defined terms.

- Piezometric Head :

$$\frac{P}{\gamma} + z \Rightarrow HGL \qquad \textbf{(2.1)}$$

- Total Head :

$$\frac{P}{\gamma}+\alpha\frac{V^2}{2g}+z \Rightarrow EGL \qquad \textbf{(2.2)}$$

- Dynamic Head :

$$\alpha\frac{V^2}{2g} \qquad \textbf{(2.3)}$$

Drawings and visualization of HGL and EGL has great importance in deciding pipe material, diameter and operational precautions. An outline of steady state analysis and visualization of HGL and EGL is presented below.

- By definition, EGL is in excess of HGL by an amount of dynamic head. If the flow velocity is zero as in the case of a large reservoir or lake, EGL and HGL coincide at the point of surface elevation.
- For real fluids, having a finite viscosity, there is always friction in the piping system thus leading downward slope of HGL throughout pipe extend.
- Exception occurs when a pump is present at any location of the pipeline. Then an abrupt increase in the elevation of EGL and HGL occurs across the pump thus discharge side of the pump has greater HGL and EGL values.
- Unlike pumps, turbines cause an abrupt decrease in the elevation of HGL and EGL by taking an amount of energy from the flow.
- If the flow discharges to a large reservoir by an abrupt expansion, then all he kinetic energy of the flow is lost then HGL drops by an amount of dynamic head.
- Zero pressure in the pipeline means HGL coincides with the topographical elevation since $P/\gamma = 0$ and piezometric head becomes z only.
- For a steady flow in a pipe with constant fluid and pipe properties throughout extend, the head loss per unit length is a constant. Thus the slope of HGL is constant throughout. The distance between EGL and HGL changes in cases of flow velocity changes.
- If the HGL falls below the pipe, P/γ becomes negative indicating pressure values are below the atmospheric pressure value. Then water vaporizes and accumulates in the highest part of the pipeline. This is called *Air Lock*. [14]

Schematic representations of above mentioned terms and situations are below.

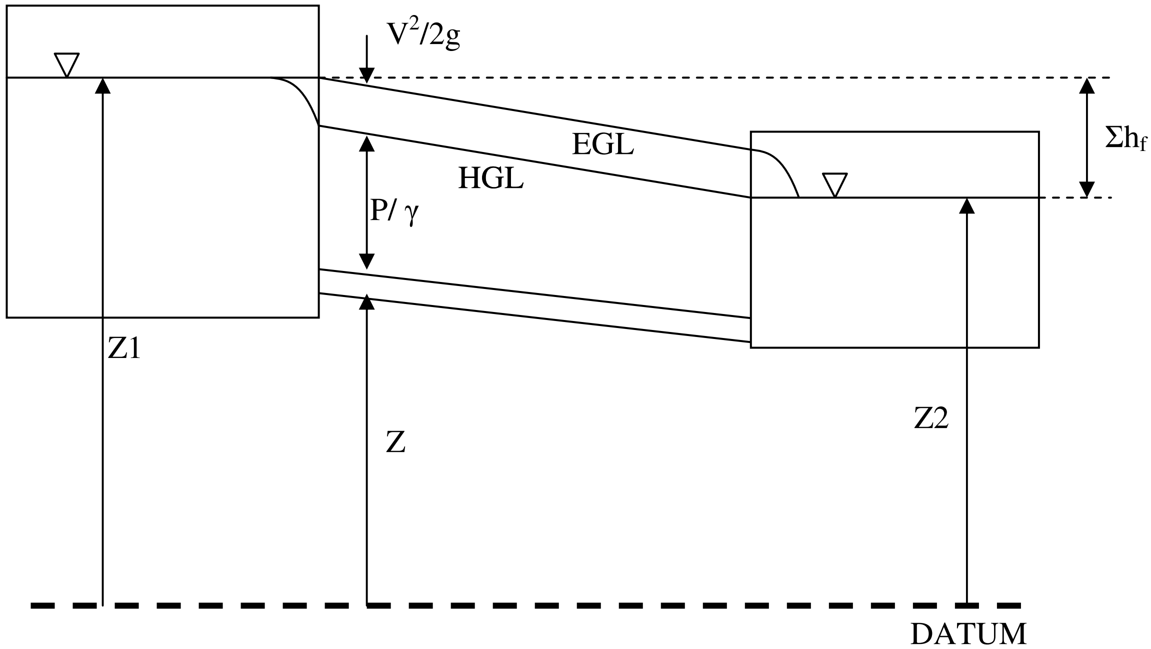


Figure 2.1 Schematic Representations of Basic Definitions

2.1.2 Friction and Losses

Friction is one of the most important parameters for both steady state and transient fluid flow. Frictional losses are the major losses in a pipeline system and they have to be compensated by means of energy suppliers like pumps. Pipe friction loss is a function of pipe length, pipe diameter, and flow velocity and friction factor. There are several methods for determining the friction factor and all utilizes Moody Diagram which is developed by the Colebrook-White Equation;

$$\frac{1}{f^{1/2}} = -0.86 \ln\left(\frac{\varepsilon_S / D}{3.72} + \frac{2.51}{f^{1/2}\,\mathrm{Re}}\right) \qquad \mathbf{(2.4)}$$

Colebrook-White equation is an implicit equation on friction factor, f, and requires an iterative procedure to obtain f value. On the other hand Chen equation is an explicit equation on f and is used for entire range of Re and ε/D;

$$\frac{1}{\sqrt{f}} = -2\log\left\{\frac{\varepsilon_S / D}{3.7065} - \frac{5.0452}{\mathrm{Re}_D}\log\left[\frac{(\varepsilon_S / D)^{1.1098}}{2.8257} + \left(\frac{7.149}{\mathrm{Re}_D}\right)^{0.8981}\right]\right\} \tag{2.5}$$

where f is taken as Darcy-Weisbach friction factor.

It is a common application to obtain an f value from Chen Equation and use that value as the first estimate of Colebrook-White Equation. This leads to a much less iteration steps in finding f value.

By the obtained value, friction loss in a pipeline system may be calculated by the following formula.

$$h_f = \frac{fL}{D}\frac{V^2}{2g} \tag{2.6}$$

This formula gives the major head loss due to pipe friction. There are also minor losses in a piping system due to some system components such as valves, bends, fittings, elbows etc. To be able to take them into consideration, Equivalent length concept is developed. In dealing with minor losses, each minor loss creator component means an equivalent length of pipe. Then using the corresponding equivalent length, minor losses can be calculated by the following,

$$h_f = f\frac{L_e}{D}\frac{V^2}{2g} \tag{2.7}$$

2.1.3 Pumps in a Pipeline System

In a pipeline system, due to friction, there are always head losses. In order to supply necessary pressure head to the system, pumps are operated for liquid pipeline systems and compressors are operated in gas pipeline systems. A pump delivers head to the liquid and supplies the necessary energy for the system. To solve a system including a pump, system characteristics equation should be solved simultaneously with pump characteristics equation thus the operating point of the system is obtained.

$$\frac{P_1}{\gamma}+\frac{V_1^{\ 2}}{2g}+z_1+h_P=\frac{P_2}{\gamma}+\frac{V_2^{\ 2}}{2g}+z_2+\sum K_L\frac{V^2}{2g}+\sum\frac{fL}{D}\frac{V^2}{2g} \qquad \textbf{(2.8)}$$

And solving for h_p

$$h_P=(z_2-z_1)+\frac{V^2}{2g}\left(1+\sum K_L+\frac{fL}{D}\right) \qquad \textbf{(2.9)}$$

Graphical representation of the pump and system characteristics is as follows;

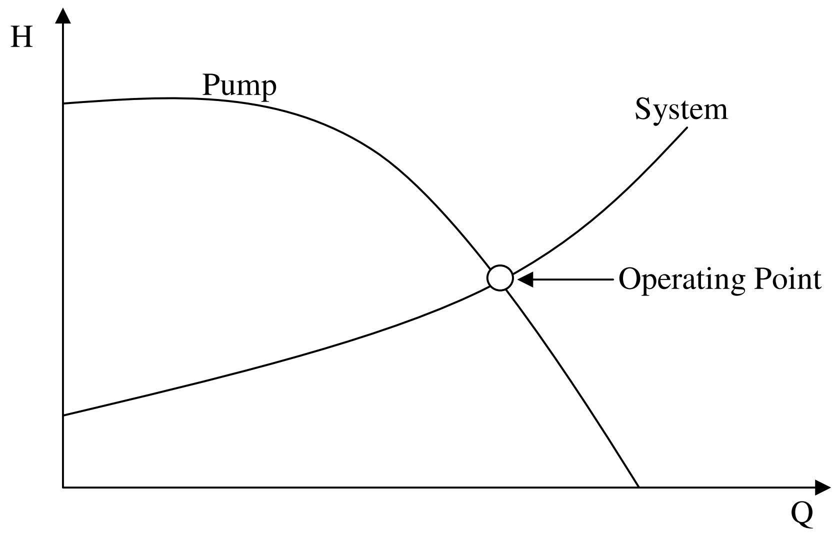


Figure 2.2 Pump and System Characteristics

Pumps are selected to match the system requirements. Systems generally operate over a range of conditions due to varying demands, changes in system conditions, and changes in friction or minor losses. For high pressure requirements, series arrangements of pump should be considered and for flexibility and reliability, parallel pumps should be used. One of the most important points in selecting pumps is the efficiency of the selected pump. Best choice is the one with design point close to its operating point.

Effects of series and parallel pumps are represented by graphs below.

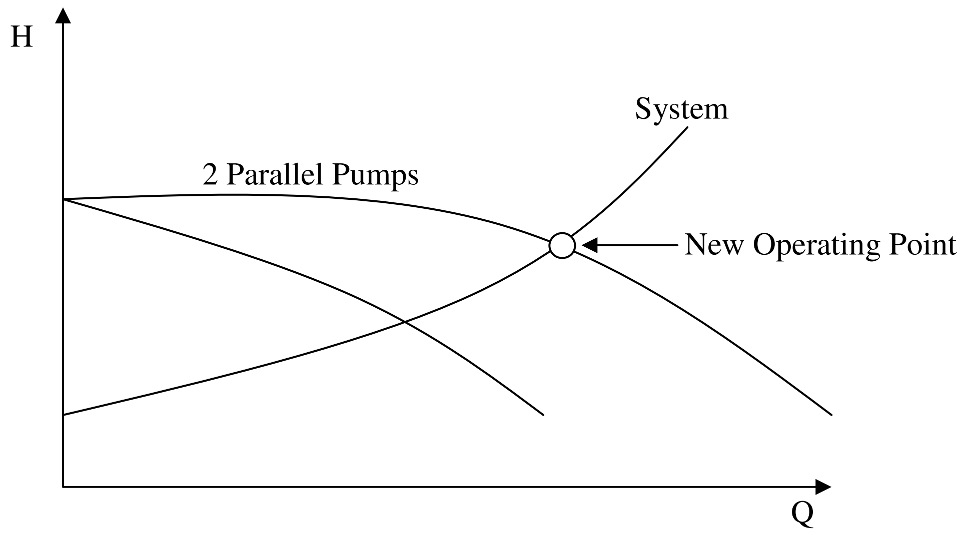


Figure 2.3 Pump and System Characteristics for 2 Parallel Pumps

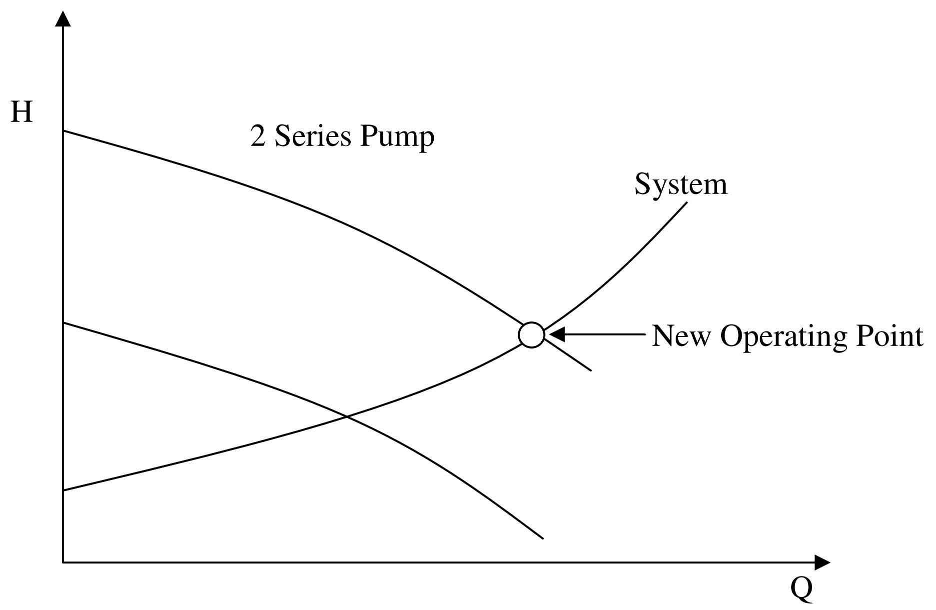


Figure 2.4 Pump and System Characteristics for 2 Series Pumps

Effects of series and parallel arrangement of pumps may be summarized as follows. Parallel pumps are more appropriate in systems with low friction loss and series pumps are more appropriate in systems with high friction losses.

2.2 Transient Flow

In unsteady flow, mean values of flow parameters vary with time. Transient flow is too complex to be solved using common algebraic methods thus requires special solution methods. Most of the cases in transient flow can be solved by using numerical methods rather than algebraic solution methods. Problems regarding to unsteady flow may be considered in 4 main groups. These are as follows.

- Changes in flow velocity are significant but slow enough that the forces are negligible compared with other forces present in the system e.g. continuous filling or emptying of a reservoir.
- Flow changes rapidly enough to cause temporal acceleration of flow. Reciprocating machinery can be an example for these sorts of situations.
- Flow changes so quickly that elastic forces come into picture as it is in cases of valve closures.
- An oscillatory motion with certain cycles of events as it is in case of a compressor surge.

Transient flow is commonly considered with individual approach instead of deduction. Following parts of the sections state a complete procedure of the individual approach to the transient flow.

2.2.1 Physical System

2.2.1.1 Definition of the Physical System

Physical model of the study is basically a system of line pipes with uniform cross-sectional area in sections and several hydraulic components like pumps, valves, reservoirs and air vessels and surge tanks which undergoes a steady state operation initially. The transients and the effects of transients on the pipe inside pressure and flow rate are investigated with setting up different possible transient scenarios. Inclination of the pipe segment is also considered in order to obtain the most general expressions for the real system. The flow is assumed to obey the steady state friction equations defined by Darcy-Weisbach throughout the analysis thus no modifications are made on the friction terms of the governing partial differential equations. Fluid for the model is chosen to be a homogenous liquid and corresponding liquid properties are used for the analysis.

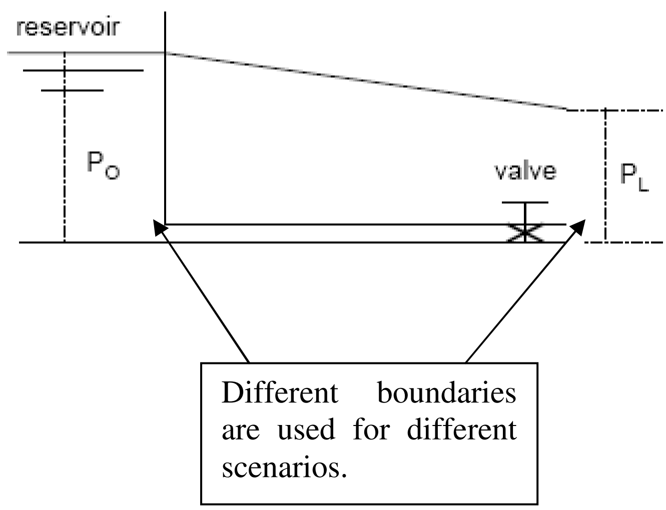


Figure 2.5 Systems with Boundary Condition View

2.2.2 Mathematical Model

Method for mathematical formulation of the study is chosen to be *individual approach* where the following steps are considered during formulation.

2.2.2.1 Control Volume

A pipe segment with moving boundaries is selected as the control volume where the gradients are assumed to be only in the flow direction leading to a lumped formulation in radial direction of the control volume.

Following schematics shows the details of the selected control volume which will help obtaining necessary flux and force balance equations. Governing differential equations will be obtained just after deriving some other auxiliary equations.

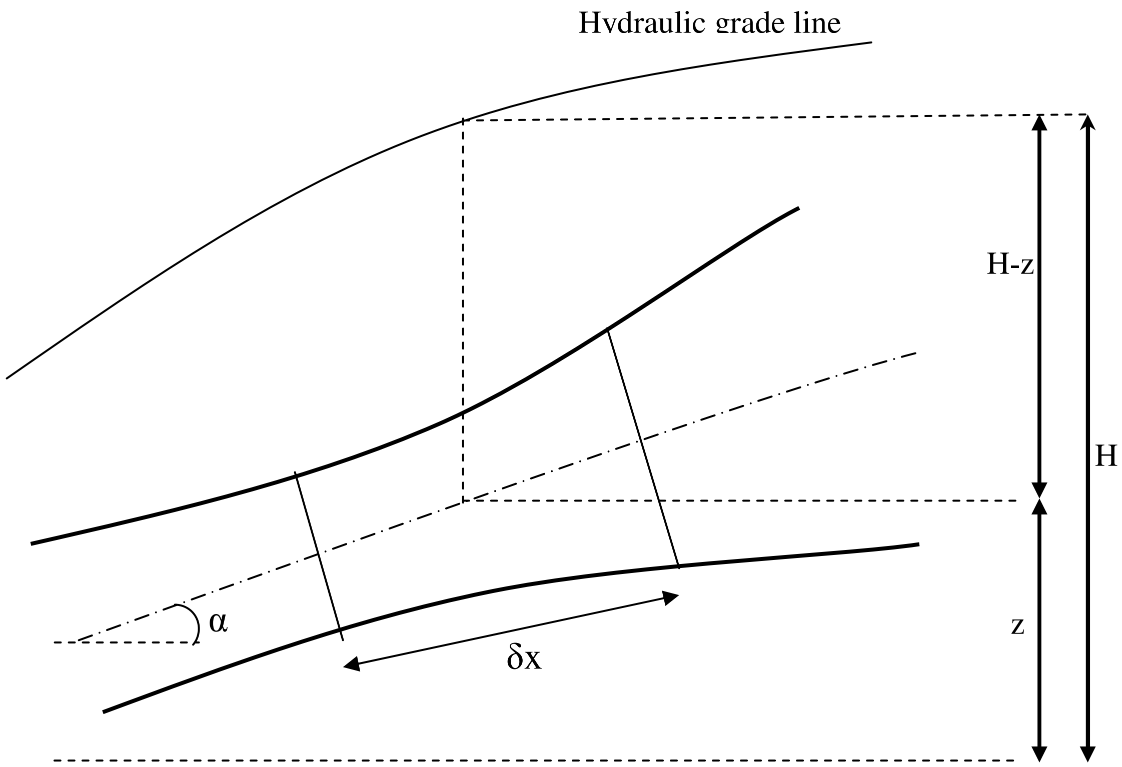
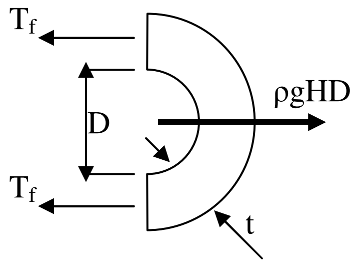


Figure 2.6 Control Volume with Moving Boundaries

2.2.2.2 Constitutive Relations

- **Radial Forces on Pipe walls**



Regardless of the support situations of a pipe, lateral stress is always defined with the following formula.

$$\sigma = \frac{T_f}{t} = \frac{\gamma HD}{2t} = \frac{D\Delta P}{2t} \tag{2.11}$$

- **Derivation of Wave Speed Equation**

Wave speed equation can be derived by considering a pipe section and applying momentum equation onto the liquid column flowing in this section. Force balances are written for the moving fluid column.

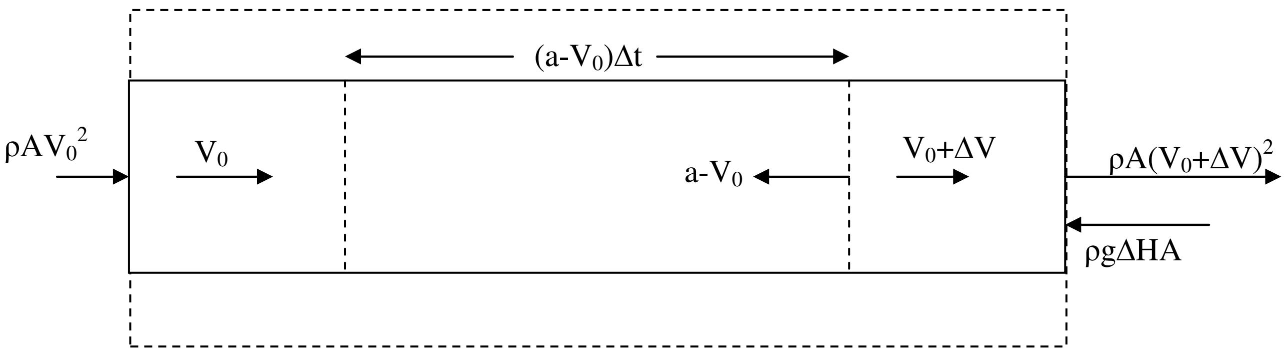


Figure 2.7 Momentum Components on the Moving Fluid Column

Writing momentum equation in x direction states the resultant net force in the x axis is equal to the time rate of change of momentum in x direction. In equation form;

$$\gamma \Delta HA = \rho A(a - V_0)\Delta V + \rho A(V_0 + \Delta V)^2 - \rho A V_0^{\ 2} \qquad \textbf{(2.12)}$$

By neglecting terms containing ΔV^2 as they are small compared with the other terms;

$$\Delta H = \frac{a\Delta V}{g}\left(1 + \frac{V_0}{a}\right) \approx \frac{a\Delta V}{g} \qquad \textbf{(2.13)}$$

V_0/a term is usually very small when compared with 1 so may be neglected. If flow is completely stopped, then the change in the velocity will be equal to the initial velocity, V_0.

From the figure, if flow suddenly stops when gate closes rapidly, pipe may stretch in length by an amount of Δs in regarding with the supporting conditions. It may be assumed that, this distance is covered in (L/a) seconds, thus has a velocity of a/LΔs. Hence velocity of the fluid is changed by an amount of (a/LΔs – V_0). After gate closure, during (L/a) seconds, an amount of $\rho A V_0 L/a$ mass enters to the system increasing the pipe cross sectional area, filling the stretched volume and compressing the fluid by the high pressure it has.

In equation form it can be expressed as;

$$\rho A V_0 \frac{L}{a} = \rho L \Delta A + \rho A \Delta s + LA\Delta \rho \qquad \textbf{(2.14)}$$

By substituting (a/LΔs – V_0) for ΔV and eliminating V_0 above equation simplifies to;

$$\frac{\Delta V}{a} = \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho} \qquad \textbf{(2.15)}$$

Now considering that the valve is closed by increments instead of a sudden closure, then the head change can be expressed as;

$$\sum \Delta H = -\frac{a}{g}\sum \Delta V \qquad \textbf{(2.16)}$$

Now using above equation to eliminate ΔV;

$$a^2 = \frac{g\Delta H}{\Delta A / A + \Delta\rho / \rho} \qquad \textbf{(2.17)}$$

By using the definition of bulk modulus of elasticity, K of the fluid;

$$K = \frac{\Delta P}{P} = -\frac{\Delta P}{\Delta\forall / \forall} \qquad \textbf{(2.18)}$$

With $\Delta\forall / \forall$ is the fractional volume change. Then equation (2.17) may be rearranged as the following;

$$a^2 = \frac{K / \rho}{1 + (K / A)(\Delta A / \Delta P)} \qquad \textbf{(2.19)}$$

As mentioned before, there may be different supporting conditions for pipes. Wave speed equation should be arranged for different cases of supporting conditions by evaluating ΔA/(AΔP) for each cases.

There are three supporting cases.

- **Case a:** pipe anchored at the upstream end only
- **Case b:** pipe anchored throughout against axial movements.
- **Case c:** pipe anchored with expansion joints

Following are the details of three different supporting conditions.

Case a:

The axial tensile stress is the force on the closed valve divided by the valve cross sectional area.

$$\sigma_1 = \frac{\gamma HA}{\pi Dt} \text{ or } \Delta\sigma_1 = \frac{D\Delta P}{4t} \qquad \textbf{(2.20)}$$

Then defining Poisson's ratio

$\eta = \dfrac{lateral\_strain}{axial\_strain} = -\dfrac{\xi}{\xi_1}$ in which total strain is equal to

$\xi_T = \xi_2 - \eta\xi_1$ And remembering that stress and strain is related by young modulus of elasticity;

$\xi_2 = \dfrac{\sigma_1}{E}$ and $\xi_1 = \dfrac{\sigma_2}{E}$

Then

$$\frac{\Delta A}{A\Delta P} = \frac{2\Delta\xi_T}{\Delta P} = \frac{2}{\Delta P}\left(\Delta\xi_2 - \eta\Delta\xi_1\right) = \frac{2}{E\Delta P}\left(\Delta\sigma_2 - \eta\Delta\sigma_1\right) = \frac{D}{Et}\left(1 - \frac{\eta}{2}\right) \qquad \textbf{(2.21)}$$

Case b:

For s pipe anchored throughout $\xi_1 = 0$ and $\sigma_1 = \eta\sigma_2$ so

$$\frac{\Delta A}{A\Delta P} = \frac{2\Delta\xi_T}{\Delta P} = \frac{2}{E\Delta P}\left(\Delta\sigma_2 - \eta^2\Delta\sigma_1\right) = \frac{D}{Et}\left(1-\eta^2\right) \qquad \textbf{(2.22)}$$

Case c:

For expansion joints throughout $\sigma_1 = 0$ and

$$\frac{\Delta A}{A\Delta P} = \frac{2\Delta\sigma_2}{E\Delta P} = \frac{D}{Et} \qquad \textbf{(2.23)}$$

And finally wave speed can be written in a simpler form

$$a = \frac{\sqrt{K/\rho}}{\sqrt{1+\left[(K/E)(D/E)\right]c_1}} \qquad \textbf{(2.24)}$$

Where c_1 takes the following values;

Case a: $c_1 = 1 - \dfrac{\eta}{2}$

Case b: $c_1 = 1 - \eta^2$

Case c: $c_1 = 1$

2.2.2.3 Basic Differential Equations for One Dimensional Unsteady Flow

As it is mentioned before, there are two main governing equations that define fluid flow. These are nonlinear partial differential equations, one being continuity equation and the other momentum equation. In deriving these equations, individual approach is applied, thus each equation is obtained by defining a control volume in the domain of interest and necessary relations are derived from this control volume.

2.2.2.3.1 Equation of Motion

Equation of motion can be derived by the help of the following free body diagram sketched for the selected control volume.

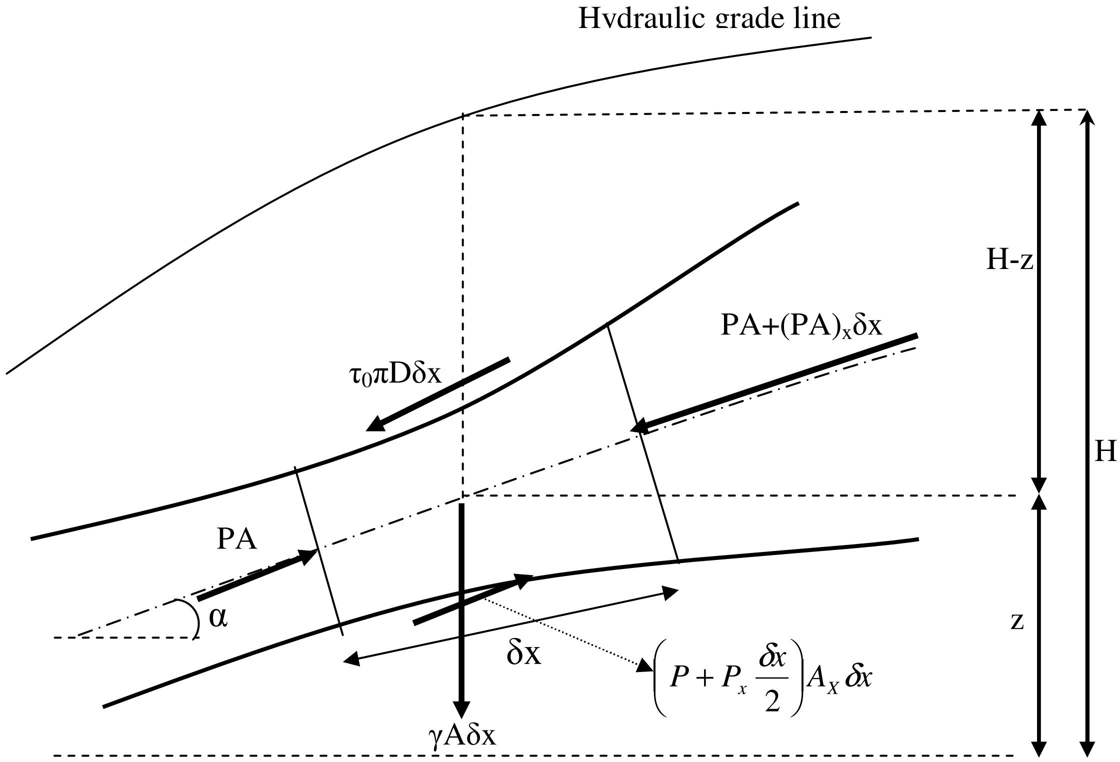


Figure 2.8 Forces on the Moving Fluid Column

The equation of motion is written for conical tube in order to take area variations into account. This equation is written in terms centerline pressure, P(x,t) and centerline velocity, V(x,t). This equation s then converted into a form using HGL, or in other words Piezometric Head. In his treatment, x and t are independent variables and Head and Flow rate re the dependent variables. Summation of forces present on the free body diagram can be written in the following equation;

$$PA - \left[PA + (PA)_x\,\delta x\right] + \left(P + P_x \frac{\delta x}{2}\right) A_x\,\delta x - \tau_0 \pi D\,\delta x - \gamma A\,\delta x \sin\alpha = \rho A\,\delta x \dot{V} \quad \textbf{(2.25)}$$

By neglecting the small quantity $(\delta x)^2$ and simplifying the equation;

$$P_x A + \tau_0 \pi D + \rho g A \sin\alpha + \rho A \dot{V} = 0 \quad \textbf{(2.26)}$$

Shear stress in transient flow is assumed to be the same with that of steady state flow as it is defined in terms of Darcy-Weisbach friction factor;

$$\tau_0 = \frac{\rho f V|V|}{8} \quad \textbf{(2.27)}$$

In the equation, the acceleration term $\dot{V}$ is for the moving fluid particle and can be written as follows

$$\dot{V} = VV_x + V_t \qquad \textbf{(2.28)}$$

By using acceleration equation and shear stress equation, equation of motion takes the form

$$\frac{P_x}{\rho} + VV_x + V_t + g\sin\alpha + \frac{fV|V|}{2D} = 0 \qquad \textbf{(2.29)}$$

This is also valid for converging or diverging pipes. In the equation P terms can be replaced by the Piezometric head, H.

$P = \rho g(H - z)$ where z is the centerline elevation of the pipe at x location. Then

$$P_x = \rho g(H_x - z_x) = \rho g(H_x - \sin\alpha) \qquad \textbf{(2.30)}$$

In above differentiation, ρ is assumed to be substantially constant when compared with H and z. above equation is valid for only liquids while equation of motion is valid for both gases and liquids. Substituting into the equation of motion,

$$gH_x + VV_x + V_t + g\sin\alpha + \frac{fV|V|}{2D} = 0 \qquad \textbf{(2.31)}$$

This is also restricted for fluid flow.

It is obvious that unsteady flow equations must hold for steady flow also, as steady flow is a special case of unsteady flow. Then final form of equation of motion may be checked for steady state flow by setting $V_x = 0$ and $V_t = 0$;

$\Delta H = \dfrac{f\Delta x V|V|}{2gD}$ as it is stated in the steady state part of the chapter.

2.2.2.3.2 Continuity Equation

In deriving the continuity equation a moving control volume is selected, and liquid column in the control volume considered to move and stretch as the pipe walls stretches and moves. Conservation law states that the time rate of mass inflow is equal to the time rate of increase of mass inside this volume. In equation form,

$$-[\rho A(V - u)]_x \delta x = \frac{D^{\cdot}}{Dt}(\rho A \delta x) \qquad \textbf{(2.32)}$$

Total derivative with respect to axial motion of pipe can be written as follows;

$$\frac{D'}{Dt} = u\frac{\partial}{\partial x} + \frac{\partial}{\partial t} \quad \textbf{(2.33)}$$

Time rate of increase of pipe length can be expressed as

$$\frac{D'}{Dt}\delta x = u_x \delta x \quad \textbf{(2.34)}$$

Expanding equation (2.32) using equation (2.34),

$$(\rho AV)_x - (\rho Au)_x + \frac{D'}{Dt}(\rho A) + \rho A u_x = 0 \quad \textbf{(2.35)}$$

Expanding equation (2.35) and simplifying leads to

$$(\rho AV)_x + (\rho A)_t = 0 \quad \textbf{(2.36)}$$

Equation (2.36) may be written as the following

$$\rho A V_x + V(\rho A)_x + (\rho A)_t = 0 \quad \textbf{(2.37)}$$

Last two terms can be rewritten using the equation (2.33) and equation (2.37) can be written as

$$\frac{1}{\rho A}\frac{D}{Dt}(\rho A) + V_x = 0$$

CHAPTER 3

METHOD OF CHARACTERISTICS

3.1 Characteristics Equations

The continuity and momentum equations were derived by individual approach in previous sections. These equations are non-linear partial differential equations in two dependent variables, velocity and pressure head and two independent variables, time and distance along the pipeline. These two non-linear partial differential equations can be transformed into four ordinary differential equations by the characteristics method. First approach to the equations will be to neglect the terms with lesser importance and after obtaining basic equations, the effects of neglected terms will be considered by parametric studies on the obtained mathematical model.

To list the simplified form of the continuity and momentum equations derived before;

$$L1 = gH_x + V_t + \frac{f}{2D}V|V| = 0 \tag{3.1}$$

$$L2 = H_t + \frac{a^2}{g}V_x = 0 \tag{3.2}$$

0 is a solution for both equations. Then any linear combination of these two equations will again be equal to zero i.e. these equations can be combined linearly with an unknown multiplier giving another equation, say L.

$$L = L1 + \lambda L2 = \lambda\left[H_x \frac{g}{\lambda} + H_t\right] + \left[V_x \lambda \frac{a^2}{g} + V_t\right] + \frac{fV|V|}{2D} = 0 \tag{3.3}$$

Any two distinct real λ values yield two equations in H and V and these equations are equivalents of equations (3.1) and (3.2) if λ is chosen appropriately, equation (3.3) will be simplified considerably. Knowing that V and H are dependent variables on x and t, taking x as a function of time, t;

$$\frac{dH}{dt} = H_x \frac{dx}{dt} + H_t \quad \text{And} \quad \frac{dV}{dt} = V_x \frac{dx}{dt} + V_t \qquad \textbf{(3.4)}$$

By a careful examination of equations (3.3) and (3.4), unknown multiplier can be chosen as the following aiming the simplification of equation (3.3)

$$\frac{dx}{dt} = \frac{g}{\lambda} = \frac{\lambda a^2}{g} \qquad \textbf{(3.5)}$$

Substituting equation (3.5) into (3.3) by using (3.4), (3.3) becomes the ordinary differential equation;

$$\lambda \frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 \qquad \textbf{(3.6)}$$

Solving equation (3.5) for λ, two particular values of λ is obtained.

$$\lambda = \pm \frac{g}{a} \qquad \textbf{(3.7)}$$

Values of λ can now be substituted into equation (3.5) with

$$\frac{dx}{dt} = \pm a \qquad \textbf{(3.8)}$$

This shows the change in position of wave related to the change in time. Values of λ can be substituted into equation (3.6). If negative value of λ is used in equation (3.5) then negative value of λ should be used in equation (3.6) and same for the positive values also. This substitution leads to two sets of equations which will be called as C^+ and C^- equations.

$$\frac{g}{a}\frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 \qquad \textbf{(3.9)}$$

$$\frac{dx}{dt} = +a \qquad \textbf{(3.10)}$$

$$-\frac{g}{a}\frac{dH}{dt}+\frac{dV}{dt}+\frac{fV|V|}{2D}=0 \tag{3.11}$$

$$\frac{dx}{dt}=-a \tag{3.12}$$

Two real distinct values of λ are used to convert the original partial differential equations to two sets of total differential equations. Equations (3.9) and (3.11) are valid where the equations (3.10) and (3.12) are valid respectively. By considering the two independent flow variables x and t in an axis, characteristics equations can be visualized as the following

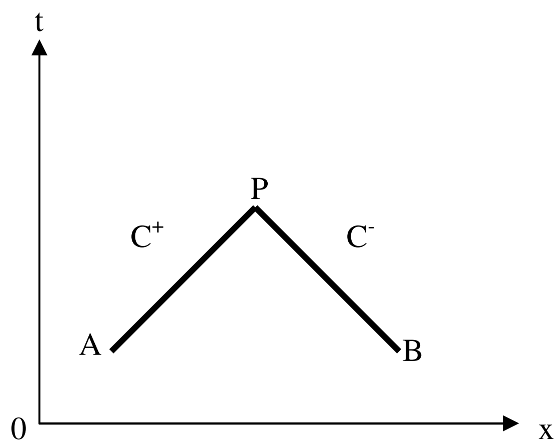


Figure 3.1 Characteristics Lines around Point P

Solution develops in the x-t plane as wave propagates sand travels during the transients. Two lines between points A and P and P and B are characteristics lines along which the equations (3.9) and (3.10) are valid.

It is important to state the fact that no mathematical assumption is made until this stage of derivations, thus present equations have the identical solutions of the very original equations of flow.

3.2 Time Discretization of Obtained Equations

To solve the obtained equations, these equations should be discretized n x-t plane and nodal solutions should be obtained. For this purpose, a pipeline section is divided into N equal reaches, thus forming N+1nodes to be solved for each time step. Time step for the calculation scheme can be calculated as $\Delta t = \Delta x/a$. Solution domain can be shown as the following

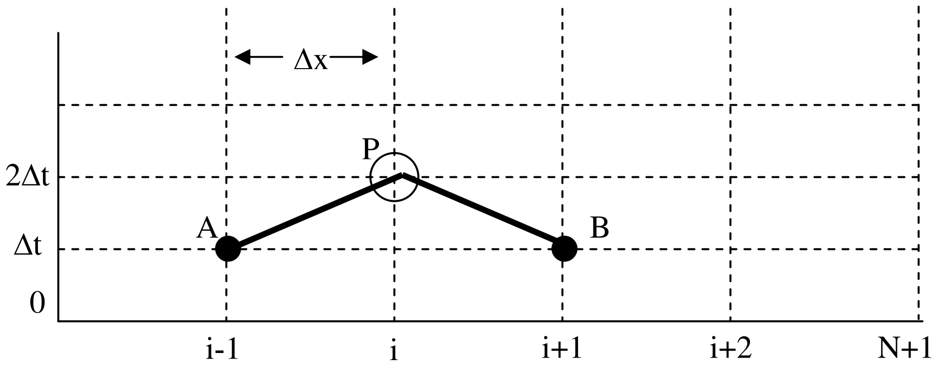


Figure 3.2 Positions vs. Time Grid for the Solution Domain

If the values of dependent variables V and H are known at points A and B, then equation (3.9) can be integrated along the line AP on which the equation is valid. Then, as a result of integration, an equation in two unknowns, V and H at point P is obtained. Similarly if the points of V and H are known at point B also, then equation (3.11) can be integrated along the line PB to have another equation with two unknowns V and H at point P. Then simultaneous solution of these two equations yields the condition at point P at a particular time.

Integration of equations can be handled by a simple manipulation of equations just multiplying equation (3.9) by $adt/g = dx/g$ and pipeline area may be introduced to the equations in order to be able to obtain equations in terms of discharge, Q, instead of flow velocity, V.

$$\int_{H_A}^{H_P} dH + \frac{a}{gA}\int_{Q_A}^{Q_P} dQ + \frac{f}{2gDA^2}\int_{X_A}^{X_P} Q|Q|dx = 0 \qquad \textbf{(3.13)}$$

It is important to note that the last term is unknown a priory and an approximation is introduced to handle that term. This approximation is a first order approximation for the evaluation of last term and is insignificant as long as the friction dominated flow is considered. With similar integration of equation (3.11) along C^- line, following equations are obtained.

$$H_P - H_A + \frac{a}{gA}(Q_P - Q_A) + \frac{f\Delta x}{2gDA^2} Q_A|Q_A| = 0 \qquad \textbf{(3.14)}$$

$$H_P - H_B - \frac{a}{gA}(Q_P - Q_B) + \frac{f\Delta x}{2gDA^2} Q_B|Q_B| = 0 \qquad \textbf{(3.15)}$$

Above two equations are compatibility equations and are the basic relations describing transient is a pipe flow. These equations can be solved for H_P and following equations can be obtained.

$$C^+ : H_P = H_A - B(Q_P - Q_A) - RQ_A|Q_A| \qquad \textbf{(3.16)}$$

$$C^- : H_P = H_B + B(Q_P - Q_B) + RQ_B|Q_B| \qquad \textbf{(3.17)}$$

In which B = a/gA and R = fΔx/(2gDA^2).

One should note that these equations must satisfy the steady state conditions which are in fact special cases of transients. Since original problem is initial value and boundary value problem, solution scheme should have a seed of initial values and should also have boundary values to be supplied. Initial values of the solution can always well be the steady state values of flow variables as they are also special cases of transients. Boundary values can be obtained by defining special boundaries and these boundaries will be considered in the following sections of this chapter.

For any interior intersection point, in other words, in every node, the two compatibility equations are solved simultaneously for the unknowns head and discharge at that node. By Introducing C_P and C_M to the equations (3.16) and (3.17), they can be rewritten as the following

$$C^{+} : H_{P_i} = C_P - BQ_{P_i} \quad \textbf{(3.18)}$$

$$C^{-} : H_{P_i} = C_M + BQ_{P_i} \quad \textbf{(3.19)}$$

C_P and C_M are always known and constants. They can be written as the following

$$C_P = H_{i-1} + BQ_{i-1} - RQ_{i-1}\left|Q_{i-1}\right| \quad \textbf{(3.20)}$$

$$C_M = H_{i-1} - BQ_{i-1} + RQ_{i+1}\left|Q_{i+1}\right| \quad \textbf{(3.21)}$$

After having above equations, head value at point P can be obtained by eliminating Q from equations (3.18) and (3.19). Then

$$H_{P_i} = \left(C_M + C_P\right)/2 \quad \textbf{(3.22)}$$

Discharge at point P can then be obtained from either equation (3.18) or (3.19).

It should be noted that all known values of H and Q are from the preceding tie step, either the result of previous calculation or the initial value given at the beginning of the solution.

Solution scheme requires the knowledge of the boundary values whenever last and first boundaries of the pipe is reached so boundary conditions should be defined and handled by special predefined functions.

3.3 Boundary Conditions

At the end of the pipeline, only one compatibility equation can be written as there are no nodes before and after the last node. For the upstream end of the pipe, only equation (3.19) is valid along the C^- characteristics line. On the other hand, at downstream, only equation (3.19) can be written which is valid along C^+ characteristics line. Auxiliary equations are needed to handle the upstream and downstream boundaries throughout transients. Each boundary is solved independent of the other boundary and the interior nodes while it conveys knowledge of the boundary to the other nodes of the pipeline. Different boundaries may be present in a pipeline and their details and solution procedures are explained during the following text.

3.3.1 Reservoir at Upstream End with Constant Head

At the upstream end of the pipeline, there may be a large reservoir which is very little affected from the transients and stays with constant head all the time. Then this boundary continuously imposes a constant head to the beginning node of the pipeline. Then head and discharge values of upstream end boundary of the pipeline can be obtained with the following relations.

$$H_{P_1} = H_R \tag{3.23}$$

And discharge can be obtained by solving equation (3.19)

$$Q_{P_1} = \left(H_{P_1} - C_M\right) / B \tag{3.24}$$

H_R is the constant head of the reservoir.

3.3.2 Reservoir at Upstream End with Specified Variable Head

At the upstream end of the pipeline, there may be a large reservoir which has a head changing with a known function, and then head at the upstream boundary can be obtained by the following relation

$$H_{P_1} = H_R + \Delta H \sin(\omega t) \tag{3.25}$$

And discharge can be obtained by solving equation (3.19)

$$Q_{P_1} = \left(H_{P_1} - C_M\right) / B \tag{3.26}$$

ΔH is the amplitude of the wave and ω is the circular frequency.

3.3.3 Discharge as a Specified Function of Time at Upstream End

A positive displacement pump may be equipped at the upstream of the pipeline and it may be expressed as an explicit function of time. Discharge at the upstream boundary can be obtained by using the specified function

$$Q_{P_1} = Q_0 + \Delta Q \left|\sin(\omega t)\right| \tag{3.27}$$

Head value at the upstream then can be obtained by solving equation (3.19).

3.3.4 Centrifugal Pump with Head-Discharge Curve Specified

A centrifugal pump can be included to a transient scenario by supplying its head discharge values in a tabulated manner or by supplying its head-discharge equation. By assuming that the pump supplies flow from a suction reservoir with the surface elevation being the datum of hydraulic grade line, following equation may be used to model the pump in the system

$$H_{P_1} = H_S + Q_{P_1}\left(a_1 + a_2 Q_{P_1}\right) \qquad \textbf{(3.28)}$$

In equation (3.28), H_S is the shut of head and a_1 and a_2 are the constants describing pump curve. Solution of equation (3.28) simultaneously with equation (3.19) gives discharge of the pump as the following

$$Q_{P_1} = \frac{1}{2a_2}\left[B - a_1 - \sqrt{(B-a_1)^2 + 4a_2(C_M - H_S)}\right] \qquad \textbf{(3.29)}$$

Head value of the pump can now be obtained from equation (3.26) with discharge known.

3.3.5 Dead End at the Downstream End of Pipe

A closed end of a pipeline causes discharge to be equal to zero thus

$$Q_{P_{NS}} = 0 \qquad \textbf{(3.30)}$$

Head value can be obtained by equation (3.19)

3.3.6 Valve at Downstream of Pipe

If hydraulic grade line datum is taken at the valve, orifice equation can be written for the valve as following

$$Q_0 = (C_D A_G)_0 \sqrt{2gH_0} \qquad \textbf{(3.31)}$$

In equation (3.31), Q_0 is the steady state flow, H_0 is the steady state head loss across the valve at full opening, C_D is the discharge coefficient and A_G is the valve opening. For other opening values equation (3.31) can be written in general form

$$Q_P = (C_D A_G)\sqrt{2g\Delta H} \quad \textbf{(3.32)}$$

Valve opening can be represented as the percent of instantaneous opening to the steady state opening of the valve. Dimensionless valve opening can be introduced to equation (3.32)

$$\tau = \frac{C_D A_G}{(C_D A_G)_0} \quad \textbf{(3.33)}$$

Dividing equation (3.32) with (3.31)

$$Q_P = \frac{Q_0}{\sqrt{H_0}}\tau\sqrt{\Delta H} \quad \textbf{(3.34)}$$

For steady flow $\tau = 1$ and for no flow through the valve, i.e. totally closed valve, $\tau = 0$. Value of τ may be greater than 1 if the valve is opened from steady state position. Solving equations (3.34) simultaneously with equation (3.18) yields to the valve discharge value

$$Q_{P_{NS}} = -BC_v + \sqrt{(BC_v)^2 + 2C_P C_v} \quad \textbf{(3.35)}$$

$$C_v = (Q_0\tau)^2 / 2H_0$$

Corresponding head can b calculated by the use of equation (3.18)

3.3.7 Orifice at Downstream of Pipe

Same equations with the valve at downstream apply with $\tau = 1$ all the time.

3.3.8 Reservoir at Downstream End with Constant Head

Pipeline may be discharging to a reservoir with constant head. Then the last node of pipeline, in other words, the downstream end boundary condition is defined by the reservoir properties. Head value at the end of pipe is equal to the reservoir head.

$$H_{P_{NS}} = H_{RD} \quad \textbf{(3.36)}$$

Discharge can be calculated by using equation (3.18)

3.3.9 Valve Inline

If the pipeline is equipped with a valve or orifice between two sections of the pipeline or between two different line pipes, then orifice equation should be simultaneously solved for each pipe end points. Flow reversal should be also allowed for the solution and no storage of fluid should be considered. With steady state pressure drop, H_0, orifice equation for positive flow is written as

$$Q_{P_{2,1}} = Q_{P_{1,NS}} = \frac{Q_0 \tau}{\sqrt{H_0}} \sqrt{H_{P_{1,NS}} - H_{P_{2,1}}} \qquad \textbf{(3.37)}$$

Equation (3.37) should be combined with equations (3.18) and (3.19) for pipes 1 and pipe 2 respectively to give the following solution

$$Q_{P_{1,NS}} = -C_v (B1 + B2) + \sqrt{C_v^{\ 2} (B1 + B2)^2 + 2C_v (C_{P_1} - C_{M_2})} \qquad \textbf{(3.38)}$$

In which $C_v = Q_0^{\ 2} \tau^2 / 2H_0$. For negative flow orifice equation can be written as the following

$$Q_{P_{2,1}} = Q_{P_{1,NS}} = -\frac{Q_0 \tau}{\sqrt{H_0}} \sqrt{H_{P_{2,1}} - H_{P_{1,NS}}} \qquad \textbf{(3.39)}$$

And again combining with equations (3.18) and (3.19)

$$Q_{P_{1,NS}} = C_v (B1 + B2) - \sqrt{C_v^{\ 2} (B1 + B2)^2 - 2C_v (C_{P_1} - C_{M_2})} \qquad \textbf{(3.40)}$$

Negative flow can be captured by the inequality

$C_{P_1} - C_{M_2} < 0$ Thus equation (3.40) should be used and otherwise equation (3.38). After obtaining discharge, equation (3.18) or (3.19) can be used in order to obtain the head value.

3.3.10 Series Junction

A series junction may be modeled for different situations as a roughness change in pipe or diameter change for a type of pipe or any combination of these situations. At the junction, equation (3.18) is available for the first pipe while equation (3.19) can be used for the second pipe. Continuity of flow and a common hydraulic grade line provides two equations for the series junctions.

$$Q_{P_{1,NS}} = Q_{P_{2,1}} \tag{3.41}$$

And

$$H_{P_{1,NS}} = H_{P_{2,1}} \tag{3.42}$$

By solving the above two equations simultaneously with equations (3.18) and (3.19),

$$Q_{P_{2,1}} = \frac{C_{P_1} - C_{M_2}}{B1 + B2} \tag{3.43}$$

3.3.11 Branch Connections

For a branching junction, continuity principle is applied for all the pipes connected at a common node. In addition to continuity, a common pressure head is assumed for all the pipes connected at the branch connection. All pipes can be divided into two types, namely incoming and outgoing pipes to and from the branch junction. Equation (3.18) is available for incoming pipes and equation (3.19) is available for the outgoing pipes.

After writing compatibility equations for the pipes, solution for the common head can be obtained in a simple equation,

$$H_P = H_{P_{1,NS}} = H_{P_{2,NS}} = H_{P_{3,1}} = H_{P_{4,1}} \tag{3.44}$$

$$Q_{P_{1,NS}} = -\frac{H_P}{B1} + \frac{C_{P_1}}{B1}$$

$$Q_{P_{2,NS}} = -\frac{H_P}{B2} + \frac{C_{P_2}}{B2}$$

$$-Q_{P_{1,NS}} = -\frac{H_P}{B3} + \frac{C_{M_3}}{B3}$$

$$-Q_{P_{1,NS}} = -\frac{H_P}{B4} + \frac{C_{M_4}}{B4}$$

and

$$H_P = \frac{C_{P_1}/B1 + C_{P_2}/B2 + C_{M_3}/B3 + C_{M_4}/B4}{\sum(1/B)} \tag{3.45}$$

Above equation can also be applied to any number of pipes including series connections.

3.3.12 Parallel Pipelines

Parallel pipelines and pipe networks consist of series connected pipes and branching connections so there is no need to define a new kind of boundary condition. Different combinations of branching connections can be used to model parallel pipelines and piping networks.

Beyond the above described boundary conditions, there are different situations that can be modeled as boundaries. These are transients caused by turbo machinery and some surge protecting devices. Before stating the procedures to handle these boundaries, it is better to state the details of friction in transients.

3.4 High Friction and Attenuation

In obtaining the equations of characteristics method, friction term was integrated with a first order approximation. If frictional effects are significant in a pipeline then first order integration of the friction term is not adequate. This situation is true for long oil pipelines, highly viscous flow in small diameter pipes and high velocity flows. First order integration of the friction term in these cases causes either wrong solutions or instability of the solution scheme. As long as the result is instable it is easy to capture by computational domain but incorrect results cannot be captured by the code itself. Changing the time step size thus changing the discretization can be a remedy for the situation. A second analysis can be performed with a smaller step size and results can be checked with the previous results. If the response of the system does not vary considerably then the results may be accepted. For the stable solution of the model, a stability criterion showing the necessary limits of discretization may be developed.

$$\frac{f\Delta t\overline{Q}}{4DA} \leq 1 \qquad \textbf{(3.46)}$$

In equation (3.46), $\overline{Q}$ is the average flow rate. As long as the friction is not very high, this criterion is satisfied.

For very high friction cases, accuracy may be improved and stability can be guaranteed by the use of a second order integration of the friction term.

Second order integration between points A-P and P-B along C^+ and C^- lines respectively, following equations can be obtained.

$$H_P - H_A + B(Q_P - Q_A) + \frac{R}{4}(Q_A + Q_P)|Q_A + Q_P| = 0 \quad \textbf{(3.47)}$$

$$H_P - H_B - B(Q_P - Q_B) - \frac{R}{4}(Q_B + Q_P)|Q_B + Q_P| = 0 \quad \textbf{(3.48)}$$

3.4.1 Procedure for 2nd order integration of compatibility equations

As it is stated in the beginning of the chapter, high friction should be considered with a careful attention. In order to have accurate results from the solution scheme, a second order integration of the compatibility equations is necessary. In equations (3.47) and (3.48), it is seen that each equation requires the information of the node being considered at the current time step which is priory an unknown. It is clear that an iterative procedure should be applied to obtain the head and discharge values of the considered node.

To handle the compatibility equations, Newton's method can be used. By subtracting equation ((3.48) from (3.49), a function of discharge can be obtained as the following

$$F = H_B - H_A + B(2Q_P - Q_A - Q_B) + \frac{R}{4}\left[(Q_A + Q_P)|Q_A + Q_P| + (Q_B + Q_P)|Q_B + Q_P|\right] = 0$$

Newton's method begins with an initial estimate for the discharge at each time step and a successive correction is applied until the defined function F is close to 0. Correction can be found from the following relation

$$F + \frac{dF}{dQ_P}\Delta Q = 0 \quad \textbf{(3.49)}$$

In equation (3.49), derivative of function F with respect to discharge is as follows

$$\frac{dF}{dQ_P} = 2B + \frac{R}{2}\left(|Q_A + Q_P| + |Q_B + Q_P|\right) \quad \textbf{(3.50)}$$

New value of discharge can be found with addition of correction term to the previous value of discharge. As the value of function F approaches to zero, value of correction gets smaller and smaller.

First estimate of discharge can be found for each time step by extrapolating previous two values. After obtaining the value of discharge, one of the equations, (3.47) or (3.48) can be used to find the head value.

3.4.2 Attenuation and Line Pack

After a flow stoppage, pressure head in the system increases an amount of ρAV_0. This pressure head increase is often called as *potential surge*. In a short pipeline or a line with very low friction, upstream of the flow is brought to rest as the wave travels in the line with the speed of sound. However in long and high friction pipelines, head drop due to friction may be much more than the potential surge thus flow is not brought to rest with the passage of compression waves. Value of the upsurge decreases and this reduction is called as *attenuation.* As the flow is partially stopped in the line and totally stopped on the valve for instance, volume stored in the pipe increases as the pipe walls expands. This situation is called line *packing*.

Procedure explained in the previous section of the chapter promotes a solution that can capture the effect of high friction and line packing.

3.5 Transients Caused by Turbo Machinery

In most of the transient situations, major reason is stoppage or start-up of a pump and associated opening and closing of valves. What pump failure actually means is the stoppage of a pump without having the opportunity to adjust valves equipped together with the pump. This may occur generally at emergency shut-down situations or power failure events. Also a wrong operation of the pumps may trigger a sequence of transient events.

Transients caused by pumps should be considered for different combinations of pumps as in series connection or parallel connection of pumps in a pumping farm. To be able to understand the hydrodynamics of pump failure, events after a pump failure should be described. After describing these events, different combinations of pump arrangements can me modeled with method of characteristics.

3.5.1 Events Following a Pump Failure Event

Main principle of a pump in pressurizing the fluid is that it transfers energy to the fluid flowing through the pump blades. It conveys energy to the fluid by the rotating impellers thus providing an increase of total dynamic head. Fluid gets the energy exerted by the rotor to the blades and fluid entering the suction flange leaves the pump with an increased pressure through the discharge flange.

Total head is basically the energy increase per unit weight of fluid.

$$H_T = \frac{V_d^{\ 2}}{2g} + \frac{P_d}{\gamma} + z_d - \left(\frac{V_s^{\ 2}}{2g} + \frac{P_s}{\gamma} + z_s \right) \qquad \textbf{(3.51)}$$

For a power failure scenario, reaction force of the fluid on the impellers of the pump causes the rotational speed reduce thus reducing the H_T. Reduction of H_T then causes the pressure waves to be transmitted upstream while the refraction waves are transmitted downstream through the pipes connected discharge and suction flanges respectively.

According to the topographical characteristics of the route through which the fluid is transferred, flow may reverse if the pump is operated against a higher elevation discharge route. As the flow reverses, by the time pump rotation reverses also causing the fluid runaway. If the pump reverse speed gets higher and higher then it causes a high pressure head at the pump which is an unwanted situation and should be considered during the design of a distribution line. A negative pressure situation may also occur at the discharge side of the pump according to the profile of the route. Negative pressure causes dissolved gases in the fluid, especially air, to come out of the solution accumulating in the highest elevation of the pipeline. This situation should also be prevented in order not to have a burst of the pipe or not to have excessively high pressures during the collapse of the vapor.

These sequences of events can also be modeled by the method of characteristics treating pumps as boundaries. Then C^+ and C^- equations will serve carrying the information of discharge and pressure between suction and discharge sides of the pump.

To be able to obtain the necessary boundary conditions for pump failure, turbo pump characteristics should be stated in detail.

3.5.2 Dimensionless Homologous Pump Characteristics

There are four main parameters in describing dimensionless homologous pump characteristics. These parameters are the total dynamic head, H, discharge, Q, torque, T, and the rotational speed of the pump N. two of these parameters are independent parameters and the other two are dependent. For given discharge and rotational speed values, torque and head values are obtained from the characteristics. Two assumptions are made for the analysis,

1. Steady state characteristics of the pumps also hold for the unsteady flow. Values of H and T are determined by the changing values of Q and N.
2. Homologous relationships are valid.

Homologous relations are described in the following text in terms of non-dimensional parameters defined for a pump.

For geometrically identical pumps, homologous equations may be presented by the following relations

$$\frac{H_1}{(N_1 D_1)^2} = \frac{H_2}{(N_2 D_2)} \quad \text{and} \quad \frac{Q_1}{N_1 D_1^{\ 3}} = \frac{Q_2}{N_2 D_2^{\ 3}} \qquad \textbf{(3.52)}$$

If the pumps are similar in geometrical parameters then different operating situations can be expressed with the following simplified forms.

$$\frac{H_1}{N_1^{\ 2}} = \frac{H_2}{N_2^{\ 2}} \quad \text{and} \quad \frac{Q_1}{N_1} = \frac{Q_2}{N_2} \qquad \textbf{(3.53)}$$

Assuming the efficiency is not changing with size,

$$\frac{T_1 N_1}{Q_1 H_1} = \frac{T_2 N_2}{Q_2 H_2} \tag{3.54}$$

Using equations (3.53) and (3.54), following relations can also be derived,

$$\frac{T_1}{N_1^{\,2}} = \frac{T_2}{N_2^{\,2}}, \ \frac{H_1}{Q_1^{\,2}} = \frac{H_2}{Q_2^{\,2}} \quad \text{and} \quad \frac{T_1}{Q_1^{\,2}} = \frac{T_2}{Q_2^{\,2}} \tag{3.55}$$

Dimensionless parameters can be used instead of the above dimensional parameters. All parameter related to pump characteristics can be made dimensionless by dividing all with their corresponding rated values.

$$h = \frac{H}{H_R}, \beta = \frac{T}{T_R} \ \upsilon = \frac{Q}{Q_R} \quad \text{and} \quad \alpha = \frac{N}{N_R} \tag{3.56}$$

After defining dimensionless parameters of the turbo-pump, homologous relations can be expressed by the following non-dimensional forms

$$\frac{h}{\alpha^2} vs \frac{\nu}{\alpha}, \qquad \frac{\beta}{\alpha^2} vs \frac{\nu}{\alpha}, \qquad \frac{h}{v^2} vs \frac{\alpha}{v}, \qquad \frac{\beta}{v^2} vs \frac{\alpha}{v} \tag{3.57}$$

When considered for computational purposes, parameters in above relations may cause problems during operations as they can change sign during time intervals. As they change sign they cross the x axis meaning that they get the value of zero thus causing a zero valued denominator. In order not to have this problem, some manipulations are done by Marchal, Flesh and Suter [1]. They used the following forms and overcame the possible difficulties

$$\frac{h}{\alpha^2 + v^2} .vs. \tan^{-1} \frac{v}{\alpha} \quad \text{and} \quad \frac{\beta}{\alpha^2 + v^2} .vs. \tan^{-1} \frac{v}{\alpha} \tag{3.58}$$

One can obtain plot of homologous relations in rectangular coordinates by plotting the angle $\Theta = x = \pi + \tan^{-1}(v/\alpha)$ against WH(x) or WB(x) where

$$WH(x) = \frac{h}{\alpha^2 + v^2} \qquad WB(x) = \frac{\beta}{\alpha^2 + v^2} \qquad x = \pi + \tan^{-1} \frac{v}{\alpha} \tag{3.59}$$

Following figures show the plots of homologous relations in both rectangular coordinates and polar diagram.

Turbine Zone	Dissipation Zone	Normal Zone	Reversed Speed Dissipation Zone
$\nu <= 0$ $\alpha < 0$	$\nu < 0$ $\alpha >= 0$	$\nu >= 0$ $\alpha >= 0$	$\nu > 0$ $\alpha < 0$

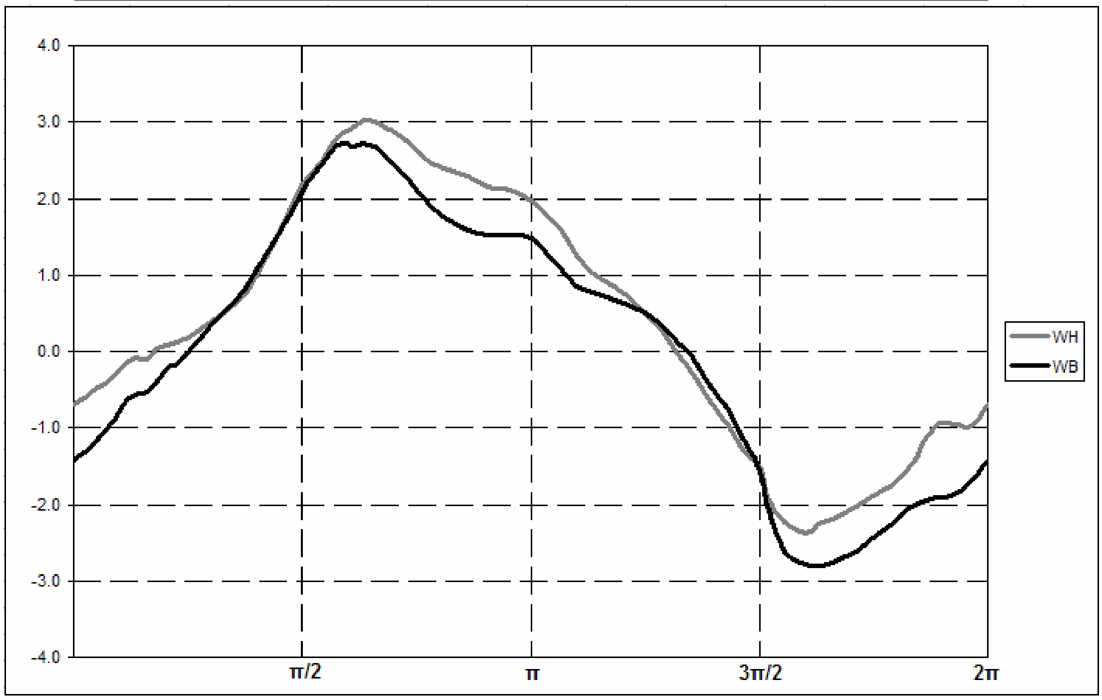


Figure 3.3 Complete Pump Characteristics [1]

Manufacturers of pumps and turbines generally supply information about the operating points of their products and with the provided data one can obtain WB and WH values. It is necessary to have enough number of points on the curves in order the plots to be well defined. For computational purposes, WB and WH data should be stored tabulated with equal increments, Δx. using an increment $\Delta x = \pi/44$ showed that it provides reasonable amount of data count 89. [1]

For many cases, complete pump data is rarely available so the designer should complete the values of WB and WH values from test data.

3.5.3 Head Balance Equation

Pump failure cases are modeled based on two equations and simultaneous solution of these two equations. These two equations are the head balance equation through the pump and torque-angular deceleration of the rotating means of the pump.

Head balance relationship can be written for a pump and valve arrangement by using the schematic representation given below.

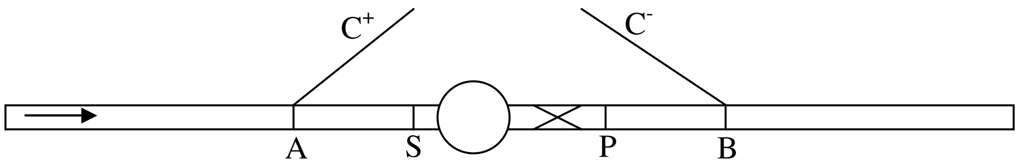


Figure 3.4 Schematic Representation of a Pump Boundary Condition

Writing the balance equation considering valve losses and pump head,

$$H_S + H_T - (valve\_head\_loss) = H_P \qquad \textbf{(3.60)}$$

In equation (3.60), H_S is the piezometric head at the suction flange of the pump which is indeed the last node of the suction pipe. C^+ equation can be written for the last reach of the suction pipe,

$$HSP(NS1) = HS(NS) - BS[QSP(NS1) - QS(NS)] - RS.QS(NS)|QS(NS)| \text{ or}$$

$$HSP(NS1) = HCP - BS.QSP(NS1) \qquad \textbf{(3.61)}$$

C^- Equation can then be written for the first node of the discharge pipe,

$$HP(1) = H(2) + B[QP(1) - Q(2)] + RQ(2)|Q(2)| \text{ or}$$

$$HP(1) = HCM + B.QP(1) \qquad \textbf{(3.62)}$$

By referring to dimensionless homologous relations, head balance equation can be expressed as follows,

$$tdh = H_R(\alpha^2 + v^2)WH(\pi + \tan^{-1}\frac{v}{\alpha}) \qquad \textbf{(3.63)}$$

As it is stated in previous sections of this chapter WH is a tabular data representing full characteristics of the pump. For a continuous data of WH and WB, each interval of data may be assumed as linear line segments. Then it is possible to obtain the proper value of WH, WB and x among the tabulated data.

Approximate location of x can be obtained extrapolating the previous values of ν and α. A line segment can be defined between two adjoining points by referring to the following figure

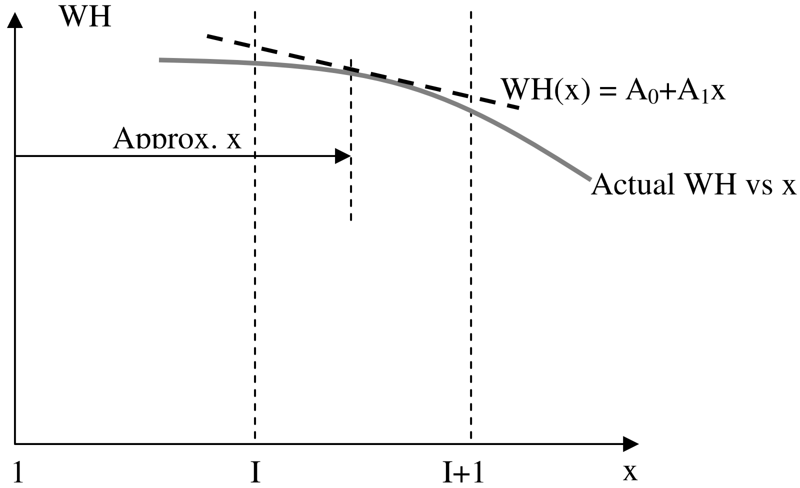


Figure 3.5 Linearization of Complete Pump Characteristics

WH versus x curve can be replaced by a line segment that represents the pump head characteristics at the vicinity of x. As it was stated in earlier sections, location of x can be approximated by extrapolating the previous α and ν values. An integer is defined locating the data point on the left, i.e. overestimates the location. Then Cartesian coordinates of the data point come out to be

(I-1)Δx, WH(I) and IΔx, WH(I+1)

Substituting the above points into WH(x) = A_0+A_1x, coefficients can be found to be,

$$A_1 = \left[WH(I+1) - WH(I)\right] / \Delta x$$

$$A_0 = WH(I+1) - I \cdot A_1 \Delta x \tag{3.64}$$

Then total dynamic head equation can be rewritten as the following,

$$tdh = H_R(\alpha^2 + v^2)\left[A_0 + A_1(\pi + \tan^{-1}\frac{v}{\alpha}\right] \tag{3.65}$$

In equation (3.60), valve head loss was included. This term can be expressed as

$$valve\_head\_loss = \frac{\Delta H v|v|}{\tau^2} \tag{3.66}$$

In equation (3.66) ΔH is the head loss across the valve orifice during rated flow rate condition. τ in the equation is the non-dimensional valve opening generally given in tabular form with respect to time variable.

All obtained equations for valve head loss and WH curve now can be substituted into the general form of total dynamic head equation,

$$HCP - BS \cdot QP(1) + H_R(\alpha^2 + v^2)\left[A_0 + A_1(\pi + \tan^{-1}\frac{v}{\alpha})\right] - \frac{\Delta H v|v|}{\tau^2} = HCM + B \cdot QP(1)$$

By defining,

HPM = HCP – HCM, QP (1) = νQ_R BSQ = (BS + B)Q_R

The equation is simplified as;

$$F1 = HPM - BSQ \cdot v + H_R(\alpha^2 + v^2)\left[A_0 + A_1(\pi + \tan^{-1}\frac{v}{\alpha})\right] - \frac{\Delta H v|v|}{\tau^2} = 0 \tag{3.67}$$

F1 is the head balance equation in terms of α and ν. Speed change equation will be obtained and solved simultaneously with the above obtained head balance equation.

3.5.4 Calculation of Speed Change

Speed change of the pump during the unsteady operation conditions will be derived in this section. Change of the rotational speed of the pump is mainly governed by the torque applied by the rotating parts. Unbalanced torque applied on the pump can be expressed as

$$T = -\frac{WR_g^{\;2}}{g}\frac{d\omega}{dt} \qquad \textbf{(3.68)}$$

In equation (3.68), W is the weight of rotating parts in the pump and entrained fluid while R_g is the radius of gyration of the rotating masses.

The unbalanced torque can be assumed to be the average of the torque at the beginning of time step and torque at the end of the time step which is an unknown priory.

Having

$$\beta = N_R \frac{2\pi}{60}\alpha \qquad \beta_0 = \frac{T_0}{T_R} \qquad \beta = \frac{T_P}{T_R} \qquad \textbf{(3.69)}$$

Equation (3.68) can be rewritten as;

$$\beta = \frac{WR_g^{\;2}}{g}\frac{N_R}{T_R}\frac{\pi}{15}\frac{(\alpha_0 - \alpha)}{\Delta t} - \beta_0 \qquad \textbf{(3.70)}$$

In equation (3.70), α_0 is dimensionless rotational speed at the beginning of the time step. Defining the variable C_{31},

$$C_{31} = \frac{WR_g^{\;2}}{g}\frac{N_R}{T_R}\frac{\pi}{15\Delta t} \qquad \textbf{(3.71)}$$

Now substituting (3.71) into equation (3.70),

$$\beta + \beta_0 - C_{31}(\alpha_0 - \alpha) = 0 \qquad \textbf{(3.72)}$$

Characteristic torque curve can also be treated as the characteristic head curve,

$$\frac{\beta}{\alpha^2 + v^2} = WB(x) = B_0 + B_1(\pi + \tan^{-1}\frac{v}{\alpha}) \qquad \textbf{(3.73)}$$

B_0 and B_1 in equation (3.73) can also be found same as A_0 and A_1. Combination of equations (3.72) and (3.73) leads to the following form,

$$F2 = (\alpha^2 + v^2)\left[B_0 + B_1(\pi + \tan^{-1}\frac{v}{\alpha})\right] + \beta_0 - C_{31}(\alpha_0 - \alpha) = 0 \qquad \textbf{(3.74)}$$

Equation (3.74) is the speed change equation.

Sometimes a check valve may be utilized at the discharge of the pump. By assuming head loss to be constant for positive flow through pump or obtaining the head loss as a function of discharge from pump tests, a criterion can be derived that assures a positive flow through the pump and the check valve equipped with it. Setting v = 0 in head balance equation,

$$F3 = HCP - HCM + H_R \alpha^2 WH(\frac{\pi}{\Delta x}) \tag{3.75}$$

If above equation is greater then zero, positive flow is guaranteed and otherwise v becomes zero by the check valve.

3.5.5 Single Pump Boundary Condition

In this section of the chapter, single pump boundary condition is obtained by solving the derived equations in the previous section. Using Newton-Raphson method, equations (3.67) and (3.74) can be solved simultaneously giving,

$$\begin{aligned} &F1 + F1_v \Delta v + F1_\alpha \Delta \alpha = 0 \\ &F2 + F2_v \Delta v + F2_\alpha \Delta \alpha = 0 \end{aligned} \tag{3.76}$$

First estimation of dimensionless speed and discharge can be obtained by extrapolating the previous two values,

$$\begin{aligned} &v = 2v_0 - v_{00} \\ &\alpha = 2\alpha_0 - \alpha_{00} \end{aligned} \tag{3.77}$$

The derivatives in equation (3.76) are evaluated as the following,

$$F1_v = -BSQ + H_R \left\{ 2v\left[A_0 + A_1(\pi + \tan^{-1}\frac{v}{\alpha}\right] + A_1\alpha \right\} - \frac{2\Delta H|v|}{\tau^2} \tag{3.78}$$

$$F1_\alpha = H_R \left\{ 2\alpha\left[A_0 + A_1\left(\pi + \tan^{-1}\frac{v}{\alpha} \right) \right] - vA_1 \right\} \tag{3.79}$$

$$F2_v = 2v\left[B_0 + B_1\left(\pi + \tan^{-1}\frac{v}{\alpha} \right) \right] + \alpha B \tag{3.80}$$

$$F2_\alpha = 2\alpha\left[B_0 + B_1\left(\pi + \tan^{-1}\frac{v}{\alpha} \right) \right] - vB_1 + C_{31} \tag{3.81}$$

By the partial derivatives of F1 and F2 defined above, equations (3.76) can be solved for the increments of dimensionless and speed and discharge,

$$\Delta\alpha = \frac{F2 / F2_v - F1 / F1_v}{F1_\alpha / F1_v - F2_\alpha / F2_v} \qquad \textbf{(3.82)}$$

$$\Delta v = \frac{F1}{F1_v} - \Delta\alpha \frac{F1_\alpha}{F1_v} \qquad \textbf{(3.83)}$$

And obtained correction values of discharge and speed can be used to improve the first estimated values of these variables. This is an iterative procedure until a predefined tolerance value is met,

$$|\Delta v| + |\Delta\alpha| < TOL$$

In which TOL is generally around 0.0002.

After solving the above equations and obtaining the values of dimensionless speed and discharge, values of constants A's and B's should be checked if they led to the correct segment of WH and WB curves. In order to check the validity, an integer expression II can be defined,

$$II = \left(\pi + \tan^{-1}\frac{v}{\alpha}\right) / \Delta x + 1 \qquad \textbf{(3.84)}$$

If II is equal to the predefined integer, I, and then it can be said that the correct segment of the curves is used, otherwise "I" should be set to the value of "II" and solution should be repeated. After 3 or 4 trials, the user should be prompted that the solution with the given data cannot be achieved.

3.5.6 Series Pump Boundary Condition

Pumps in series arrangement can be considered mainly in two groups. Pumps connected with a pipe of length less then aΔt can be considered a single pump of a total head of each separate pump. On the other hand, if the length of the pipe between pumps is more then aΔt then each pump should be considered as separate boundary conditions. This situation can be handled by the procedure explained in the single pump failure section. For the former situation, governing equations can be derived as the following,

Continuity equation:

$$QP_d(1) = QP_s(NS1) = v_1 Q_{R1} = v_2 Q_{R2} = \ldots = v_N Q_{RN} \qquad \textbf{(3.85)}$$

Speeds of the pumps are independent of each other. They can fail independently at different times.

Head balance equation for the system can be expressed as

$$HPM - BSQv + \sum h_p - \sum \frac{\Delta H v|v|}{\tau^2} = 0 \qquad \textbf{(3.86)}$$

From now on, equations written for dingle pump boundary condition can be applied to each pump in the series arrangement. Obtained equations can be solved by building a matrix of coefficients and following set can be obtained,

$$-\begin{bmatrix} F1_v & F1_{\alpha 1} & \dots & F1_{\alpha N} \\ F2_v & F2_{\alpha 1} & \dots & F2_{\alpha N} \\ \dots & \dots & \dots & \dots \\ FN1_v & FN1_{\alpha 1} & \dots & FN1_{\alpha N} \end{bmatrix} \begin{bmatrix} \Delta v \\ \Delta \alpha_1 \\ \dots \\ \Delta \alpha_N \end{bmatrix} = \begin{bmatrix} -F1 \\ -F2 \\ \dots \\ -FN1 \end{bmatrix} \qquad \textbf{(3.87)}$$

As stated before, unknown values can be obtained by the iterative correction of discharge and speed values,

$$v = v + \Delta v$$

$$\alpha_1 = \alpha_1 + \Delta \alpha_1$$

$$\dots$$

$$\alpha_N = \alpha_N + \Delta \alpha_N$$

It can be seen that, with N=1, above equations reduce to the equations of single pump failure equations.

3.5.7 Parallel Pump Boundary Condition

Boundary condition for parallel pumps has a very similar solution procedure with that of series pumps boundary conditions. A head balance equation should be derived for the parallel branches and each individual pump should have the torque equation of itself. To represent the general solution scheme for parallel pumps, 2 pumps can be considered.

Governing equations of parallel pumps would be,

$$F1 = H_{PA} + tdh_1 - \frac{\Delta H_1 v_1 |v_1|}{\tau_1^{\ 2}} - H_{PB} = 0$$

$$F2 = H_{PA} + tdh_2 - \frac{\Delta H_2 v_2 |v_2|}{\tau_2^{\ 2}} - H_{PB} = 0$$

$$F3 = \left(\alpha_1^{\ 2} + v_1^{\ 2}\right)\left[B_{01} + B_{11}(\pi + \tan^{-1}\frac{v_1}{\alpha_1}\right] + \beta_{01} - C_{311}(\alpha_{01} - \alpha_1) = 0$$

$$F4 = \left(\alpha_2^{\ 2} + v_2^{\ 2}\right)\left[B_{02} + B_{12}(\pi + \tan^{-1}\frac{v_2}{\alpha_2}\right] + \beta_{02} - C_{312}(\alpha_{02} - \alpha_2) = 0 \qquad \textbf{(3.88)}$$

And continuity takes the following form,

$$Q_{PA} = Q_{PB} = v_1 Q_{R1} + v_2 Q_{R2} \qquad \textbf{(3.89)}$$

It should be noted that, if valve of any pump closes completely i.e. τ, percent opening of valve, goes to zero, then that parallel branch should be removed from the solution matrix.

$$\begin{bmatrix} F1_v & F1_{\alpha 1} & \dots & F1_{\alpha N} \\ F2_v & F2_{\alpha 1} & \dots & F2_{\alpha N} \\ \dots & \dots & \dots & \dots \\ FN1_v & FN1_{\alpha 1} & \dots & FN1_{\alpha N} \end{bmatrix} \begin{bmatrix} \Delta v \\ \Delta \alpha_1 \\ \dots \\ \Delta \alpha_N \end{bmatrix} = \begin{bmatrix} -F1 \\ -F2 \\ \dots \\ -FN1 \end{bmatrix} \qquad \textbf{(3.90)}$$

As it is applied for the series pumps, above equations together with compatibility equations form a set of equations in v_1, v_2, α_1 and α_2.

3.5.8 Pump Boundary with no Failure

Unless the failure of a pump causes the transients, pumps continue with its steady state operating speeds. On the other hand dimensionless discharge v changes with the effect of a valve closing and or another pumps' failure.

3.6 Surge Protecting Devices

Possible transient scenarios and related boundary conditions are described in the previous sections of this chapter. During a pipeline design, all possible scenarios should be simulated and final design should be modified according to the results of these transients. For many times required modifications of the pipeline design with respect to transient events are uneconomical or unreasonable. For these cases, transient may be prevented by the use of auxiliary pipeline components designed for surge protection. These devices basically operate as dampers for a specified range of pressure wave frequencies and limiters for high and low pressures. Together with these devices, some other measures may be taken in operational manner for the safety of the pipeline.

Surge protection devices can be modeled and simulated by Method of Characteristics. As for other pipeline components, discharge and the pressure head are the parameters to be solved in surge tank boundary conditions.

Surge protecting devices work with the principle of supplying the necessary amount of liquid to the system in order to compensate for the negative pressures and store and /or remove liquid in order to prevent excess pressures.

3.6.1 Surge Tanks

Surge tanks are simply open top reservoirs connected to piping systems. They may have different sizes, different shapes and open tops. They also may have different connection types that restrict inflow and outflow.

An *orifice* surge tank, as the name implies, has a restriction between the main line and the tank. These types of surge tanks generally have lower discharge coefficients for inflow then that of outflow.

A *differential* surge tank is two surge tanks in arrangement one being a simple surge tank and the other an orifice surge tank.

It should be noted that surge tanks except for the one way type surge tanks, should extend up to the HGL. A *one way* surge tank does not need to extend up to HGL and are generally used for column separation prevention.

Schematic representations of different surge tanks are represented below,

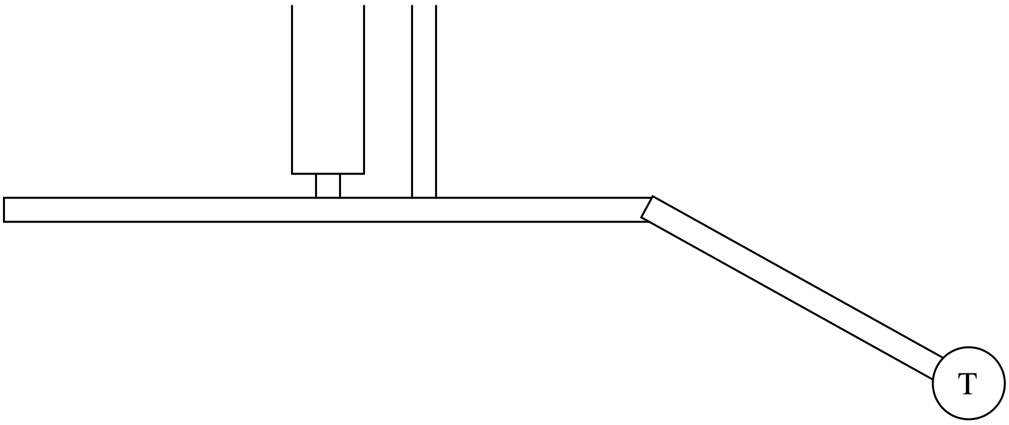


Figure 3.6 Differential Surge Tank

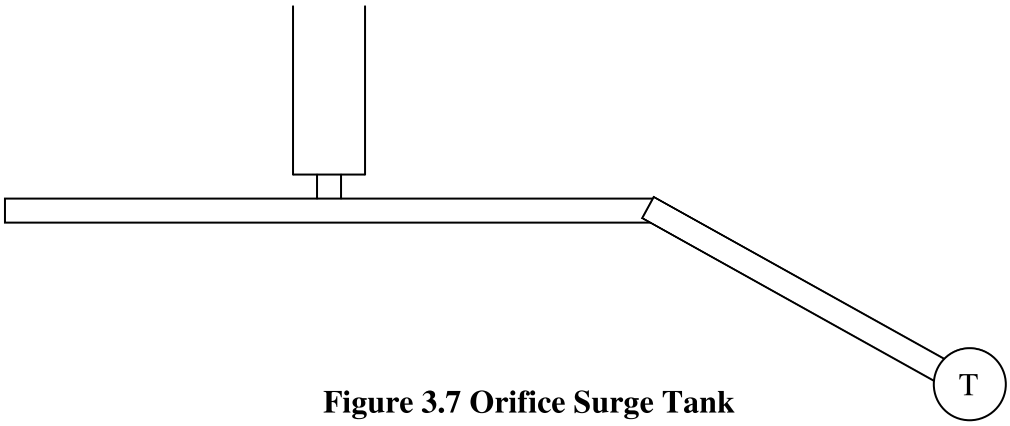


Figure 3.7 Orifice Surge Tank

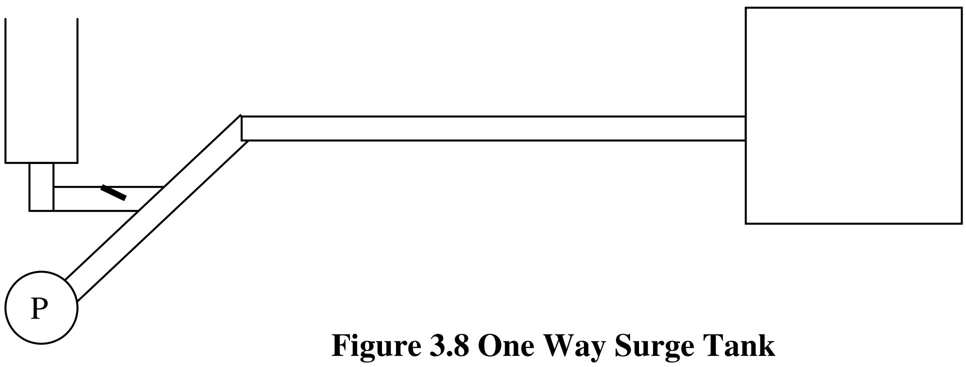


Figure 3.8 One Way Surge Tank

Mathematical modeling of a simple surge tank using "Method of Characteristics" is outlined and governing equations are derived in the following text. First of all surge tank should be represented schematically,

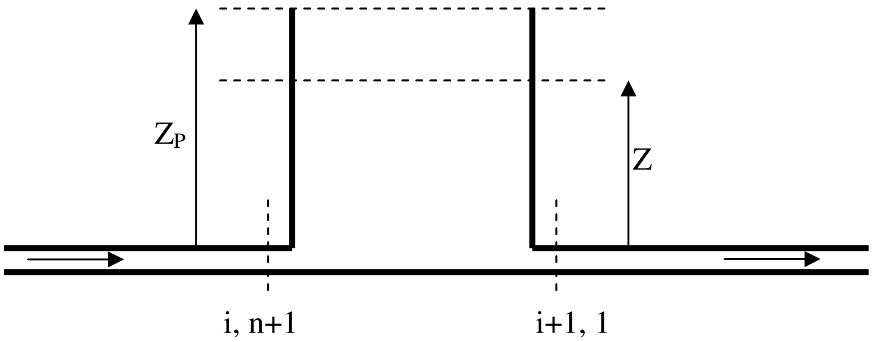


Figure 3.9 Surge Tank as an Interior Boundary

Characteristics equations for the above schematic figure now can be written the way they are defined in the previous sections of the chapter.
C^+ equation for the last node of pipe i,

$$H_{P_i} = C_P - BQ_{P_i} \qquad \textbf{(3.91)}$$

C^- equation for the first node of the pipe i+1,

$$H_{P_i} = C_M + BQ_{P_i} \qquad \textbf{(3.92)}$$

Writing continuity equation for the intersection point of two pipes and the surge tank,

$$Q_{P_{i,n+1}} = Q_{P_{1+1,1}} + Q_{P_{SurgeTank}} \qquad \textbf{(3.93)}$$

Where $Q_{Psurgetank}$ is the flow rate into or out from the surge tank.
When losses in the inlet of the surge tank are neglected, then the head balance can be written as the following,

$$H_{P_{i,n+1}} = H_{P_{i+1,1}} = z_P \quad \textbf{(3.94)}$$

Z and Z_P are the height of liquid column in the surge tank at the beginning and at the end of the time step respectively. If the time step size, Δt, is chosen small enough then liquid surface elevation at the end of the time step can be written as the following,

$$Z_P = Z + \frac{1}{2}\frac{\Delta t}{A_S}(Q_{PS} + Q_S) \quad \textbf{(3.95)}$$

Q_{PS} and Q_S are the flow rate values at the end and at the beginning of the time step. A_s is the cross sectional area of the surge tank.

Solving equations (3.91) to (3.95), Head and discharge values can be obtained at the pipe-surge tank junction. It should be noted that the standpipe between the tank and the main line assumed to be very short and therefore neglected. [2]

3.6.2 Air Vessels

Air vessels are chambers that have air and liquid inside. They are also used for surge protection. They also have orifices located at the inlet in order to restrict inflow and outflow. Orifice used in the chamber should be such that it allows outflow much more freely then it lets inflow thus it can prevent low pressures and it does not require very large volumes.

Air vessels are used generally just after the pumps to prevent negative surge pressures due to a possible power failure in the pump or pump station. [2]

Characteristic equations for an air vessel can be outlined as follows,

C^+ equation for the last node of pipe i,

$$H_{P_i} = C_P - BQ_{P_i} \quad \textbf{(3.96)}$$

C^- Equation for the first node of the pipe i+1,

$$H_{P_i} = C_M + BQ_{P_i} \quad \textbf{(3.97)}$$

Writing continuity equation for the intersection point of two pipes and the air vessel,

$$Q_{P_{i,n+1}} = Q_{P_{1+1,1}} + Q_{P_{AirVessel}} \qquad \textbf{(3.98)}$$

Where $Q_{Pairvessel}$ is the flow rate into or out from the air vessel.

When losses at the junction are neglected, then the head balance can be written as the following,

$$H_{P_{i,n+1}} = H_{P_{i+1,1}} = z_P \qquad \textbf{(3.99)}$$

If the enclosed air is assumed to obey the polytropic relation, then following relation is valid,

$$H^*_{Pair} \forall^m_{Pair} = C \qquad \textbf{(3.100)}$$

In above equation, H^*_{Pair} and V^*_{Pair} are the absolute head and volume of the enclosed air at the end of the current time step. C is constant and can be obtained by using steady state values of H and V.

By using equations from (3.51) to (3.55), values of discharge and head at the junction between air vessel and main pipeline can be obtained. During calculations, head loss through the orifice may be obtained by the following relation,

$$h_{Porf} = C_{orf} Q_{Porf} \left| Q_{Porf} \right| \qquad \textbf{(3.101)}$$

There are different procedures for sizing surge tanks and air vessels. Some of these procedures are numeric while some others are algebraic and graphical. Parmakian [4] outlines a complete procedure of sizing air vessels and surge tanks by graphical means according to the type of orifice used at the inlet.

CHAPTER 4

COMPUTER PROGRAMME

4.1 Computer Code

4.1.1 General

In this thesis, a computer program is developed to design a steady state pipeline system and simulate the system with different transient scenarios. Computer program is developed by Visual Studio .Net 2005 which enables creating visual user interfaces with powerful graphic libraries. Computer code is developed in different layers which are responsible for different duties of the program such as computation, import and export events, data handling and databases, graphical and visual objects and compatibility with the operating system. Capabilities and working principles of the computer program is presented in the chapter and sample cases are studied by using different components defined in the program.

In the program, a set of different pipeline components are present and can be used to design different configurations. These components are modeled based on the theory of transient flow in pipeline systems and a special case of transient flow, steady state flow, can also be simulated. Among the components, some are modeled as individual elements while some other are treated as lumped elements of different number of same individual components. Pump stations with parallel and series connected pumps are of lumped components group.

Main component of the computer program is a single pipe, properties of which can be input by the user or a range of standard pipes and properties are provided by a pipe database.

Components simulating boundary conditions can be divided into three main groups according to their generic locations in the system. First boundary element group is the upstream boundaries. Another boundary element type is the interior boundary type which is always bracketed by two pipes at both upstream and downstream. Finally a downstream boundary element group can be defined, members of which all have an upstream pipe connected to them. Detailed properties and working principles of each individual component are stated below.

- **PIPE**

  Pipe component modeled in the program is the main component of the system. Each and every single pipeline component in the system should be connected to each other with the help of a single pipe or a set of series connected pipes. Connection properties of a single pipe are as follows,

  After and before each interior boundary element, a pipe should be connected. Pipe object defined in the program has 2 connection nodes one at the upstream and the other at the downstream of the pipe. To form a set of series connected pipes, between each pipe, a *series connection* boundary element, a member of interior boundary elements group, should be connected. On the other hand, in order to form parallel connections of pipes with different numbers, interior boundary elements called *YConnector* and *YDivider* should be used. Properties of these interior boundary elements are stated in the below text.

  Pipe object is simply responsible for calculating the values at the interior nodes of the pipes. The downstream and upstream boundary nodes of a pipe are not calculated in the Pipe boundary element object. Upstream and downstream values of pipes are calculated at the interior, downstream or upstream boundary element objects connected to the pipes.

  Size and hydraulic properties of a pipe object can be input by the user and also a pipe database is provided in the program which enables to select standard pipes and materials from a range of commercial products.

  One limitation on a pipe object is its length that each and every pipe object in the system should have the same length because of computational concerns. For pipes with different length in the system, combination of different pipe objects should be used. This limitation is due to the computational method applied in the software. Use of pipe segments with same length overcomes the difficulty of creating complex solution matrices. Following figure is the representation of a pipe object in the program.

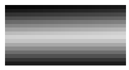


Figure 4.1 Representation of a Pipe

- **UPSTREAM CONSTANT HEAD**

Upstream constant head reservoir is one of the three upstream reservoirs defined in the program. Upstream constant head reservoir is simply a reservoir that continuously imposes a predefined constant head value to the very upstream of the system. This boundary element has just a single connection at the downstream which should be connected to a pipe. Head and discharge value of the upstream boundary node of the connected pipe is determined by this boundary condition element. Elevation of the reservoir and height of the liquid column in the reservoir is input by the user. Examples of this boundary element can be large reservoirs with very wide base cross sections and unchanging liquid height like lakes and large storage tanks continuously filled. Following figure is the representation of an upstream constant head reservoir object in the program.

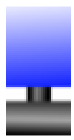


Figure 4.2 Representation of an Upstream Constant Head Reservoir

- **UPSTREAM VARIABLE HEAD**

Upstream variable head reservoir is one of the three upstream reservoirs defined in the program. Upstream variable head reservoir is simply a reservoir that continuously imposes a predefined variable head value to the very upstream of the system. Head variation of the reservoir can be approximated with a sinusoidal function of time, amplitude and frequency. A tabulated data can be also provided to the program which describes the head value of the upstream with respect to time. As in the case of all upstream boundary elements, this boundary element also has just a single connection at the downstream which should be connected to a pipe. Elevation of the reservoir, mean height of the liquid column in the reservoir and frequency of the variable head function are input by the user. Examples of this boundary element can be reservoirs with changing liquid heights like wavy lakes or large storage tanks being emptied. Following figure is the representation of an upstream variable head reservoir object in the program.

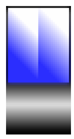


Figure 4.3 Representation of an Upstream Variable Head Reservoir

- **UPSTREAM SPECIFIED DISCHARGE**

Upstream specified discharge boundary element object is the last upstream object defined in the computer program. This boundary element simply simulates positive displacement pumps and reciprocating hydraulic elements. As in the all upstream elements, this boundary element also calculates the upstream boundary node of the connected pipe. In contrast with the previous two boundary elements, this upstream boundary element object imposes a discharge value to the upstream of the system rather then imposing a head value. Upstream specified discharge boundary object has also a single connection node which enables connection of a pipe only. Discharge characteristics of this boundary element are input by the user through the data grid in the user interface. Discharge of the upstream element is modeled by a function of time, frequency and amplitude. Following figure is the representation of an upstream specified discharge object in the program.

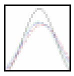


Figure 4.4 Representation of an Upstream Specified Discharge

- **SERIES JUNCTION**

Despite not imposing any additional boundary value to the system, series junction calculates the adjacent nodes of two series connected pipes and is necessary to carry the required information between series pipes. This virtual boundary element has two connection nodes at upstream and downstream. All pipes, in case of not having any other interior boundaries, should be connected to each other by series connection boundary element. Following figure is the representation of an upstream specified discharge object in the program.

Figure 4.5 Representation of a Series Junction

- **AIR VESSEL**

Air Vessel boundary element is another interior boundary element in the program. It has two connection nodes at upstream and downstream which are to be connected by pipes only. Air Vessel is a boundary element which acts as a damping element for excess and low transient pressure by supplying and accepting liquid flow into the pipeline system and into the vessel. Air vessel boundary element has 4 different parameters that define the vessel characteristics. First parameter is the initial air volume present in the vessel which is continuously calculated through transients. Air vessel cross sectional area and air vessel height are geometric properties of the vessel which are design parameters for the vessel. Orifice constant is another parameter related to air vessel which should also be provided by the user. Orifice constant can be adaptive meaning different orifice constants for inflow and outflow. In the program, both inflow and outflow discharge constants of orifice are assumed to be equal, implying a symmetric orifice geometry. Air vessel boundary element should be located at the highest elevation points of the system as long as it is possible. For low transient pressures, effect of air vessel may not be observed while for high pressure values air vessel can be considered a quite effective precaution.

In air vessel design, initial pressure head at the vessel connection and initial air volume in the vessel is considered in order to obtain the isothermal constant. Air is assumed to obey isothermal gas law and PV is constant all the time.

Following figure is the representation of an upstream specified discharge object in the program.

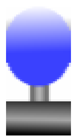


Figure 4.6 Representation of an Air Vessel

- **SINGLE PUMP**

In single pump boundary element, a single pump with known full pump characteristics is modeled. During the launch of the program, generic torque and Head characteristics data is loaded and can be modified by the user. Program allows both user input and data import for the pump characteristics. In order to simulate a non-tripping pump, time of failure of the pump is initially 10000 seconds. For longer simulation times, in order to be able to simulate the non-tripping pump, time of failure should be set to a larger value then the total simulation time. Rated discharge and rated Head values of the pump are also be provided by the user and these data should be compatible with the complete pump characteristics data. Properties of rotating parts in the pump should also be input by the user and these data can be obtained from manufacturer's catalogues. Generic values are also initially provided by the program and user can modify these parameters. All pumps are also equipped with valves, closure characteristics of which can be approximated by a function or input by the user in a tabulated form. Total time for valve 100% closure is input by user and program does not allow closing of the valve as long as the pump is not tripping. Valve closure is initiated following a pump trip or shut down. If the valve is to be open throughout the transients in case of a pump trip, tabulated data of percent valve closure should be input 100 for all the time values or if the valve closure is modeled by the function of time, total closing time for valve should be set to values larger then 10000.

Single pump boundary element uses full pump characteristics data which are obtained by experimentation of pumps and corresponding rotational speed, rated head, rated torque, rated discharge and radius of gyration values. In cases where these parameters are not compatible with each other, pump boundary condition element does not converge to a reliable solution. In order to have reliable solutions by this boundary element, smaller time increment values are recommended.

Time step size of 0.1 seconds is observed to give reliable results by testing with smaller step sizes of 0.05 seconds and 0.025 seconds. Effect of time step size is due to the necessity of an initial estimate of pump head and discharge at the beginning of each time step. Initial estimates of these values are obtained by extrapolating the previous two time step values. Mesh size and number also play an important role in both stability of the whole domain and pump boundary condition.

Pump boundary element has also two connection nodes that connect the element to the downstream (discharge) and upstream (suction) pipes of the pump. In the program, a single pump is directly connected to the pipe without any intermediate components. Intermediate piping between pump and valve is not modeled in the system but taken into account by the pump boundary element object itself. Following figure is the representation of a single pump in the program.

Figure 4.7 Representation of a Single Pump

- **PUMP STATION WITH SERIES IDENTICAL PUMPS**

In addition to single pump boundary condition, there are pump station boundary elements in the program. These boundary element objects have two connection nodes one for suction and one for discharge side. Pump stations with series identical pumps utilize any number of series pumps with using identical pumps and pump characteristics. Working principle of this boundary condition is basically applying a total head of specified number of single pumps while the discharge remains equal to that of a single unit. This boundary condition element also provides initial generic pump full characteristics data as in a single pump.

Failure of the station is simulated with the failure of all pumps in the station simultaneously. Following figure is the representation of a pump station with series identical pumps in the program.

- **PUMP STATION WITH PARALLEL IDENTICAL PUMPS**

Pump station with parallel identical pumps boundary element objects have two connection nodes one for suction and one for discharge side. Pump stations with parallel identical pumps utilize any number of parallel pumps with using identical pumps and pump characteristics. Working principle of this boundary condition is basically applying a total discharge of specified number of single pumps while the head remains equal to that of a single unit. This boundary condition element also provides initial generic pump full characteristics data as in a single pump.
Failure of the station is simulated with the failure of all pumps in the station simultaneously. Following figure is the representation of a pump station with parallel identical pumps in the program.

Figure 4.8 Representation of a Pump Station with Identical Parallel Pumps and Identical Series Pumps

- **Y-JUNCTION (DIVIDER and CONNECTER)**

In the computer program, parallel lines of different pipes can be simulated with the help of two boundary elements, one Y-junction divider and other Y-junction connecter. Y-junction divider has two connection nodes one being at the upstream and the other at the downstream. Upstream connection node of the junction object allows single pipe connection while downstream node allows two pipes to be connected. 3 or more parallel routes can be formed using multiple y-connecter and y-divider objects connected to each other with pipes. These boundary element objects do not impose any additional hydraulic boundary condition to the system but are responsible for the steady state flow rate division and transient pressure wave distribution. Following figure is the representation of Y-Junctions in the program.

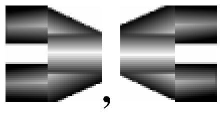


Figure 4.9 Representations of Y-Junctions, Connecter and Divider

- **VALVE IN LINE**

In computer program, flow restriction devices located at the interior points of the pipeline system are simulated by Valve in Line boundary condition object. Valve in Line boundary condition object has two connection nodes allowing single pipe connection to each node, at upstream and downstream. Valve in Line object acts as a valve or orifice with known discharge characteristics and closure characteristics of the valve can be input by the user either with a function of time or with a tabulated data of percent opening versus time. When the percent opening value of zero is reached, valve does not allow flow through and equals the discharge value of the boundary to zero. In the program, initially all valves are fully open and has no steady state head losses. Default equation defined for the percent opening versus time characteristics of the valve is

$\tau = \left(1 - \frac{t}{t_c}\right)^{E_M}$. In the equation, t is the current time value; t_c is the total closing time of the valve, and E_m is valve time constant. Following figure is the representation of an inline valve in the program.

- **DOWNSTREAM CONSTANT HEAD RESERVOIR**

In the program, one of the three downstream boundary elements is downstream constant head reservoir. Downstream boundary elements all have a single node allowing a single pipe connection at the upstream. Downstream constant head reservoir imposes a constant head at the very end of a single route throughout the transients. This boundary condition element is very similar to upstream constant head reservoir. Downstream constant head reservoir has a singe property to be defined by the user, the height of the liquid column in the reservoir. The boundary element has a default 150 meters of liquid column height.

The liquid height in the reservoir may be obtained by a idle run for steady state calculation. After obtaining the steady state head at the downstream end, one can set this value to the liquid height value. Bottom elevation of the reservoir is automatically calculated from the previous pipe properties.

Downstream constant head reservoir also has the same representation with that of upstream constant head reservoir. Following figure is the representation of a downstream constant head reservoir.

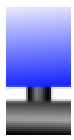


Figure 4.10 Representation of a Downstream Constant Head Reservoir

- **DOWNSTREAM VALVE**

In computer program, flow restriction devices located at the downstream of pipes are simulated by Downstream Valve boundary condition object. Downstream valve boundary condition object has one connection node allowing single pipe connection to its upstream. Downstream valve object acts as a valve or orifice with known discharge characteristics and closure characteristics of the valve can be input by the user either with a function of time or with a tabulated data of percent opening versus time. When the percent opening value of zero is reached, valve does not allow flow through and equals the discharge value of the boundary to zero. In the program, initially all valves are fully open and has no steady state head losses. Default equation defined for the percent opening versus time characteristics of the valve is

$\tau = \left(1 - \frac{t}{t_c}\right)^{E_M}$. In the equation, t is the current time value, t_c is the total closing time of the valve, and E_m is valve time constant. Following figure is the representation of an downstream valve in the program.

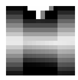


Figure 4.11 Representation of a Downstream Valve

- **DOWNSTREAM DEAD END**

Downstream dead end is a boundary condition element which can be used to simulate an obstacle in the pipeline end not allowing any flow rate through. This boundary condition element object also has a single connection node at its upstream allowing a single pipe connection. Downstream dead end boundary condition may also be simulated with a very fast closing downstream valve. Downstream dead end boundary condition is represented with the following figure.

Figure 4.12 Representation of a Downstream Dead End

4.1.2 Main Form of The Program and Interface Properties

Computer program has a main form which comprises the main body of the program. A graphical editor pad is used as the workspace and auxiliary forms and toolboxes are used for design and simulations. Parts of the program are explained with the help of screen shots. Following Figure illustrates the main window of the computer program.

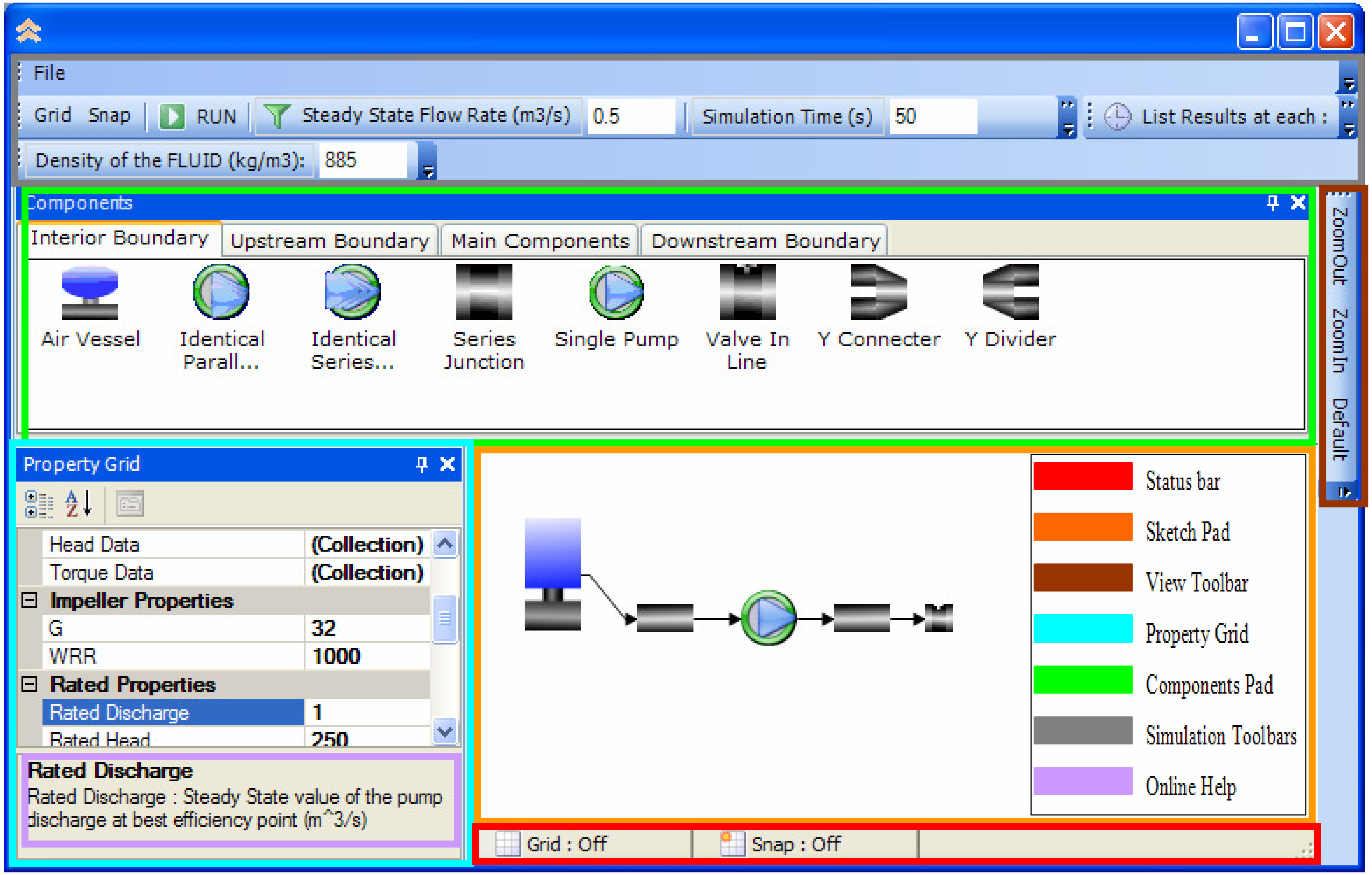


Figure 4.13 Views of the Main Form and Parts of the Main Form

All main parts of the computer program are listed above. Definitions of these parts are described in detail in the following text.

- **Sketch Pad**

Sketch Pad is the main part of the program which is used to design and simulate different configurations and scenarios. Sketch Pad assumes pipeline component shapes by drag and drop or by a context menu located in the right click of the mouse. Seth pad has the following capabilities,

  - **Rendered View:** All pipeline components are displayed with rendered graphical representations.
  - **Mimic View**: All pipeline components are displayed with mimics of these components.
  - **Zoom in & Zoom out**: Whole Sketch Pad can be zoomed in and out by zoom in and zoom out buttons. After zooming in, sketch pad can be explored by the help of automatically displayed vertical and horizontal scroll bars.
  - **Customization**: Sketch pad has customizable properties like background color, background gradient type, background image, and some permission on shape handling like restricting the pad to canvas, restricting addition of new shapes etc. background of the sketch pad can also be covered by an image selected from any folder.
  - **Grid & Snap**: Sketch pad can display grids and spacing of these grids can be set by the user. In addition, snapping property to these grid points is also embedded in the program. User can enable and disable these properties.
  - **Multi select** on the sketch pad is possible by using the context menu or by selecting a region by mouse.

- **Context Menu:** All pipeline components can be added onto the sketch pad through the context menu. Context menu is displayed on the right click.
- **Save and Open:** Sketch pad can be saved in any desired location and saved files can be loaded.
- **Save as Image:** For report generation purposes, scenario composed on the sketch pad can be saved as image in any common display format like jpg, png, bmp and tiff.
- **Print Preview and Print:** Sketch pad can be printed and a print preview is also available in the program.

- **Components Panel**

Components panel is another main part of the program that contains all available components in the program. Components panel is divided into 4 main tabs displaying different pipeline component groups. Following are the tabs in the components panel and corresponding components displayed in these tabs;

Upstream Boundaries:

Upstream Constant Head

Upstream Variable Head

Upstream Specified Discharge

Main Components

Pipe

Interior Boundaries

Air Vessel

Single Pump

Identical Parallel Pumps

Identical Series Pumps

Series Junction

Y-Divider

Y-Connecter

In Line Valve

Downstream Boundaries

Downstream Constant Head Reservoir

Downstream Valve

Downstream Dead End

All the component objects in the components pad are to be dragged and dropped onto the sketch pad in order to construct different simulation scenarios and pipeline systems. Component objects may also be added to the sketch pad by the help of the context menu from which any o the components can be clicked to be added to the system.

- **Property Grid**

Property grid is a common grid object which allows user input through the grids defined for each component. Each component defined in the program has different parameters to be provided by the user and these parameters are input through the property grid. On the load of the program, each component object displayed in the components pad but they are not initialized unless they are added to sketch pad. This property of the components provides an important amount of time saving in cpu of the computer. When a component object is added to the system, corresponding component class is initiated and object is generated. Properties of each component added to sketch pad can then be viewed by double clicking on the object. Some of the component objects do not have any parameters to be input such as a series junction or divider and connector junctions. Following part of the section describes the property grids of the components defined in the program.

- **Property Grid for PIPE**

Pipe object has a property grid that enables user input pipe properties. A pipe has different parameters defining pipe material properties and pipe geometric properties. Mesh properties are also provided through the pipe property grid.

In the computer program, some of the flow parameters are calculated by the program with the provided input. On the other hand some of these parameters can also be input by the user through the interface. Speed of sound is one of these parameters. With the given data, program calculates the speed of sound in each pipe segment. User can also provide a speed of sound data for each pipe object present in the system. Computer program uses calculated speed of sound as long as the user enters 0 for speed of sound value. If user enters a different value, computer program uses that speed of sound value for the simulation. Parameters of a single pipe and corresponding property grid are presented in the following figure.

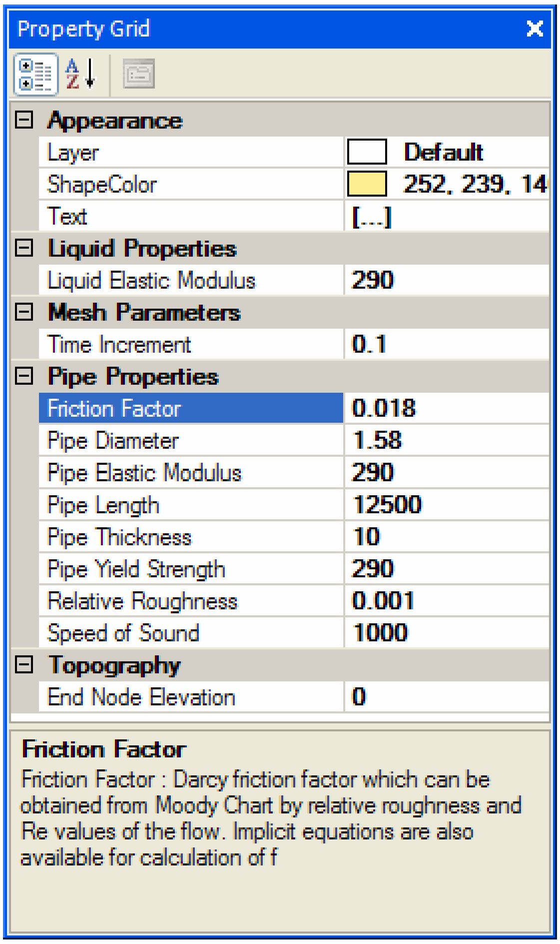


Figure 4.14 Property Grid for Pipe

- **Property Grid for UPSTREAM CONSTANT HEAD RESERVOIR**

Upstream constant head reservoir has a property grid which is much simpler than that of a pipe. In upstream constant head property grid, two parameters should be provided by user. One of these parameters is the upstream elevation. This parameter sets the elevation of the very first pipe in the system and the remaining topographical characteristics are dependent on this elevation. The other parameter related to the upstream reservoir is the liquid column height which is added to the elevation parameter in order to obtain the first point on the hydraulic grade line. Parameters of an upstream constant head reservoir and corresponding property grid are presented in the following figure.

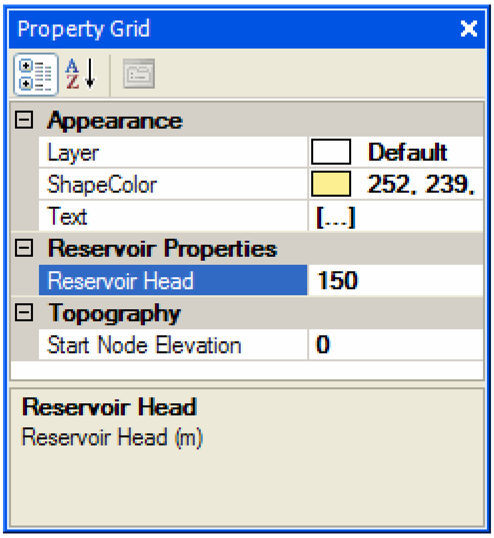


Figure 4.15 Property Grid for Upstream Constant Head Reservoir

- **Property Grid for UPSTREAM VARIABLE HEAD RESERVOIR**

Upstream variable head reservoir has a property grid which is used to describe the variable head characteristics of the upstream reservoir. Three parameters are required to describe the characteristics of the variable head reservoir. These are mean head of the reservoir, frequency of the head variations and magnitude of the variations. These values are to be provided by the user and a sinusoidal function is used to approximate the head characteristics. Following figure illustrates the property grid for upstream variable head reservoir.

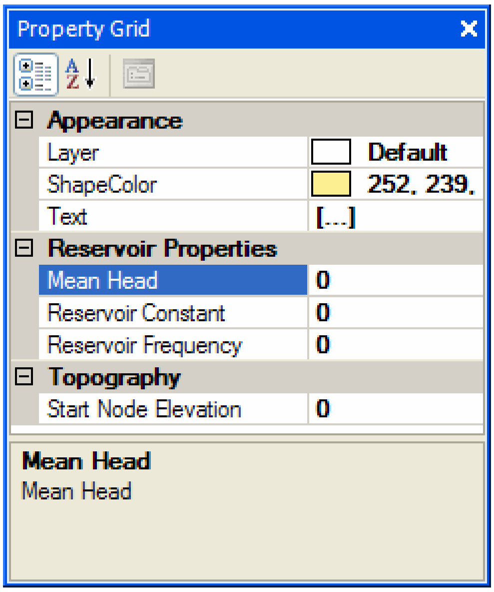


Figure 4.16 Property Grid for Upstream Variable Head Reservoir

- **Property Grid for UPSTREAM SPECIFIED DISCHARGE**

Upstream specified discharge has a simple property grid which has the parameters to describe the discharge characteristics at the upstream of the system. User should input the related parameters through the property grid which are used to approximate the discharge characteristics function. Initial flow rate for steady state operation of the system should be equal to the mean discharge value of the upstream specified discharge. In case the main program is run with a different flow rate then that is specified in the upstream variable discharge property grid, computer program will run for the specified flow rate then in a few seconds will accept the value entered through the property grid. Following figure is the representation of an upstream specified discharge boundary condition object.

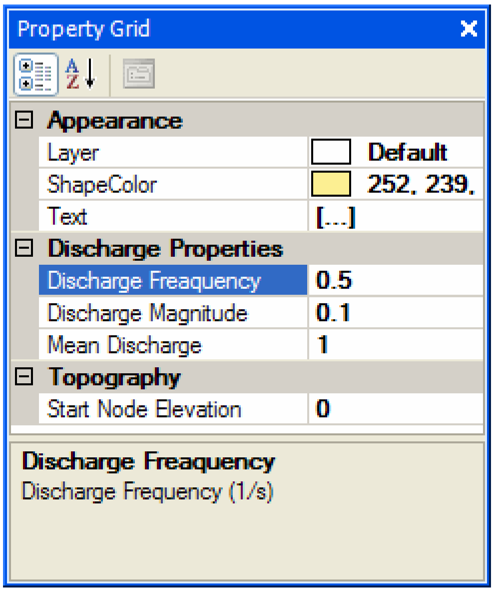


Figure 4.17 Property Grid for Upstream Specified Discharge

- **Property Grid for DOWNSTREAM CONSTANT HEAD RESERVOIR**

Downstream constant head reservoir has a property grid which is very similar with that of an upstream constant head reservoir. In downstream constant head property grid, one parameter should be provided by user which is the liquid column height which is added to the elevation parameter in order to obtain the last point on the hydraulic grade line. Reservoir bottom height will be automatically set by the program to the value of the last pipe end node elevation. Parameters of a downstream constant head reservoir and corresponding property grid are presented in the following figure.

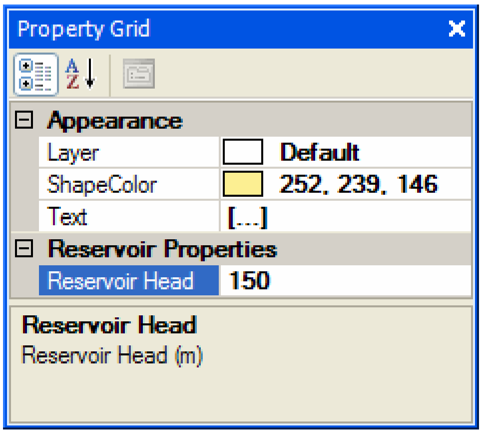


Figure 4.18 Reservoir Head for a Downstream Constant Head Reservoir

- **Property Grid for AIR VESSEL**

Air vessel object in the program has a property grid through which the user should input related air vessel parameters. An air vessel is represented with its geometrical and initial hydraulic properties. User should input the cross sectional area and height of the air vessel values of which are provided by the program with some default values. User should also input the initial volume of the air present in the vessel. Air vessel object automatically calculates the initial pressure head on the vessel and simulates the behavior of the vessel throughout the transients. User should also input the atmospheric pressure but it is provided by the program by a default value and should rarely be changed. Property grid of an air vessel object and corresponding parameters are illustrated in the following figure.

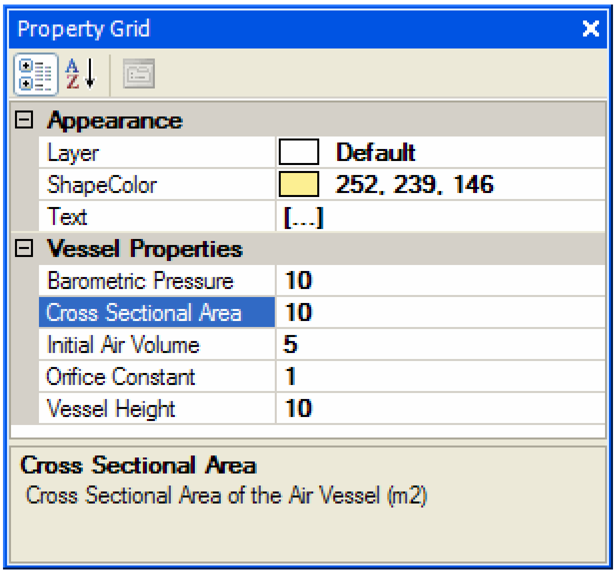


Figure 4.19 Property Grid for an Air Vessel

- **Property Grid for VALVE IN LINE**

Both valve boundary objects in the program have identical property grids and valve properties. Valve boundary object is represented by two parameters or a tabulated data of closure properties. Closing or opening characteristics of a valve is represented by a function of time and a time constant or these properties can be input as a tabulated data of percent opening versus time. If user provides both time constant and full closure time parameters, program uses these values. On the other hand, if one or both of these parameters are not provided, than program uses the tabulated data input by the user. With the tabulated data, computer program interpolates intermediate values of valve opening characteristics. Following figure represents the property grid of valves in the program.

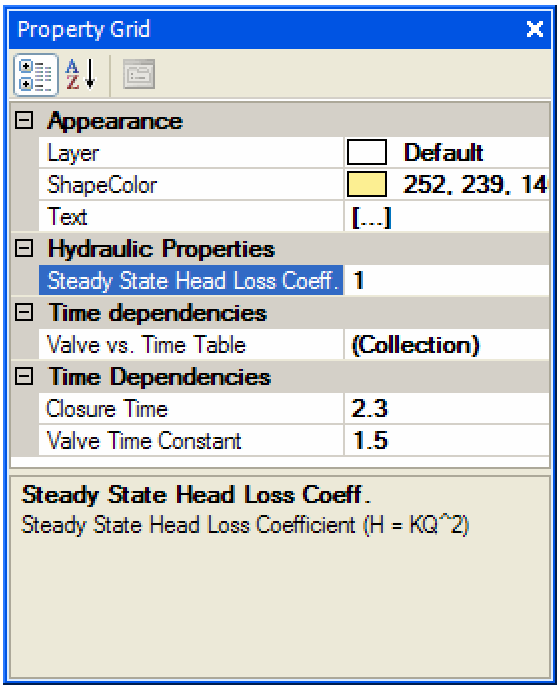


Figure 4.20 Property Grid for a Valve

- **Property Grid for PUMPS**

There are three different pump boundary conditions in the program. A single pump boundary condition and two pump station boundary conditions with series and parallel connected pumps. Property grid for these three different boundary condition elements has identical property rows. In pump station boundary conditions, an additional property is displayed to identify the number of parallel or series connected pumps. Generic default values for all properties are provided by the computer program and can be modified by the user. Following figure is the property grid for pump boundary conditions.

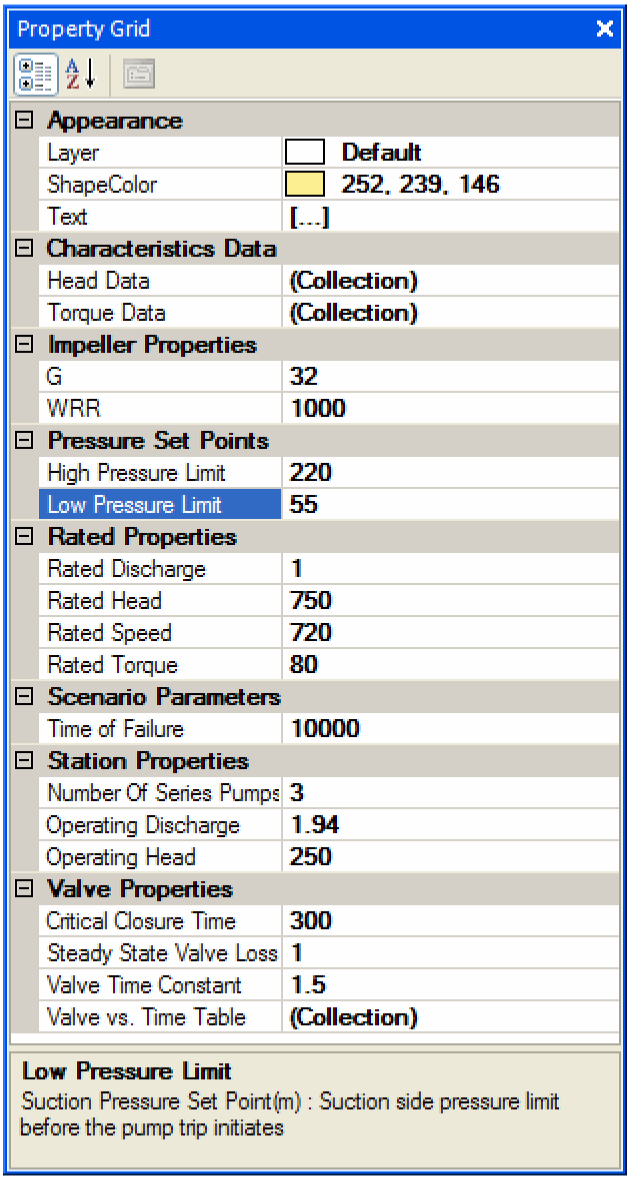


Figure 4.21 Property Grid for Pump Boundary Element

CHAPTER 5

CASE STUDIES

5.1 CASE – Transient Flow in a Transmission Pipeline

5.1.1 Introduction

In this case study, IRAQ-TURKEY Pipeline (ITP) is considered. The transient flow is simulated under different transient scenarios ("Surge Analysis"). First of all, the steady state operation results are obtained and introduced to the simulation program and several transient scenarios are initiated from this steady flow solution.

Results of the simulations are plotted by the coded computer program and presented in this thesis. Main focus is on the suction and discharge sides of pumping stations and points on the route that may be critical due to both negative and positive pressure values.

5.1.2 System Description

5.1.2.1 Actual System

Here the simulation is not based on the current system but on the situation as in the capacity expansion to 7000 m^3/h. The reason for this is that detailed data and several "Surge Analyses" by Worldwide accredited engineering companies is available for comparison.

ITP is a pipeline system of length 985.3 km. 345 km of the line is in Iraq and has a diameter of 46 inches. Remaining 640.3 km of the line is in Turkey with 46 inches of 556.8 km and 30 inches of 83.5 km. Pipe material is X60, which confirms 5LX grade as defined in American Petroleum Institute Standards (API 5LX-X60). There are regions of the line that crosses rivers. Line crosses Tigris River at 75 km and

Euphrates River at 758 km. Simulations are done with 4 pumping stations with the following location properties.

Table 5.1 Pump Stations and Locations

Station ID	Distance (km)	Elevation (m)
PS3	236	473
PS3A	298	802
PS4	335	963
PS5	699	639

In all pumping stations, there are 4 pumps, 3 in operation and 1 for standby. These pumps are in series arrangement each being double volute, double suction centrifugal type. Each pump has a rated discharge of 4977 m^3/h. Total heads per station varies between the values of 251 m and 446 m. Following figure represents the topographical properties of the considered system.

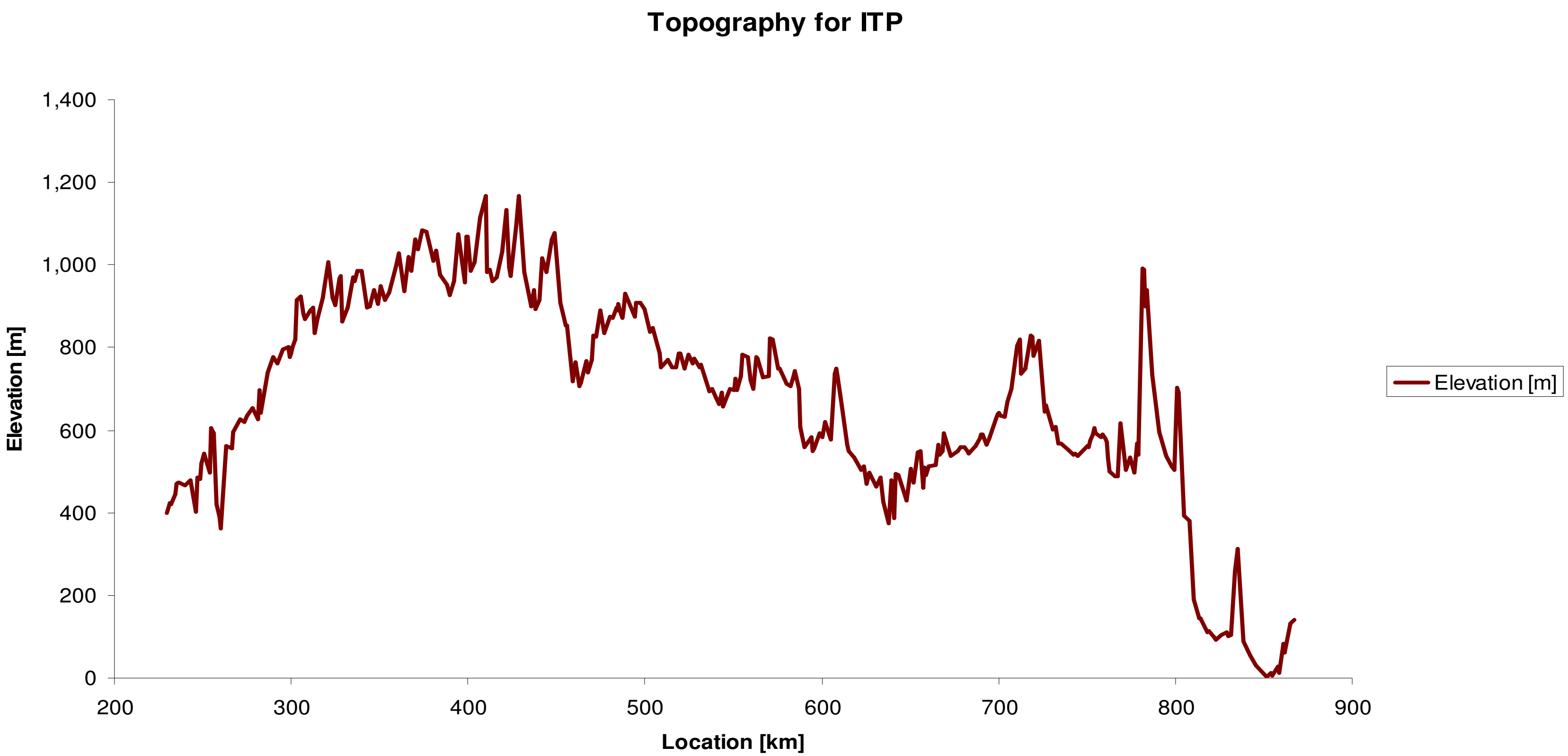


Figure 5.1 Topography of ITP

Figure 5.2 Main Components on the ITP System

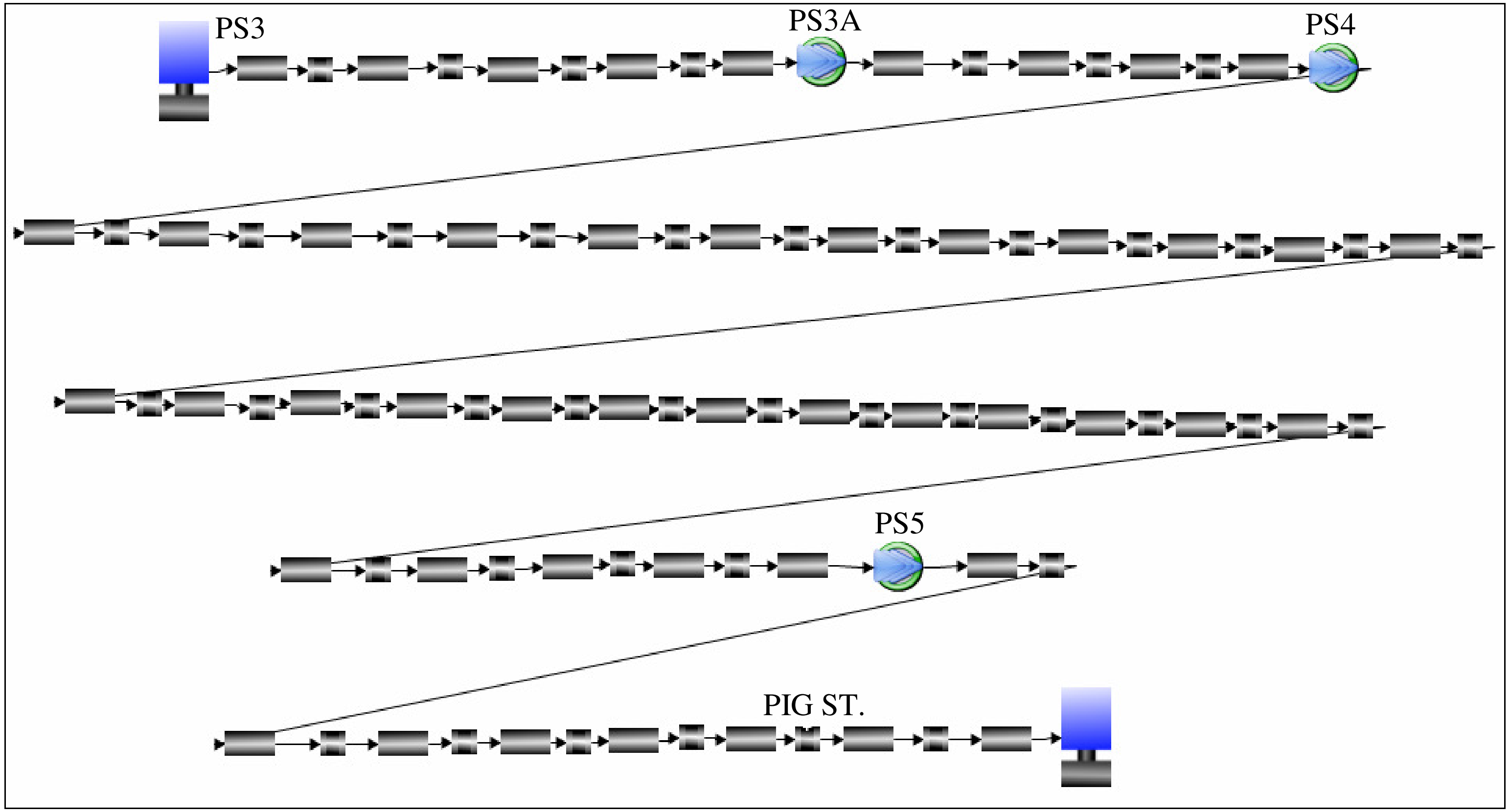


Figure 5.3 Main Components on the ITP System

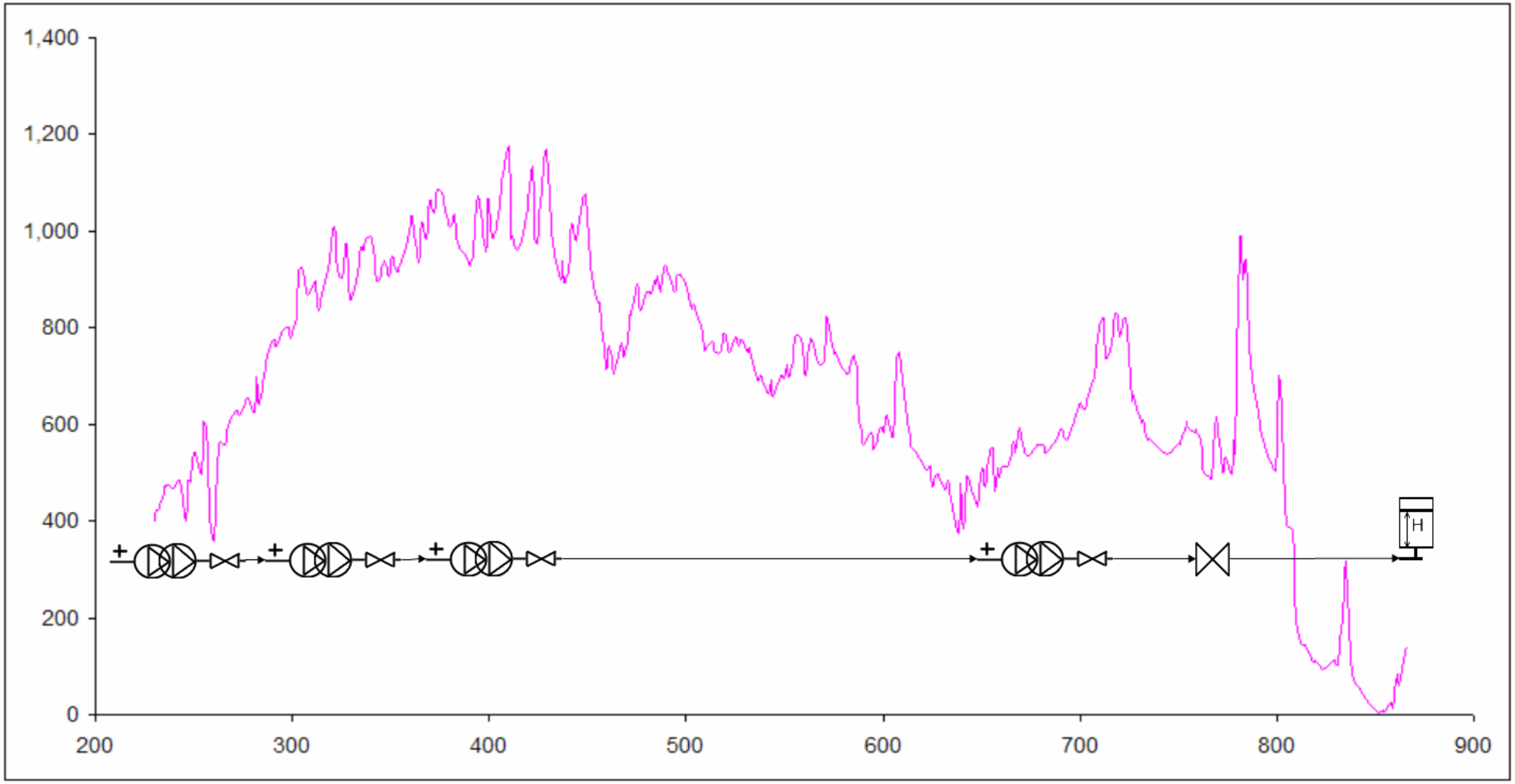


Figure 5.4 Mimic Diagram Composed in the Computer Program

PS-3 PUMPING STATION

There are four pumps one being for stand-by and three main pumps series connected. There are suction and discharge pressure control units that maintain the desired suction and discharge pressures by changing the speed of hydraulic converter unit.
Pressure set points for the suction and discharge sides of the station are 478 m liquid column and 1160 m of liquid column respectively.
Closure time for the inlet and outlet valves is quoted to be 340 seconds.
In the computer model, all pumps are modeled as a lumped element with an equivalent head and discharge value. PS3 Pumping Station has an equivalent pressure head of 415 meters of liquid column. All pumps are assumed to have same rotational speed throughout transients thus they all trip together. This assumption is based on the theory that states the applicability of equivalent pump assumption in case of a simultaneous failure such as an electricity shortage. High and low pressure set points, on the other hand, is applied for the discharge and suction sides of the pumps are set for the whole station element.

PS-3A PUMPING STATION

In PS-3A station, there are also two directly coupled and one hydraulically coupled pump is utilized. In PS-3A there are also pressure control units which are 822 m and 1310 m for suction and discharge sides of the stations. In PS-3A, there is a station bypass but station bypass is not modeled and utilized for the scenarios. As in the previous station, closure time of suction and discharge side valves is 340 seconds.

PS-4 PUMPING STATION

In PS-4 there are three pumps in series arrangement with two directly coupled and one hydraulically coupled to the other two pumps. A forth stand-by pump is also present in the pumping station.

For security purposes, PS-4 has pressure set points at suction and discharge sides of the station. Pressure set points for the station are 1000 m and 1490 m for low pressure and high pressure switches respectively.

PS-5 PUMPING STATION

In PS-5 station, there are 4 pumps one being stand-by and three on duty. Three pumps are connected series and are modeled do be driven by the same actuator thus fail all together. As in the other pump stations, in PS-5 pump station, there are high and low pressure set point at the discharge and suction sides of the station respectively. The values set for the limits are 1320 m and 830 m. for high and low set points respectively. A total head of 216 meters liquid column is delivered by the pump station at a flow rate of 4300 m^3/h.

PIGGING STATION

Pigging station is located at 901.8^{th} km of the pipeline. Diameter of the line changes from 46 inches to 30 inches at pigging station. Station valve closure time is 340 seconds with high pressure set point value of 1110 meters of liquid column.

5.1.3 Scenario 1 – Closing of Valves in Pigging Station

One of the alternative configurations of ITP line is the operation of two parallel pipelines having diameters 46” and 40”. In scenarios of the case study, 4300 m^3/h flow rate is considered to flow in 46” pipeline. In the scenario, pigging station valve is closed in 340 seconds. Because of the closure, line pressure increases at upstream of the valve and travels to the downstream of PS-5 Station. After some time pressure increases at the downstream of the pump station and when reaches to the pressure set point of the station, PS-5 is shut down. PS-5 station is considered as a lumped element consisting of 3 series connected pumps failing together. Full pump characteristics of a single pump is input and applied for all three pumps in the station. Wave propagation and pressure envelope for the scenario is presented in the following figures.

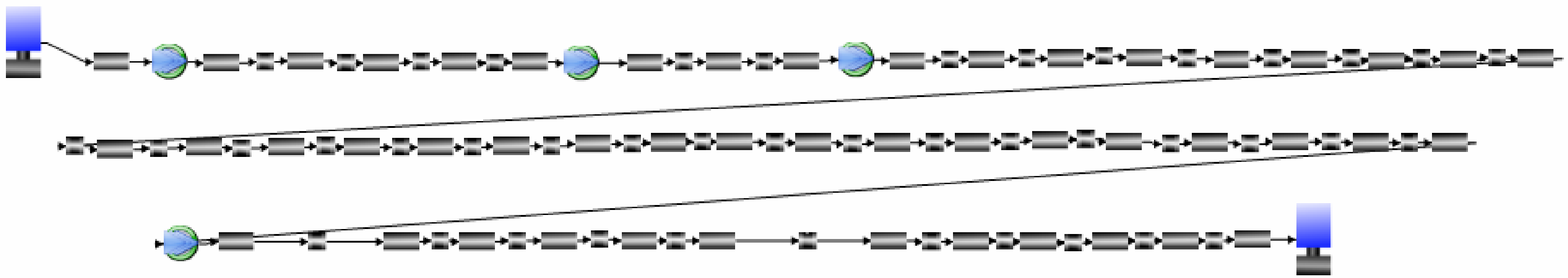


Figure 5.5 Mimic View of Scenario-1

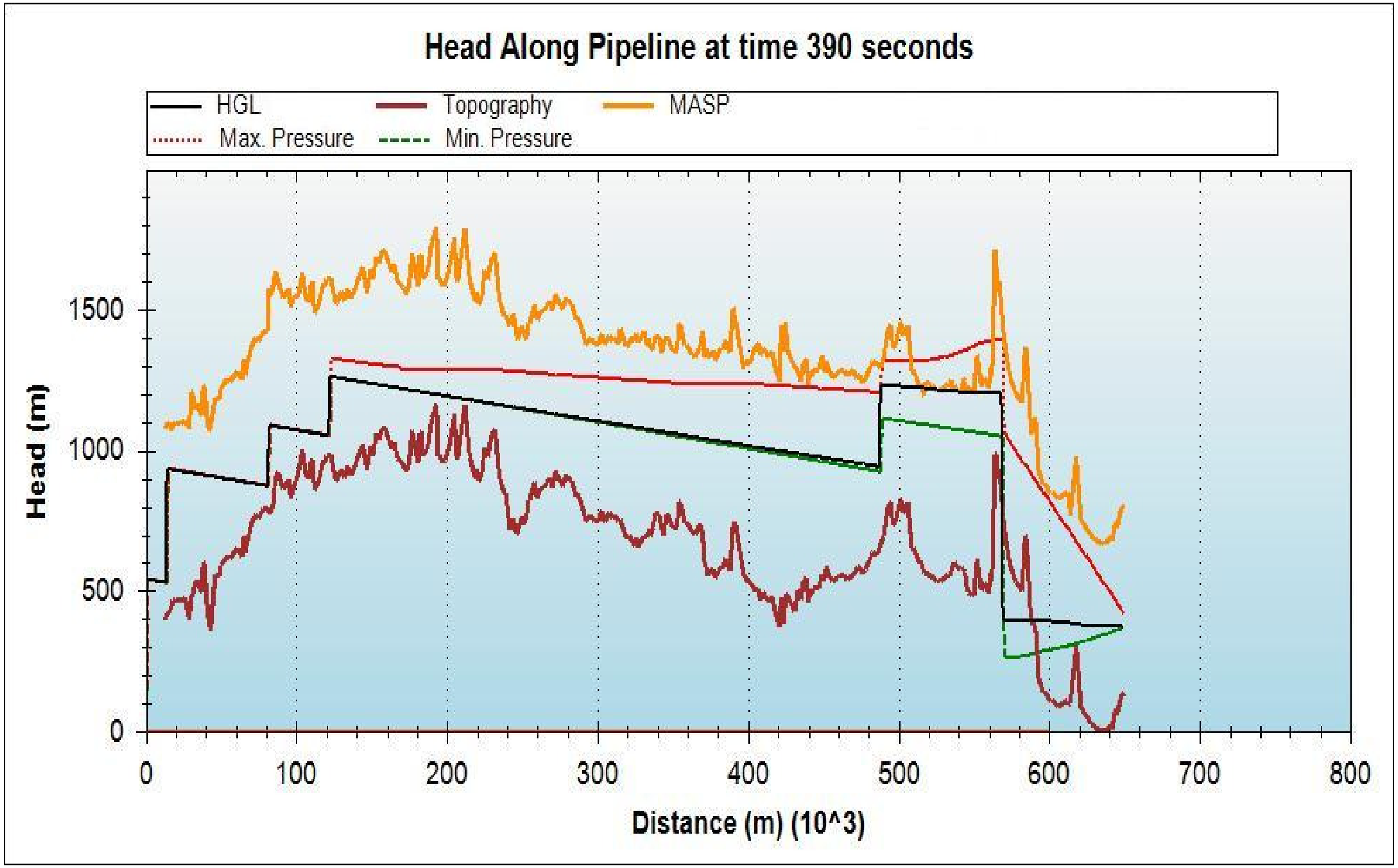


Figure 5.6 Instantaneous Head an Pressure Envelope for Scenario-1 at 390th second

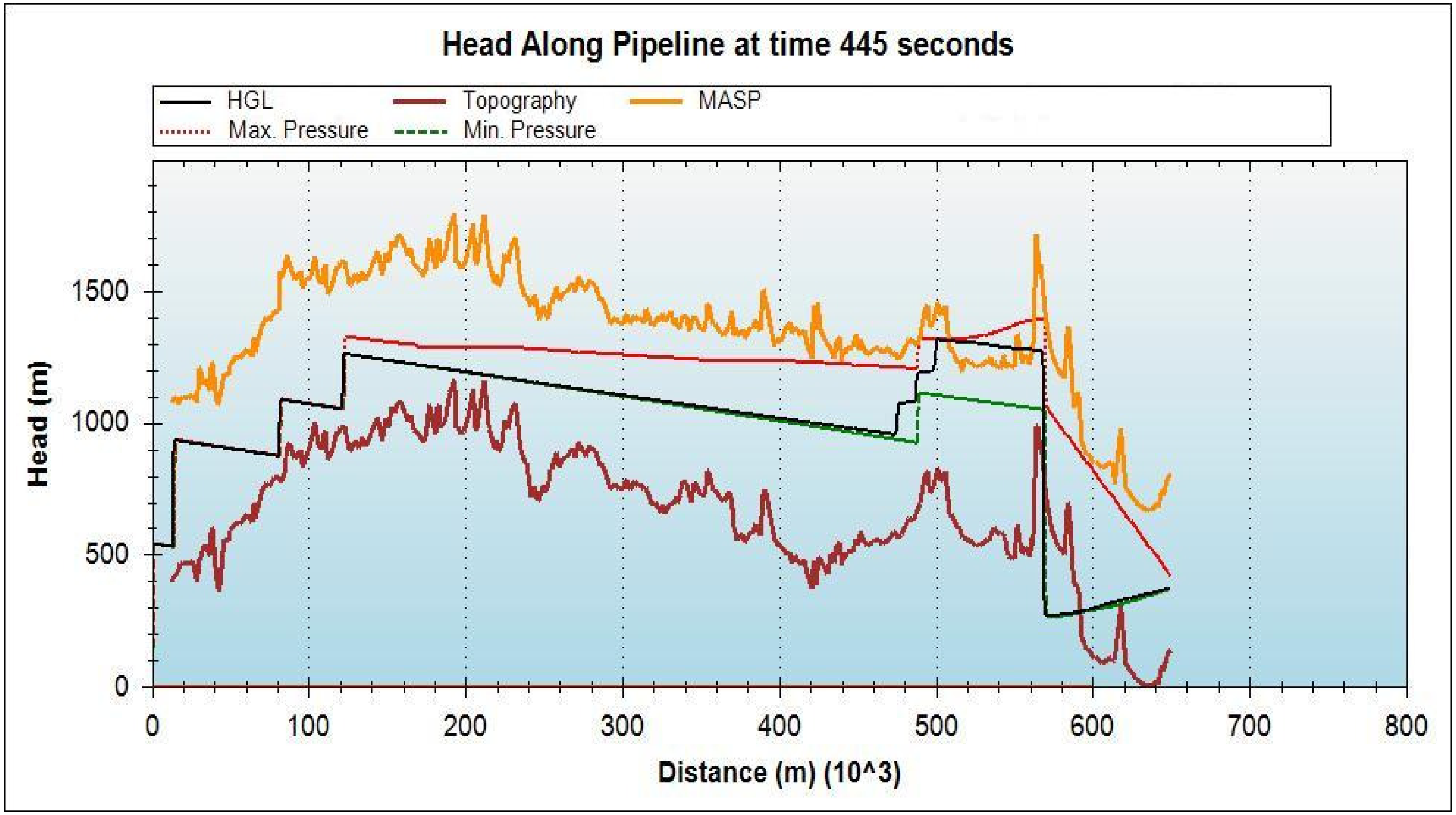


Figure 5.7 Pressure Envelope and Head Distribution at the instant of PS-5 Station Failure

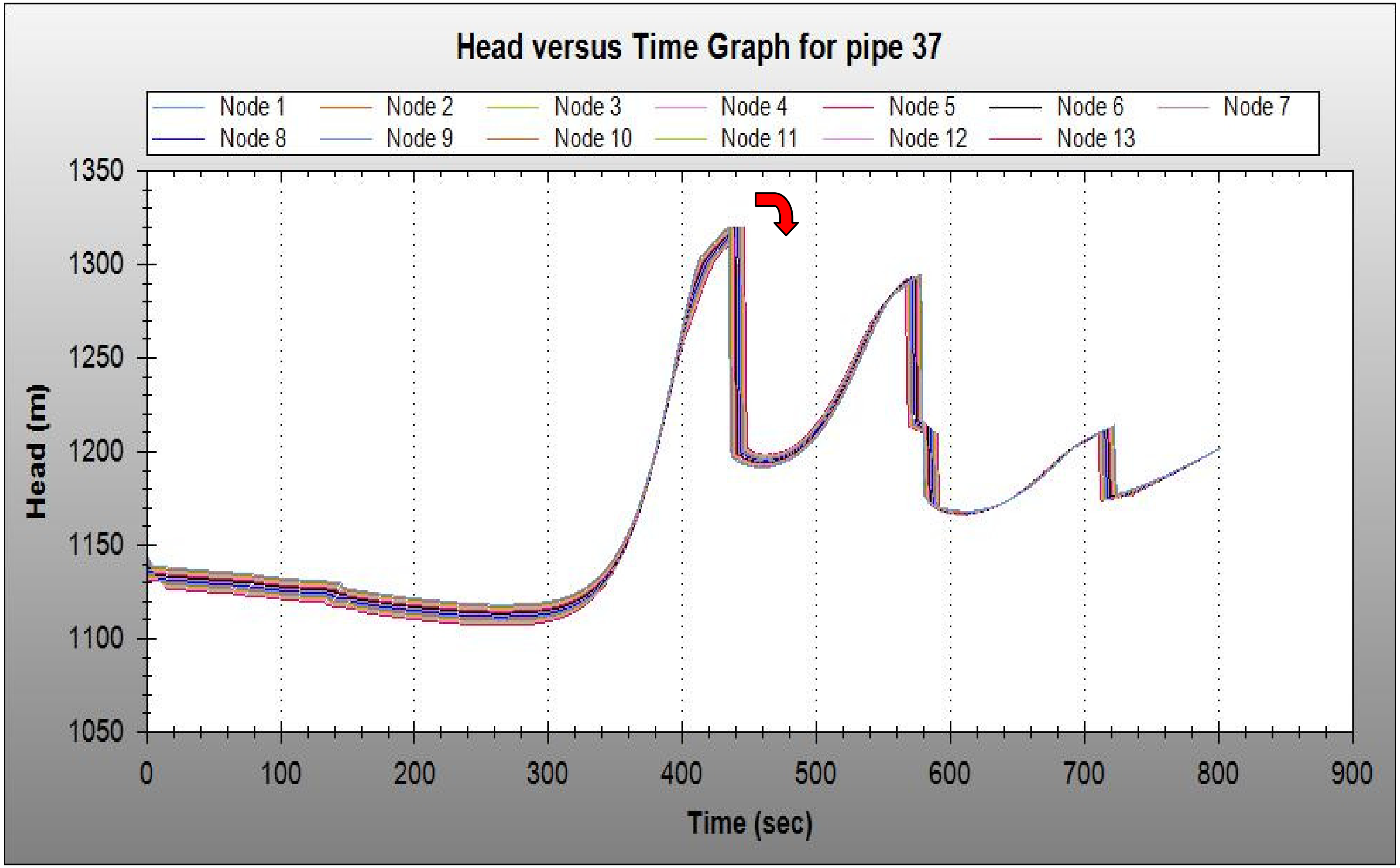


Figure 5.8 Pressure vs. Time History along Discharge Pipe of PS-5

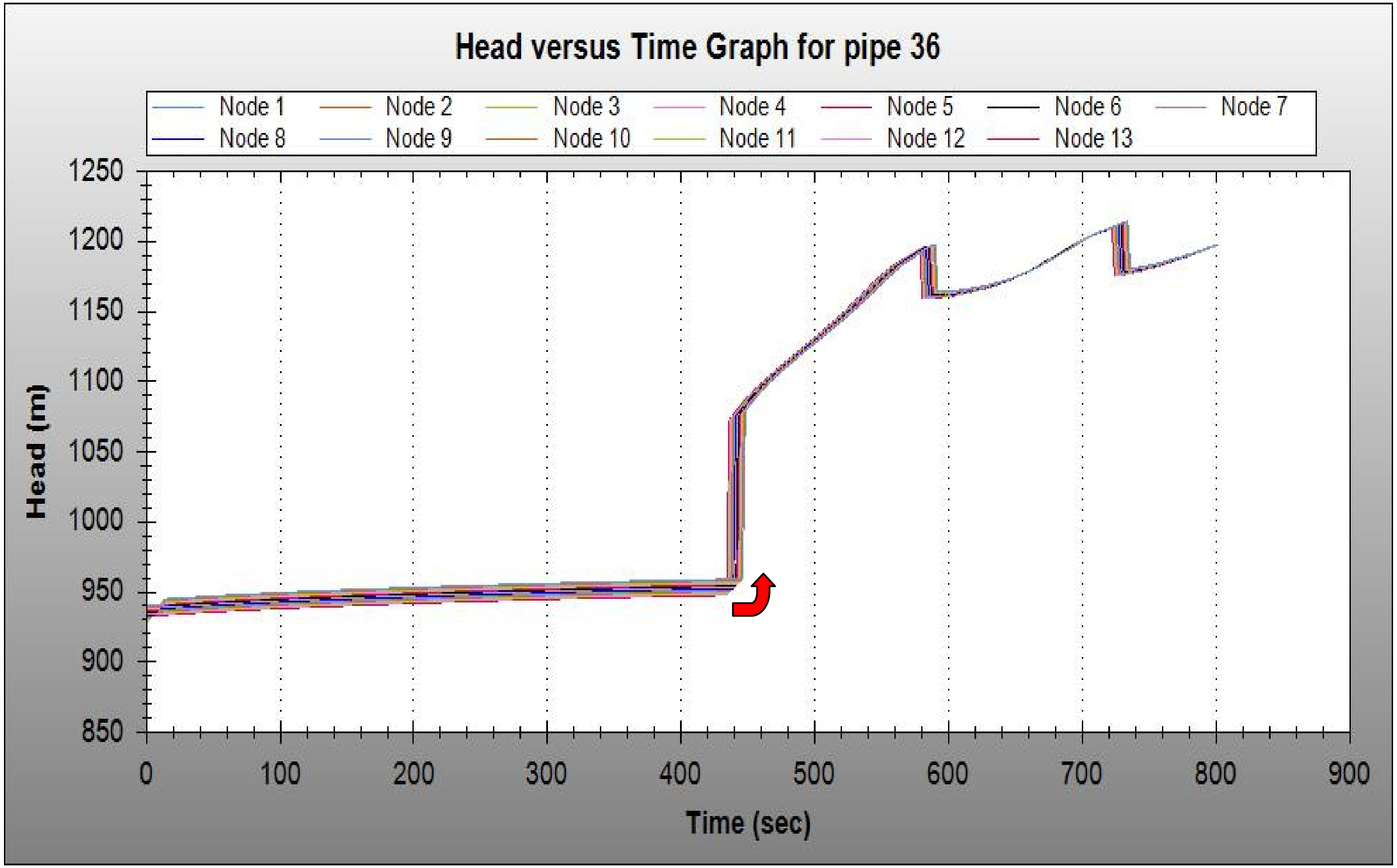


Figure 5.9 Pressure vs. Time History along Suction Pipe of PS-5

5.1.4 Scenario 2 – Closing of Line Valves in Pigging Station – Discharge Line of PS-5 is Equipped With and Air Vessel

In this scenario, pig station valves are closed in 340 seconds because of a possible pipe blast. During the closure of pig station valves, propagating negative and positive pressures are tried to be damped by an air vessel with a volume of 4000 m^3. Results are presented in the following graphs and compared with the results of Scenario-1 which does not utilize an air vessel.

Wave propagation, pressure envelope and pressure time history are presented below.

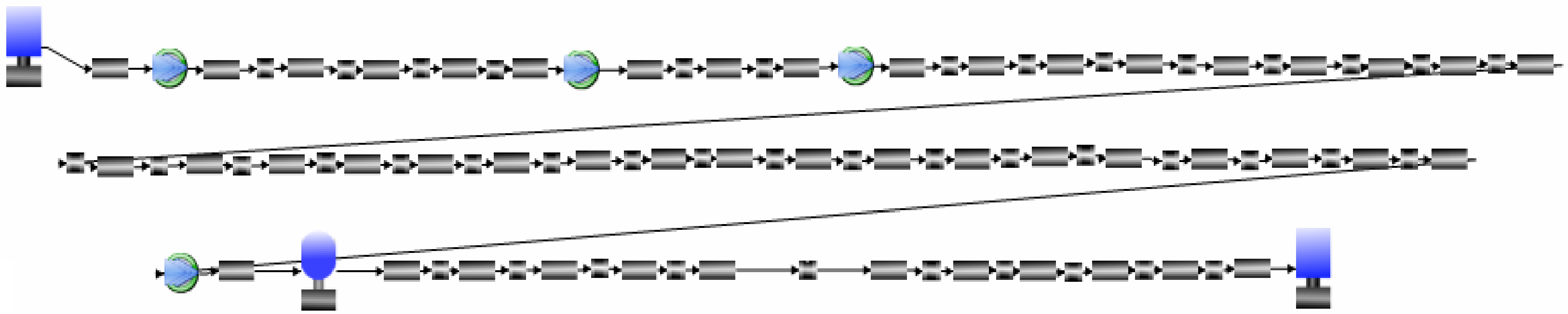


Figure 5.10 Mimic View of Scenario-2

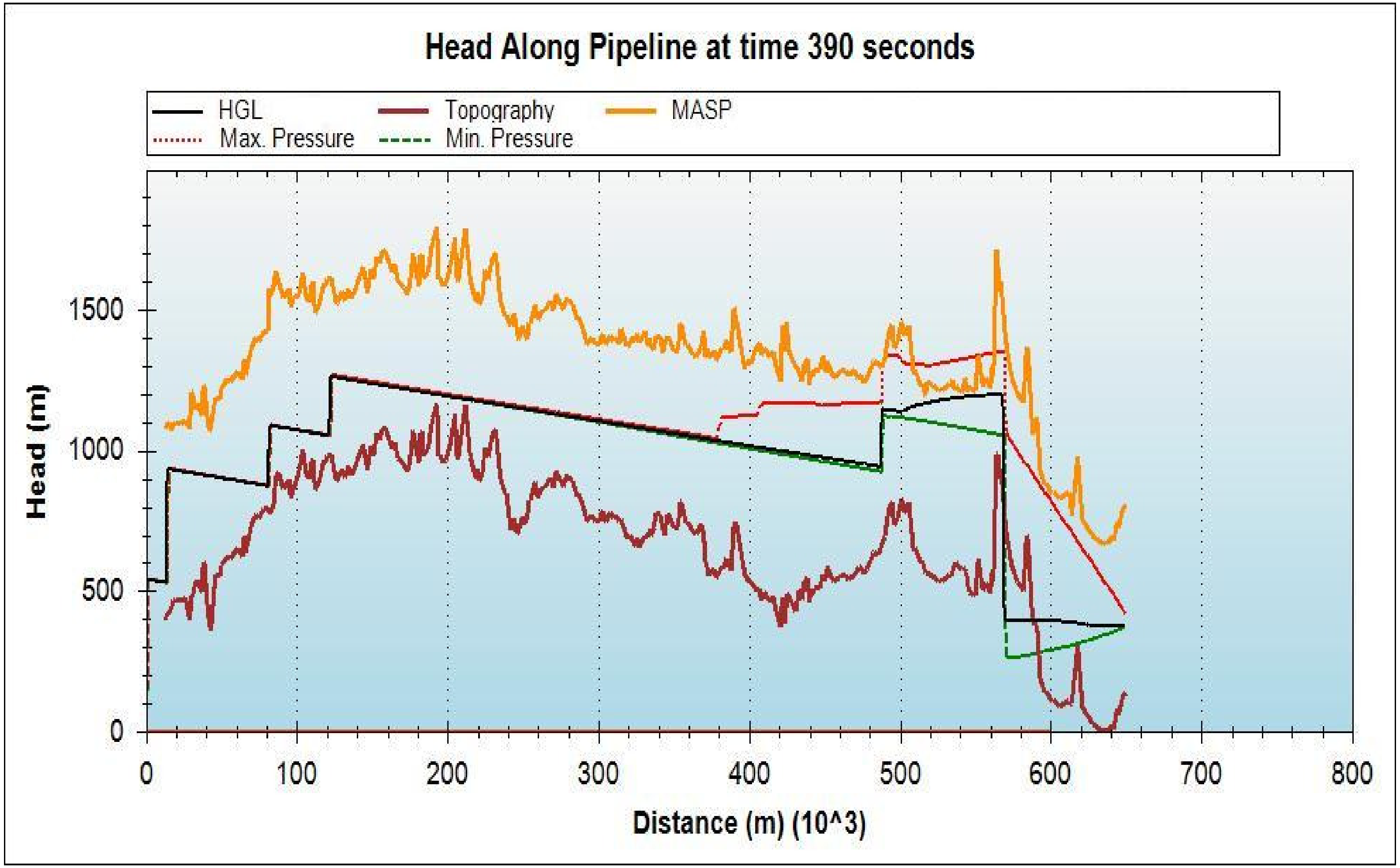


Figure 5.11 Instantaneous Head an Pressure Envelope for Scenario-2 at 390th second

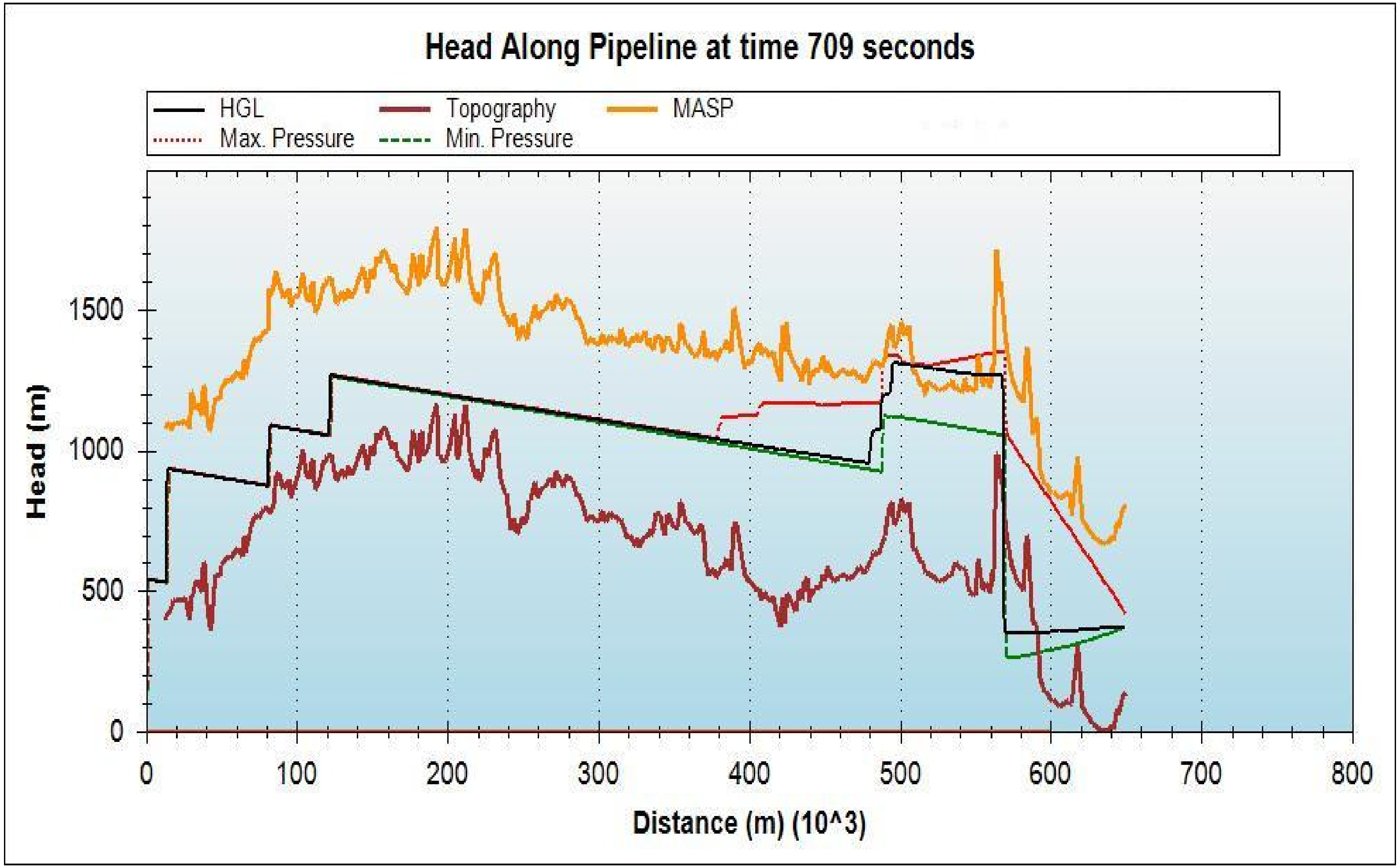


Figure 5.12 Pressure Envelope and Head Distribution at the instant of PS-5

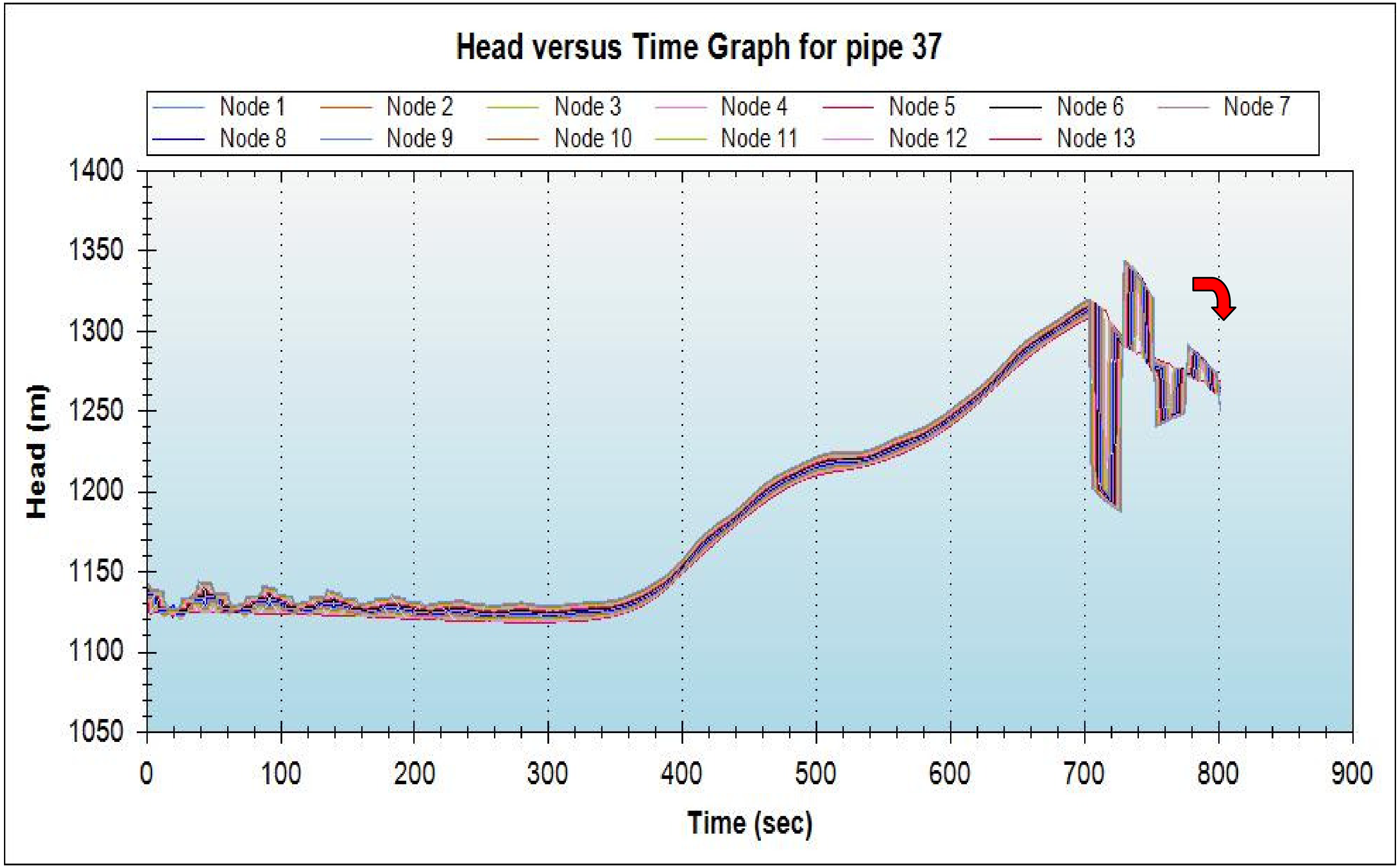


Figure 5.13 Pressure vs. Time History along Discharge Pipe of PS-5

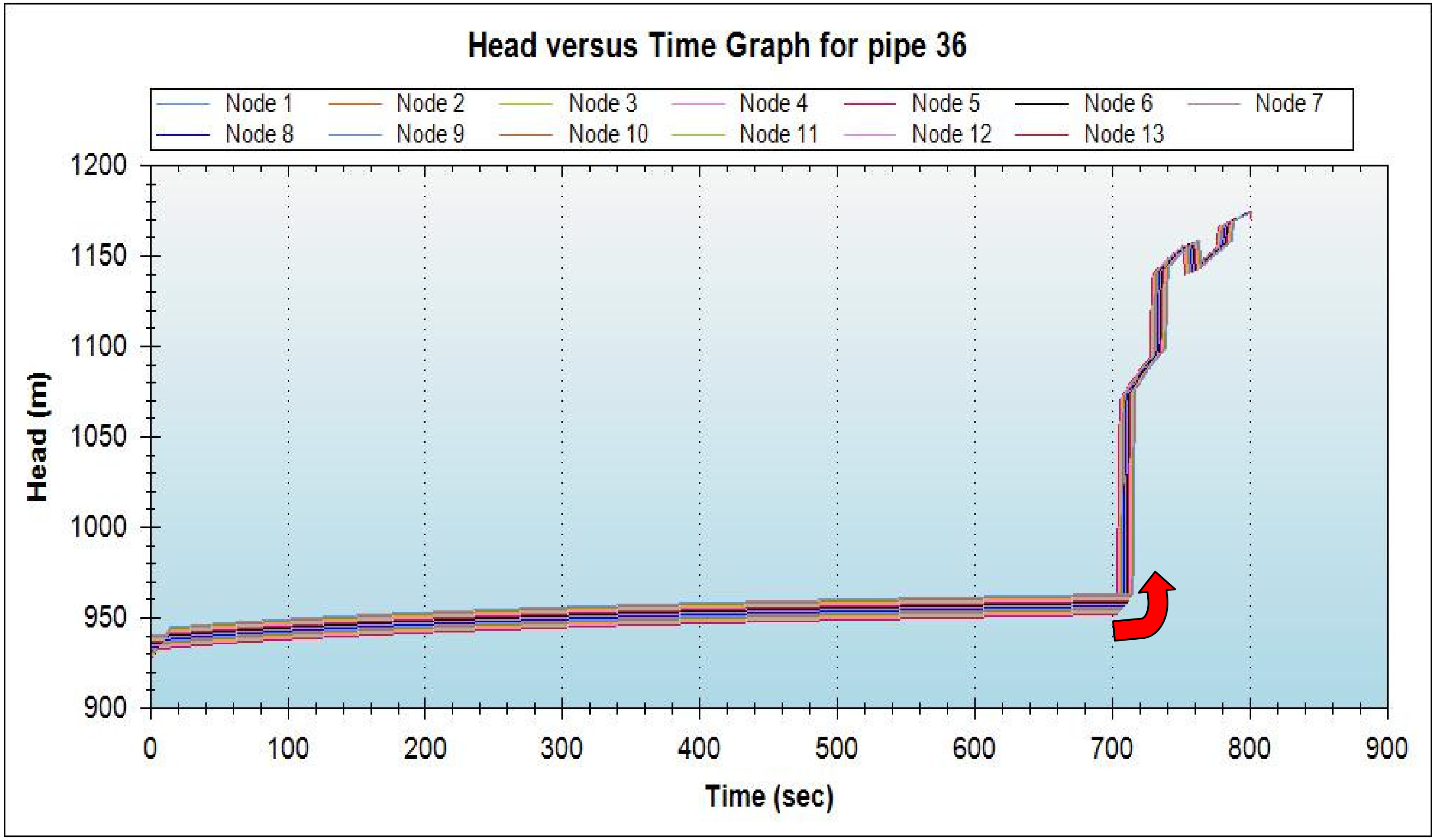


Figure 5.14 Pressure vs. Time History along Suction Pipe of PS-5

5.1.5 Scenario 3 – Closing of Line Valves in Pigging Station – Two Air Vessels are utilized – At Discharge Line of PS-5 and At Discharge Line of Pig Station

In this scenario, pig station valves are closed in 340 seconds because of a possible pipe blast. It is seen that for the firs two scenarios, pressure values during transients exceeds MASP and falls below the atmospheric pressure thus causing pipe blasts and column separation. In order to prevent these effects, a second air vessel is suggested and simulated to compare the results. Addition of the second air vessel drastically changes the characteristics of the transient pressures for negative pressure line but is again in lack of positive surge prevention. Following figures represent the results of the simulations run for Scenario-3.

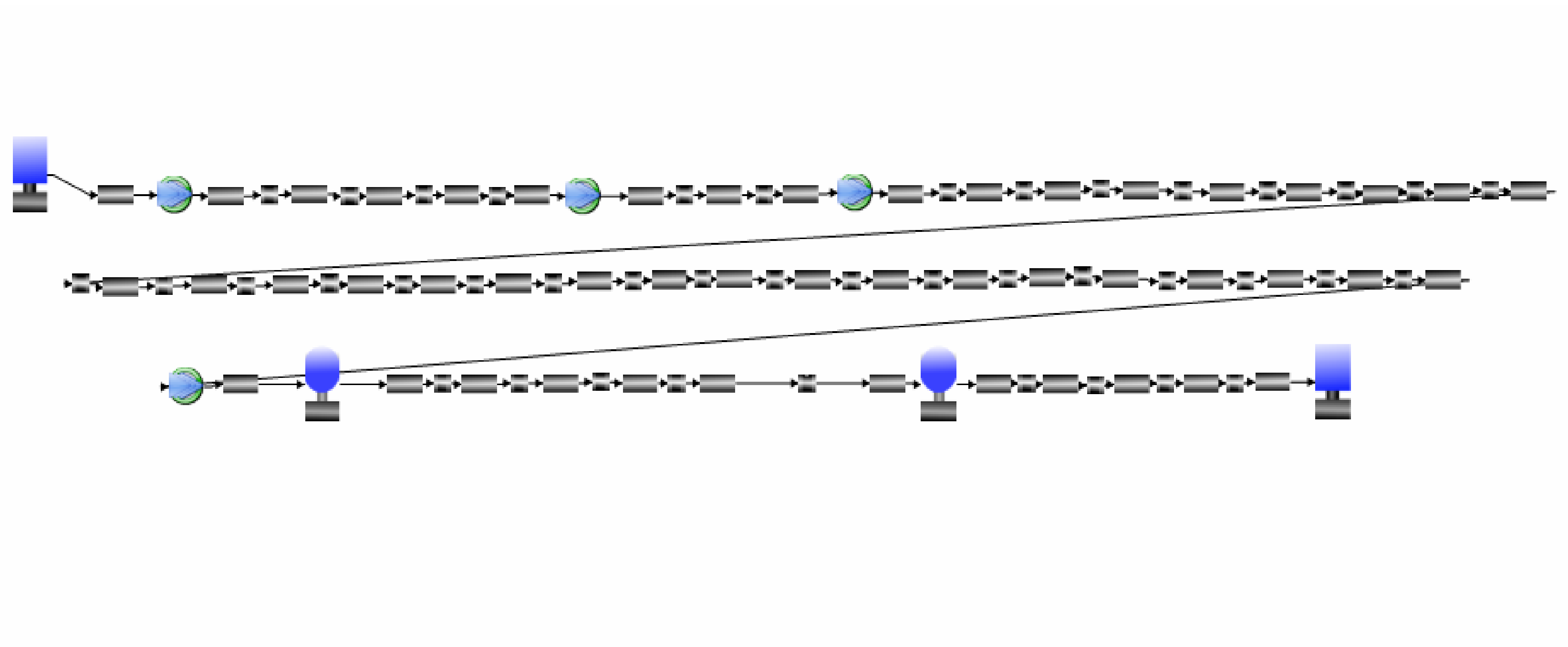


Figure 5.15 Mimic View of Scenario-3

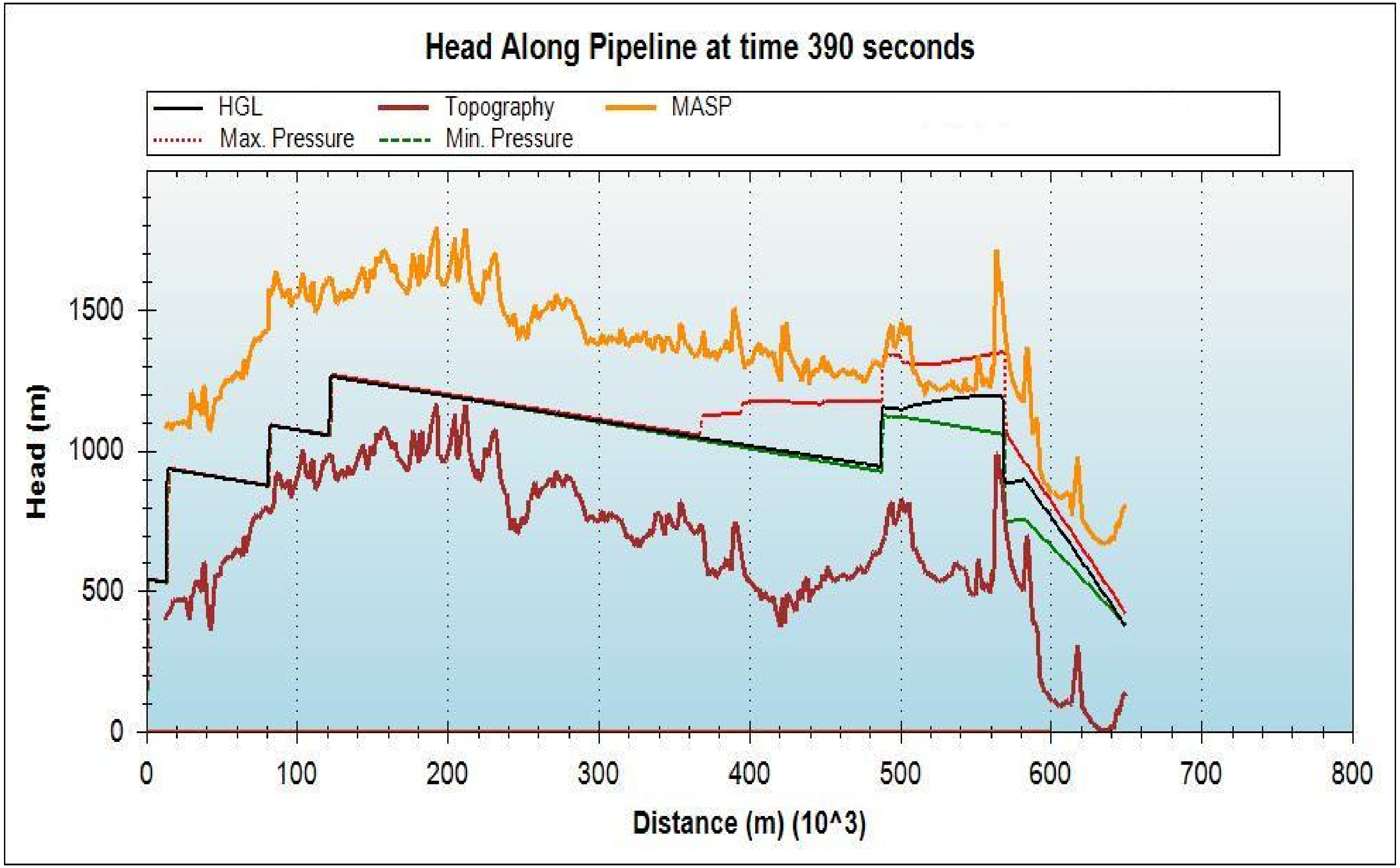


Figure 5.16 Instantaneous Head an Pressure Envelope for Scenario-3 at 390th second

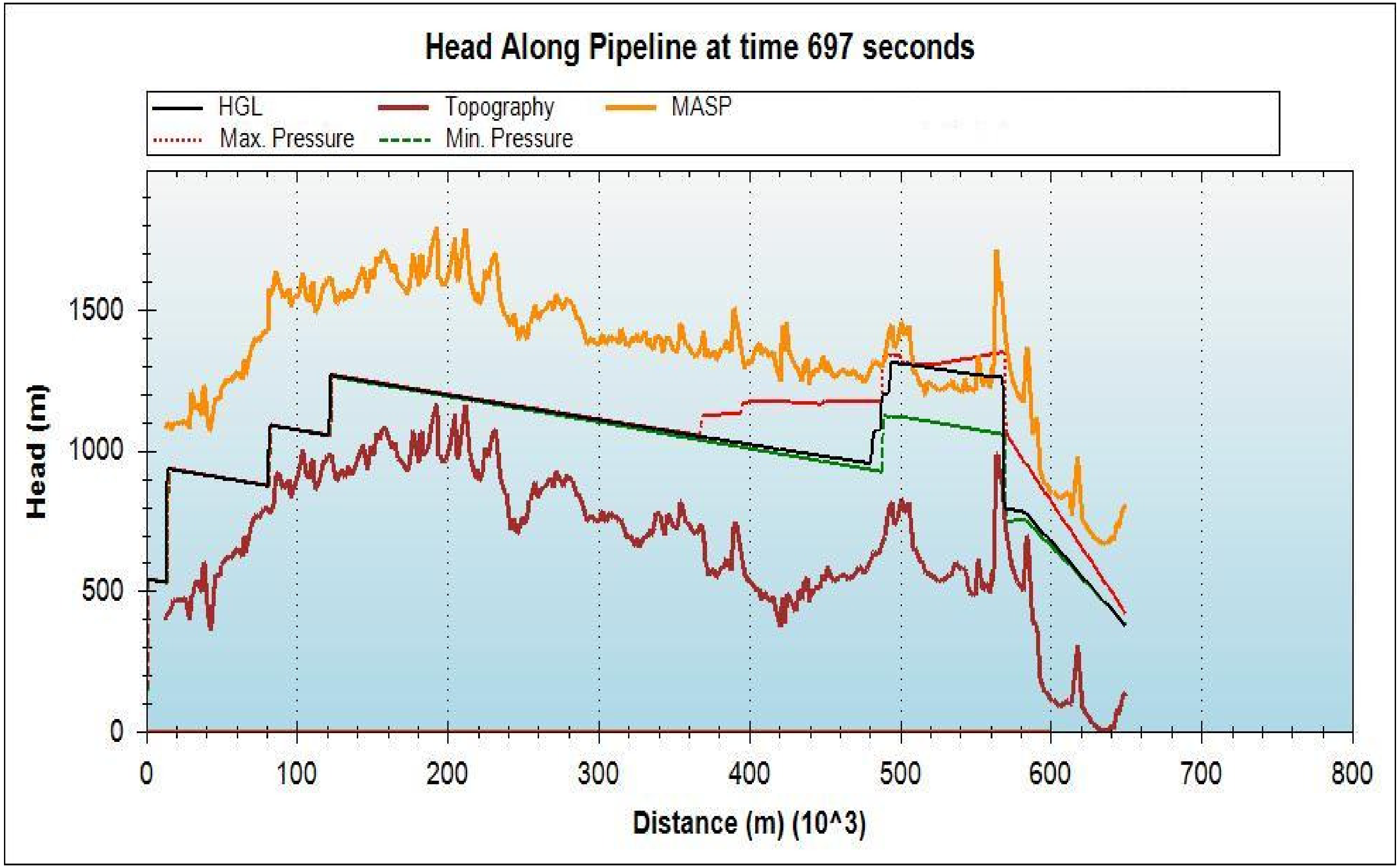


Figure 5.17 Pressure Envelope and Head Distribution at the instant of PS-5

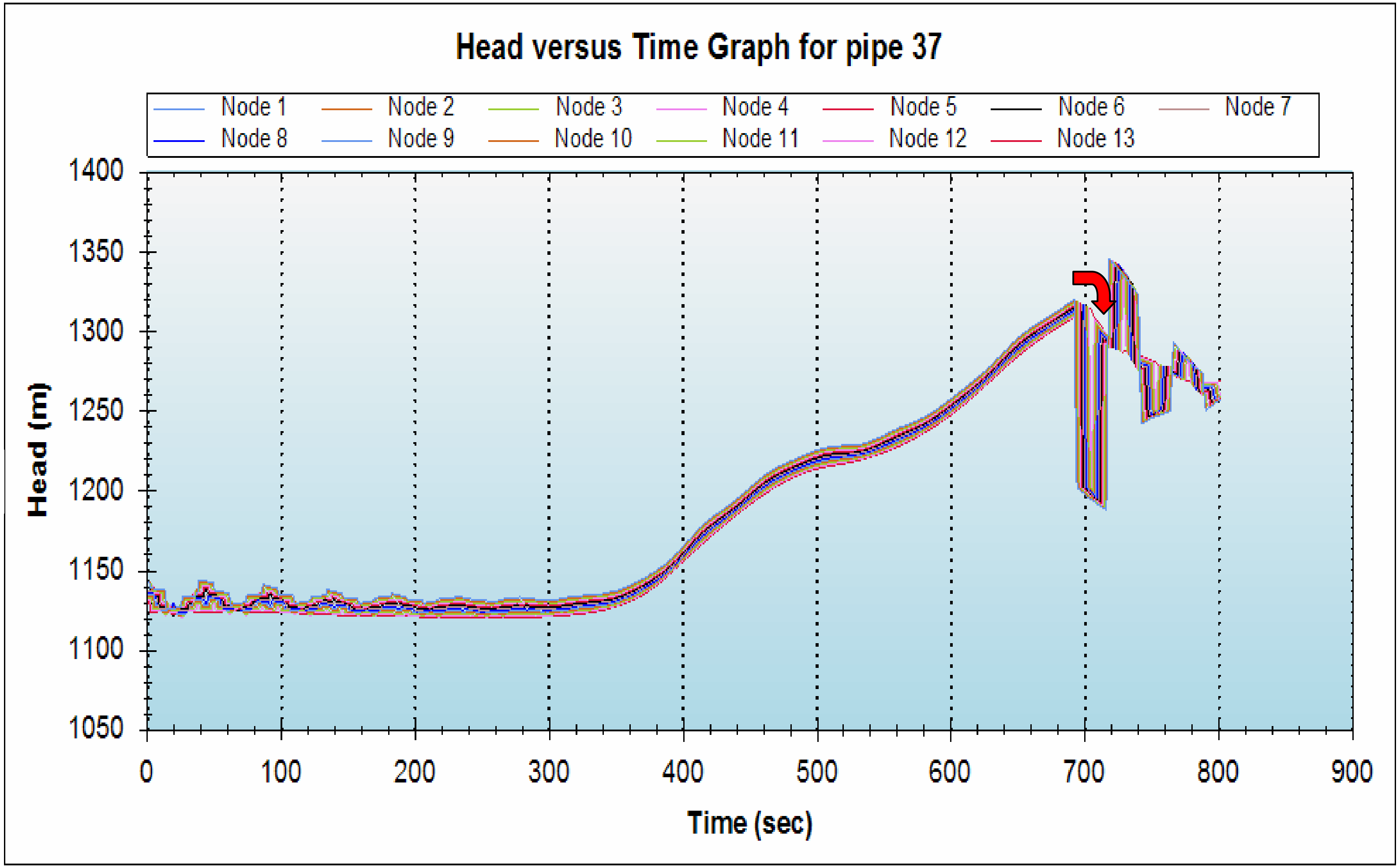


Figure 5.18 Pressure vs. Time History along Discharge Pipe of PS-5

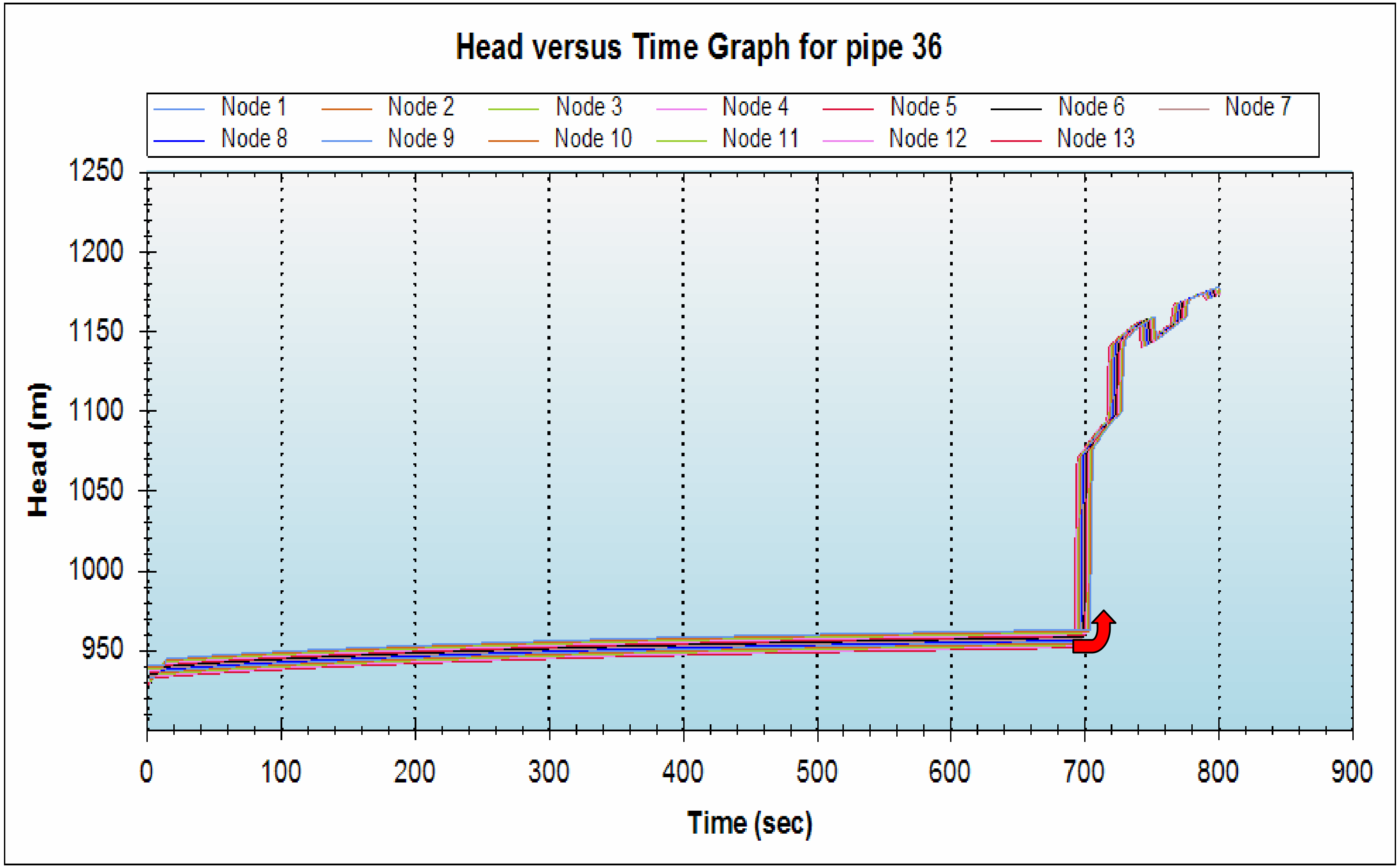


Figure 5.19 Pressure vs. Time History along Suction Pipe of PS-5

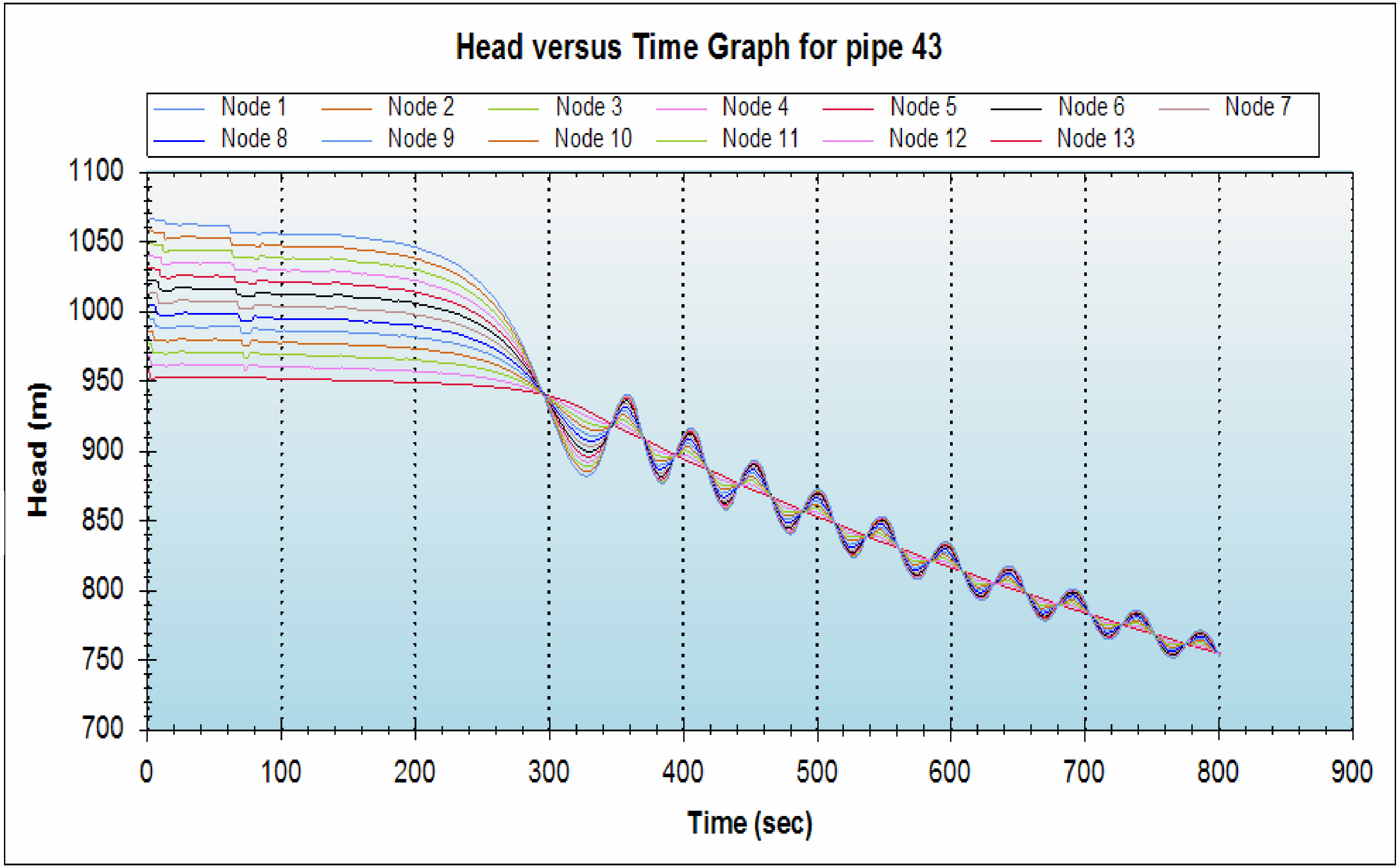


Figure 5.20 Pressure vs. Time History along Discharge Pipe of Pig Station

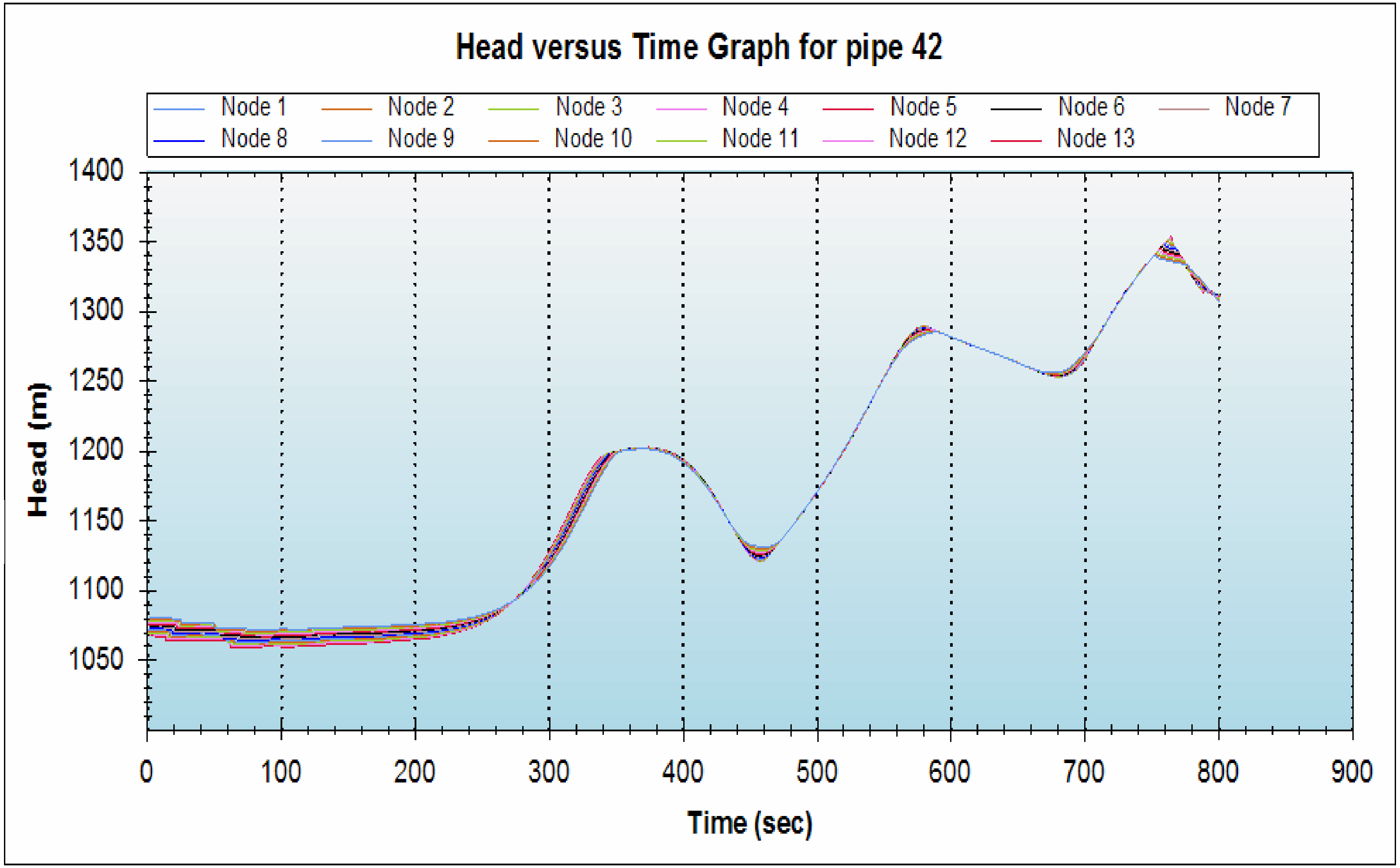


Figure 5.21 Pressure vs. Time History along Suction Pipe of Pig Station

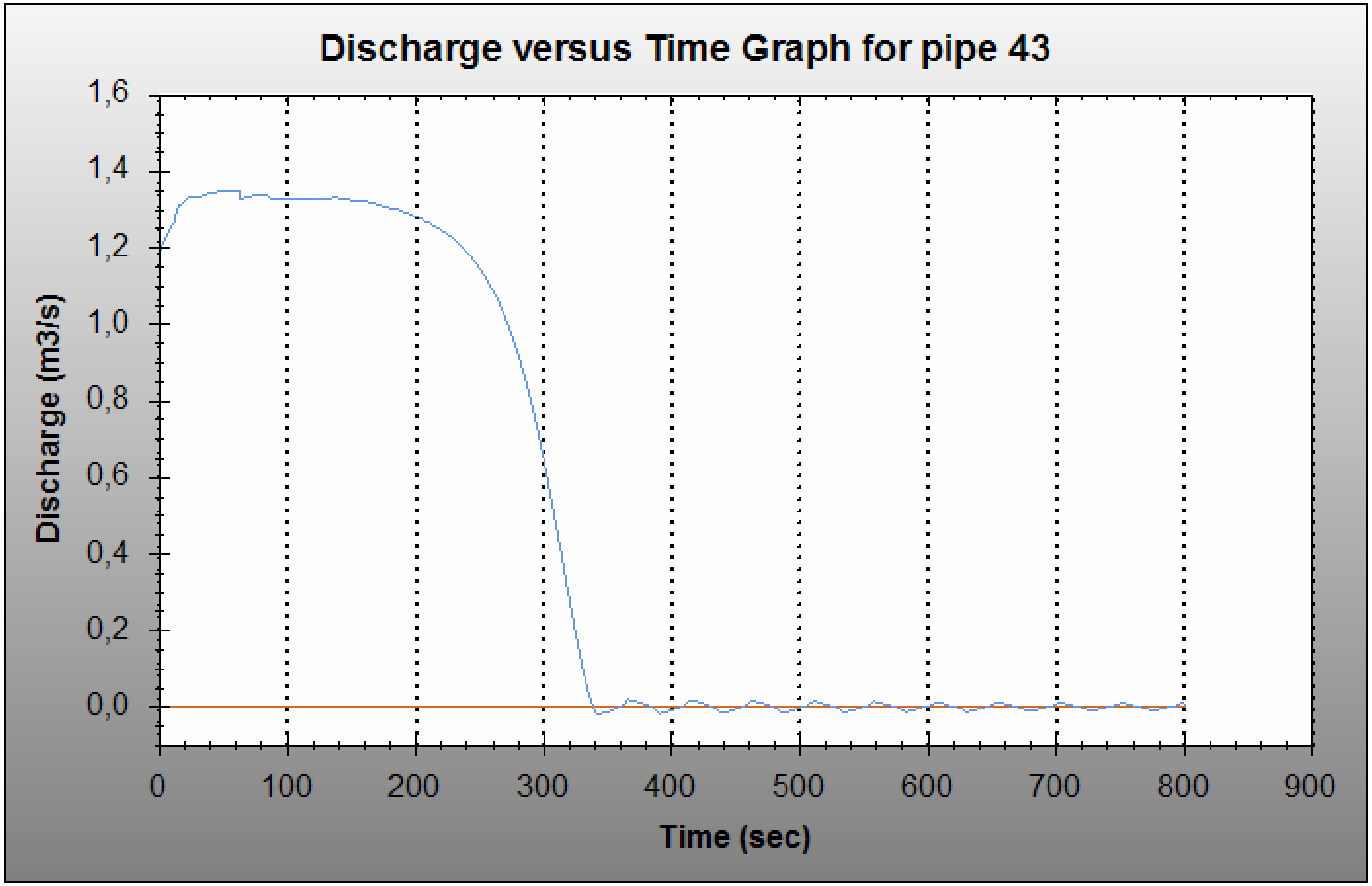


Figure 5.22 Discharge vs. Time History along Upstream of Air Vessel

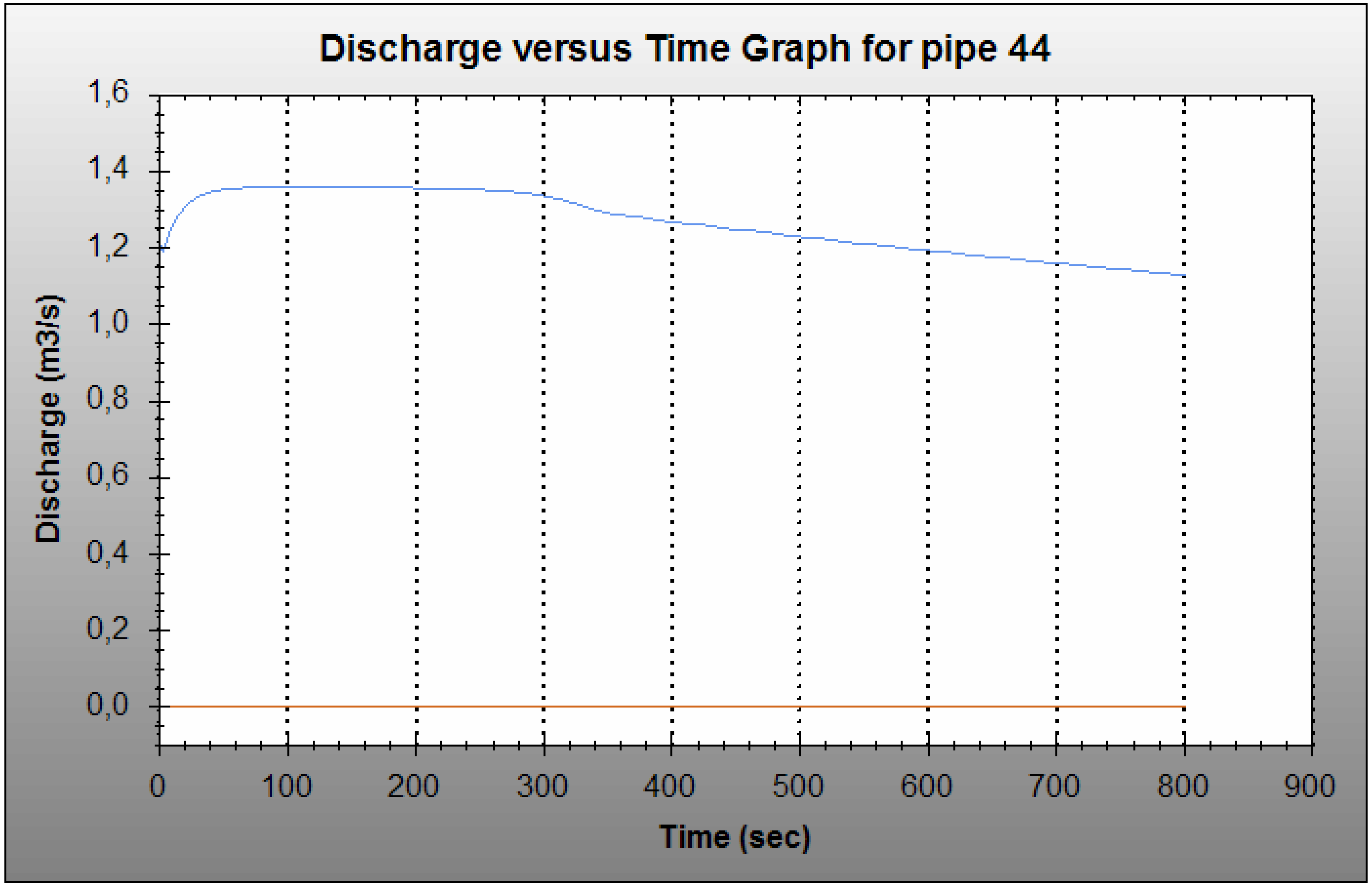


Figure 5.23 Discharge vs. Time History along Downstream of Air Vessel

5.1.6 Scenario 4 – Closing of Line Valves in Pigging Station – A Two-Parallel Pipeline Section Considered

In this scenario, pig station valves are closed in 340 seconds because of a possible pipe blast. In this scenario a pipeline section with two parallel pipelines of 87.5 km is considered between PS-5 and PS-4. One of these lines simulates the first installation of the system and the other line is considered to simulate a new installation. Both parallel lines has 46" diameter and have the same length. Effect of aging of line pipes is also considered by including the pipeline efficiency parameter into the simulations. Older line has an efficiency of 88% while the new installation has 100%. This case is indeed the first stage of a comparative study with case 5 which utilizes an air vessel in one of the parallel lines. Following figures represent the composed system in the computer program and the graphical results for two pipeline segments (12500 meters of each) in the middle of two parallel lines.

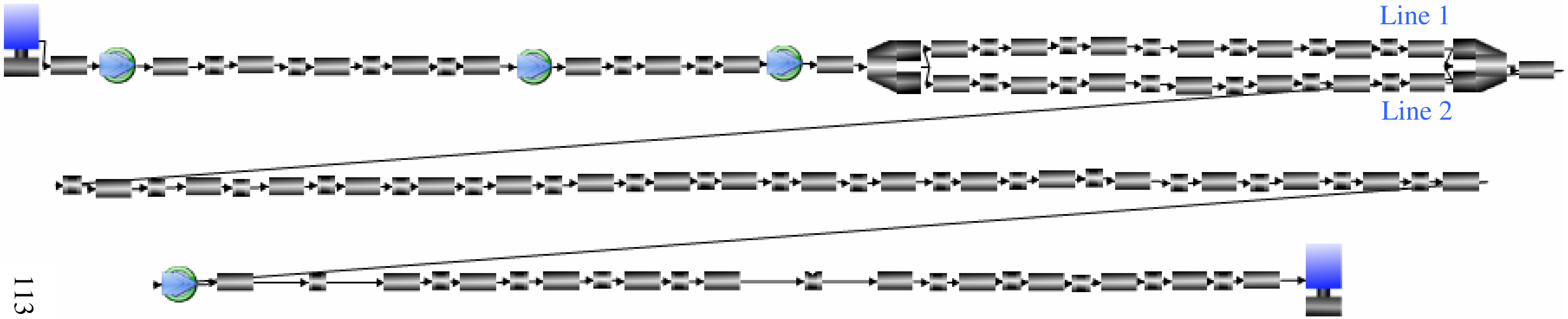


Figure 5.24 Mimic View of Scenario-4

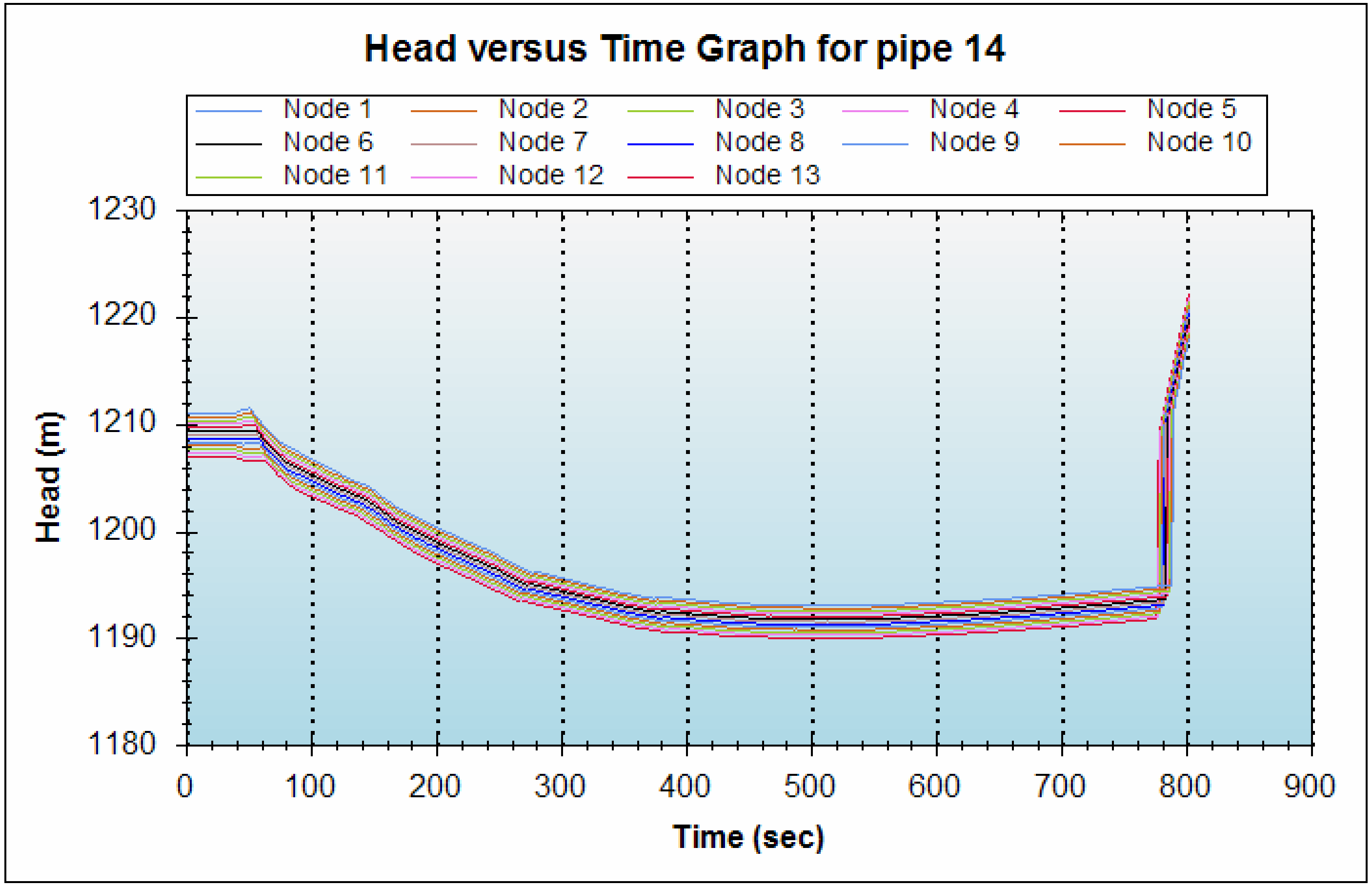


Figure 5.25 Pressure vs. Time History of 12500m section of Line 1

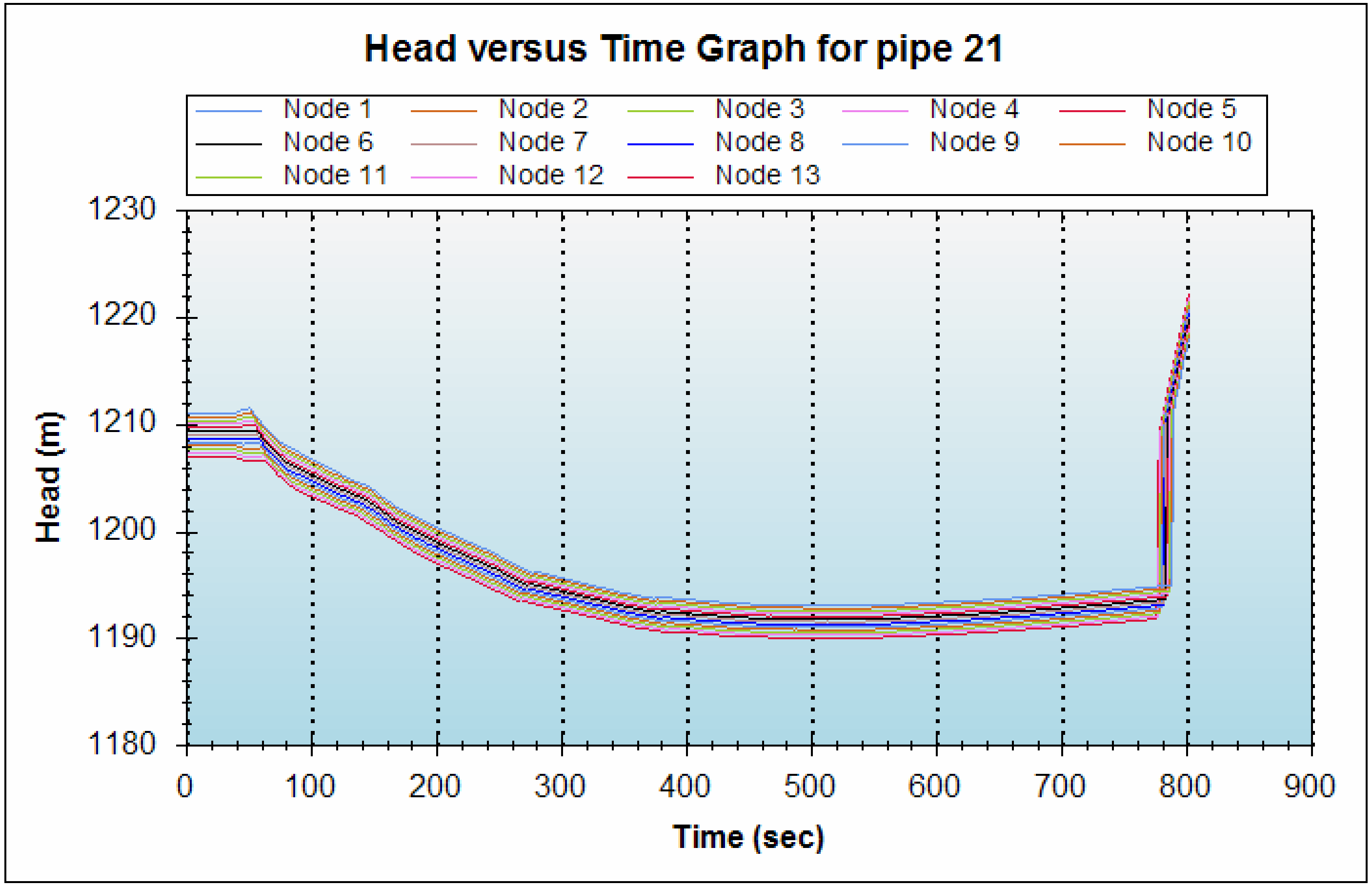


Figure 5.26 Pressure vs. Time History of 12500m section of Line 2

5.1.7 Scenario 5 – Closing of Line Valves in Pigging Station – A Two-Parallel Pipeline Section Considered – Air Vessel Installed

In this scenario, pig station valves are closed in 340 seconds because of a possible pipe blast. In this scenario, as in the scenario 4, a pipeline section with two parallel pipelines of 87.5 km is considered between PS-5 and PS-4. This scenario is a comparative study in order to observe the effect of an air vessel installed on one of the parallel lines. A 4000 m^3 air vessel is installed on Line 1 and the results are obtained for this configuration. Following figures represent the composed system in the computer program and the graphical results for two pipeline segments (12500 meters of each) in the middle of two parallel lines.

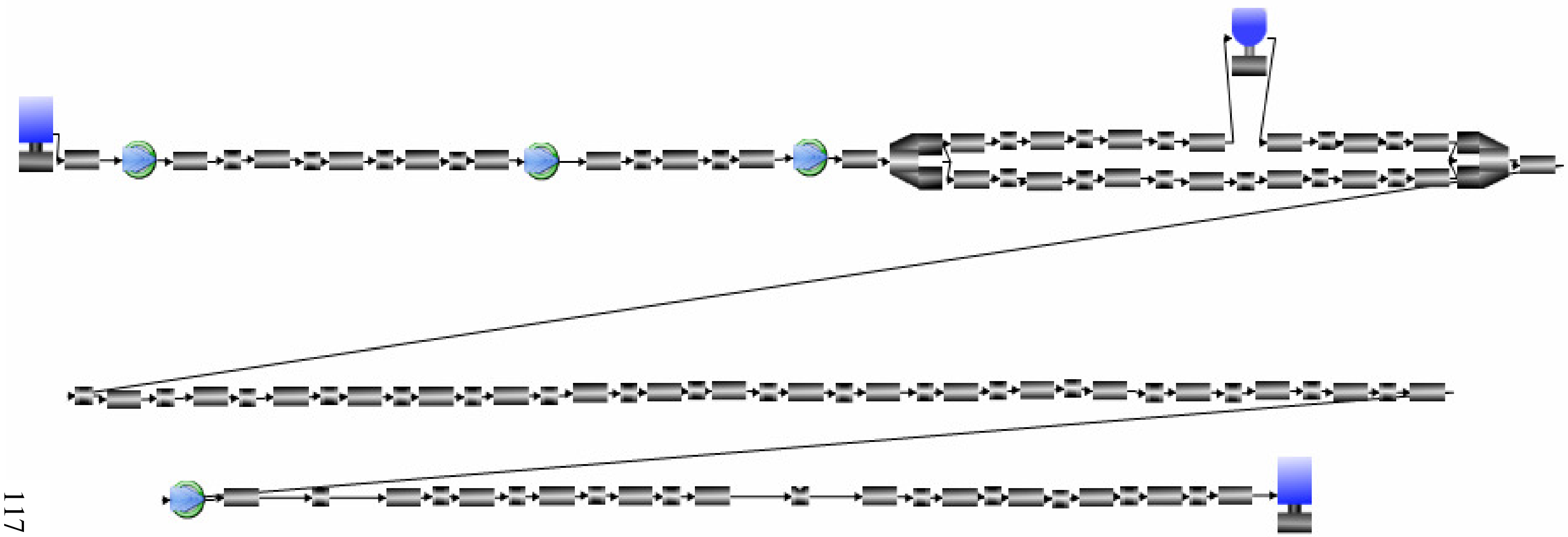


Figure 5.27 Mimic View of Scenario-5

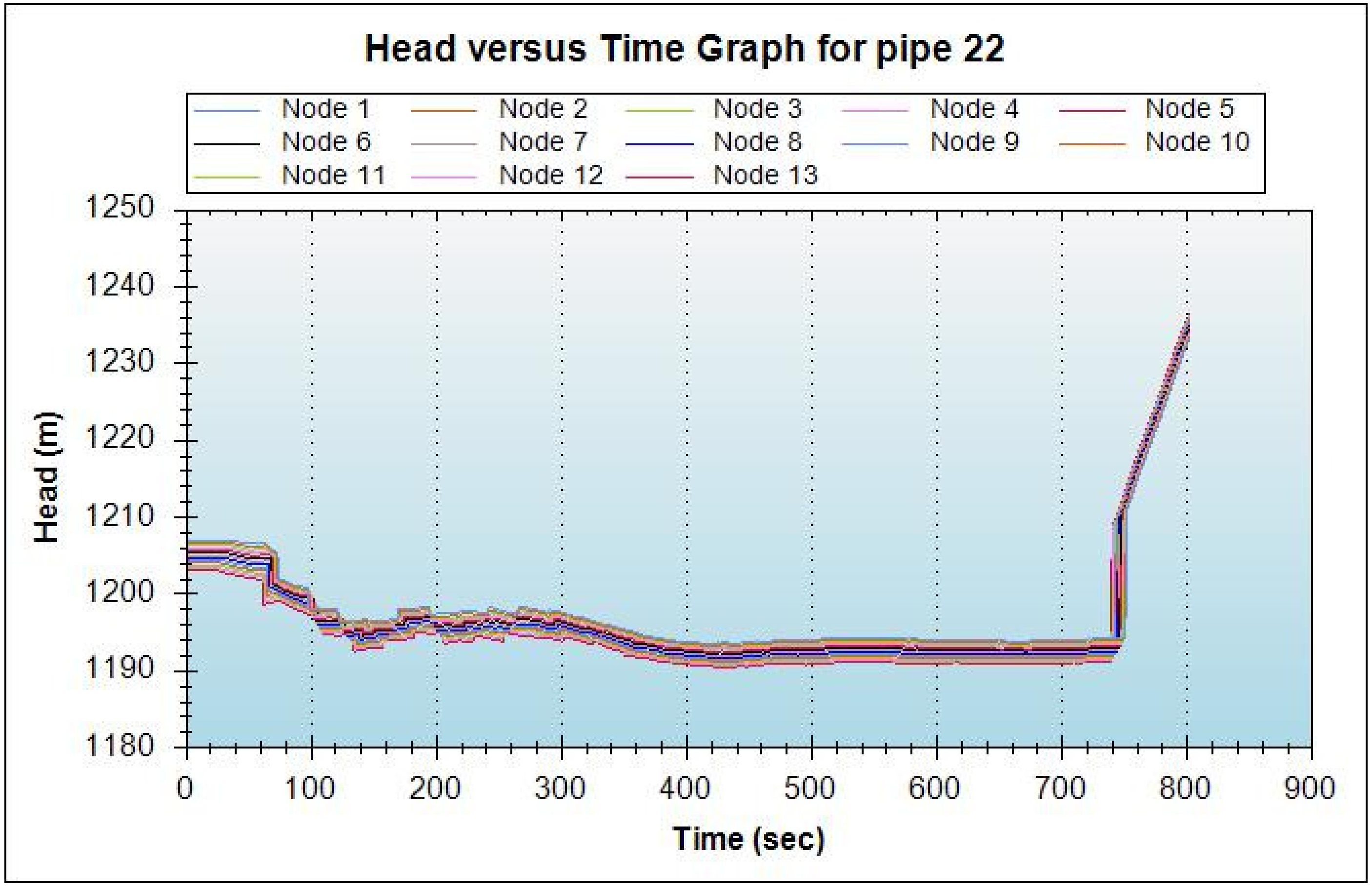


Figure 5.28 Pressure vs. Time History at the Middle Section of Line 2 Scenario-5

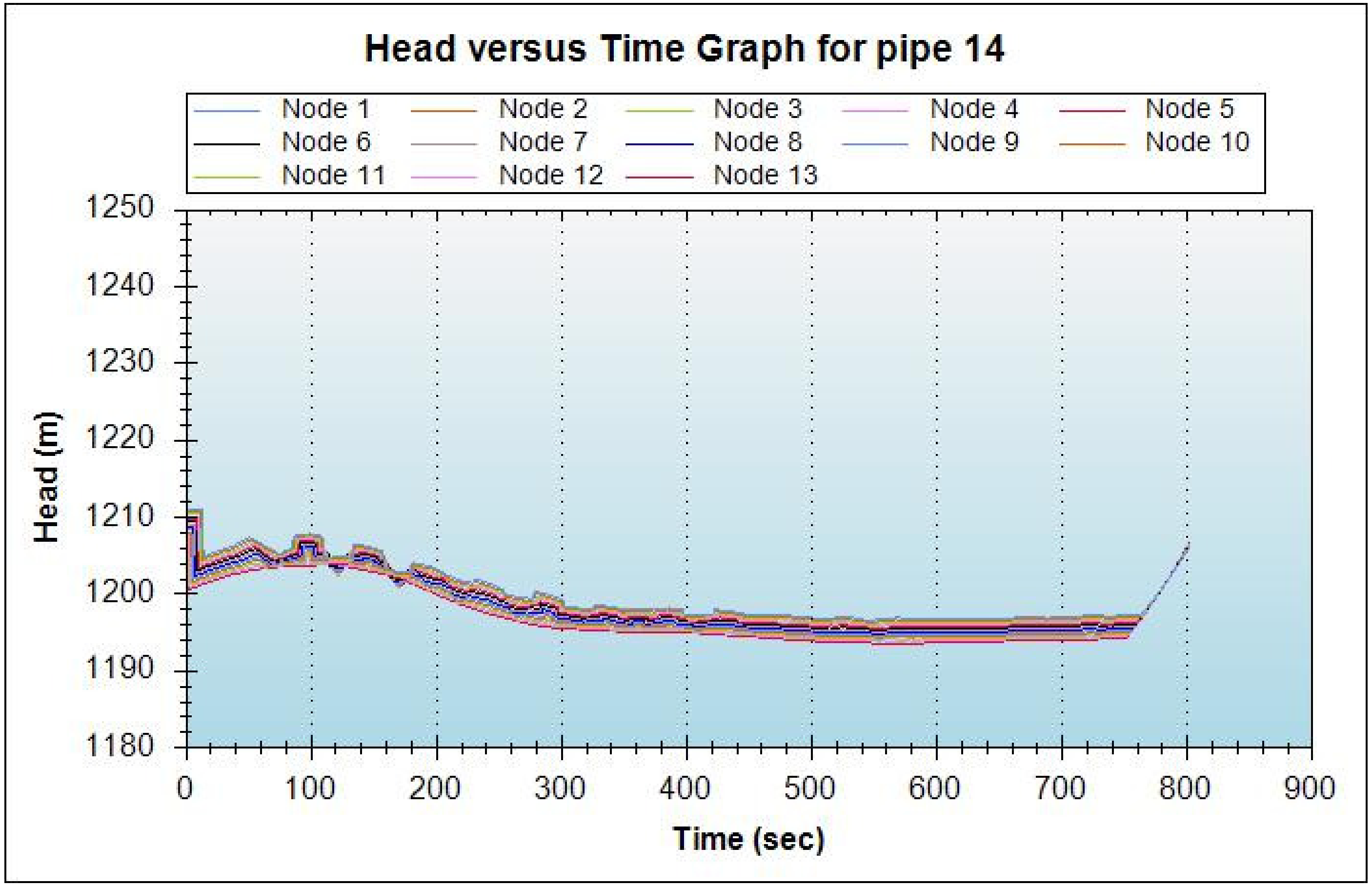


Figure 5.29 Pressure vs. Time History at the Middle Section of Line 1 Scenario-5

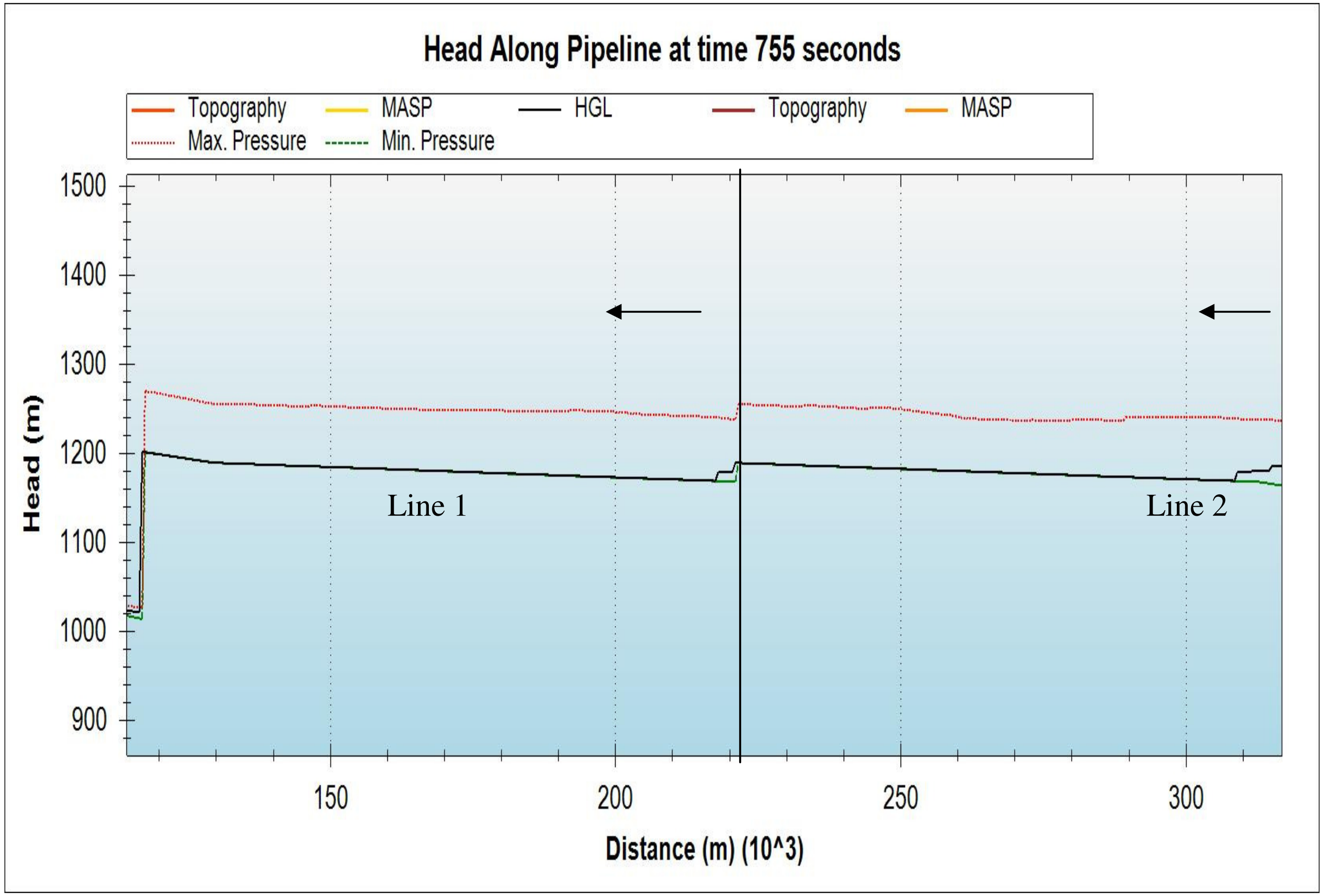


Figure 5.30 Instant of Transient Pressure Arrival at the Junction of two Parallel Lines

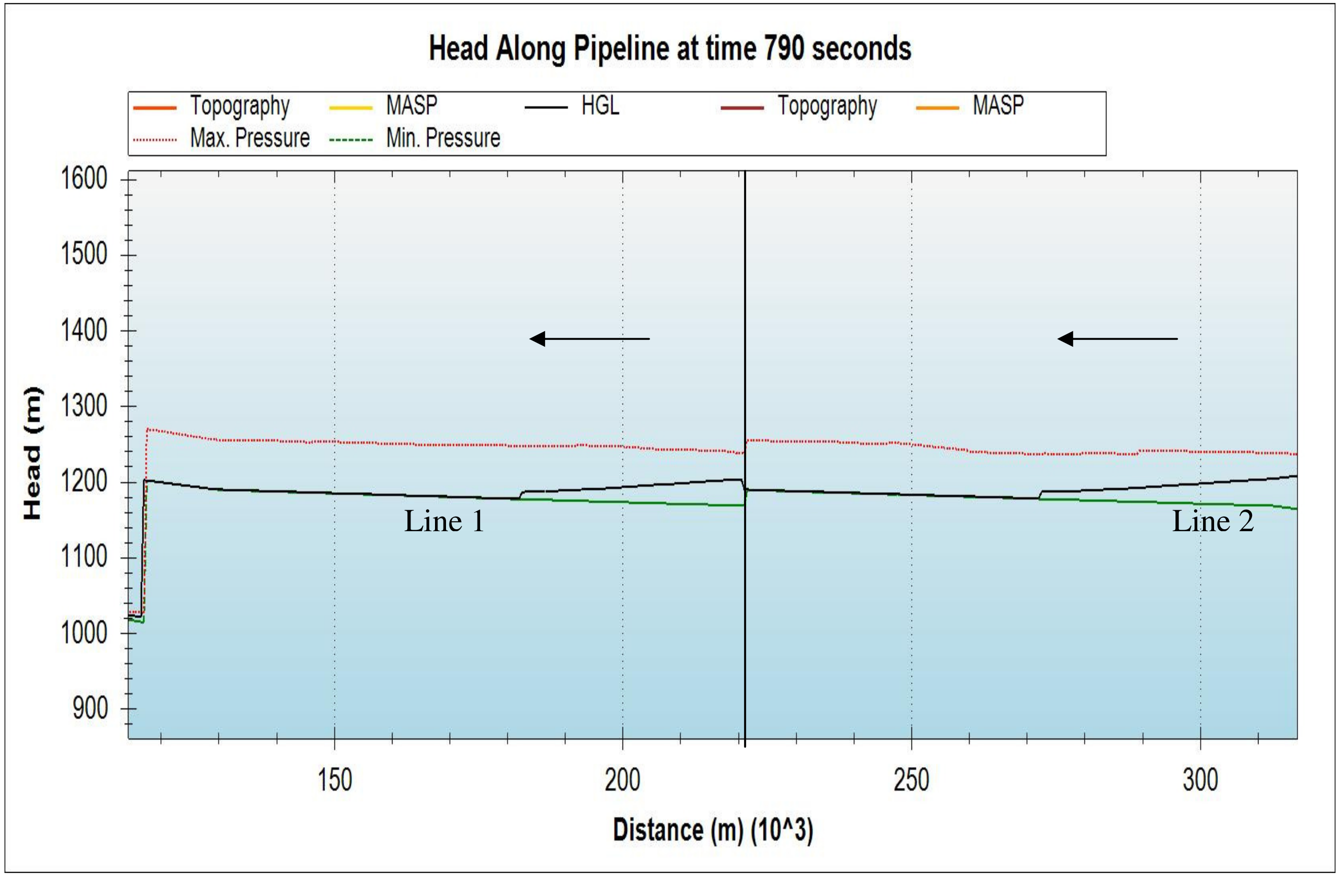


Figure 5.31 Propagation of Transient Pressure through two Parallel Lines

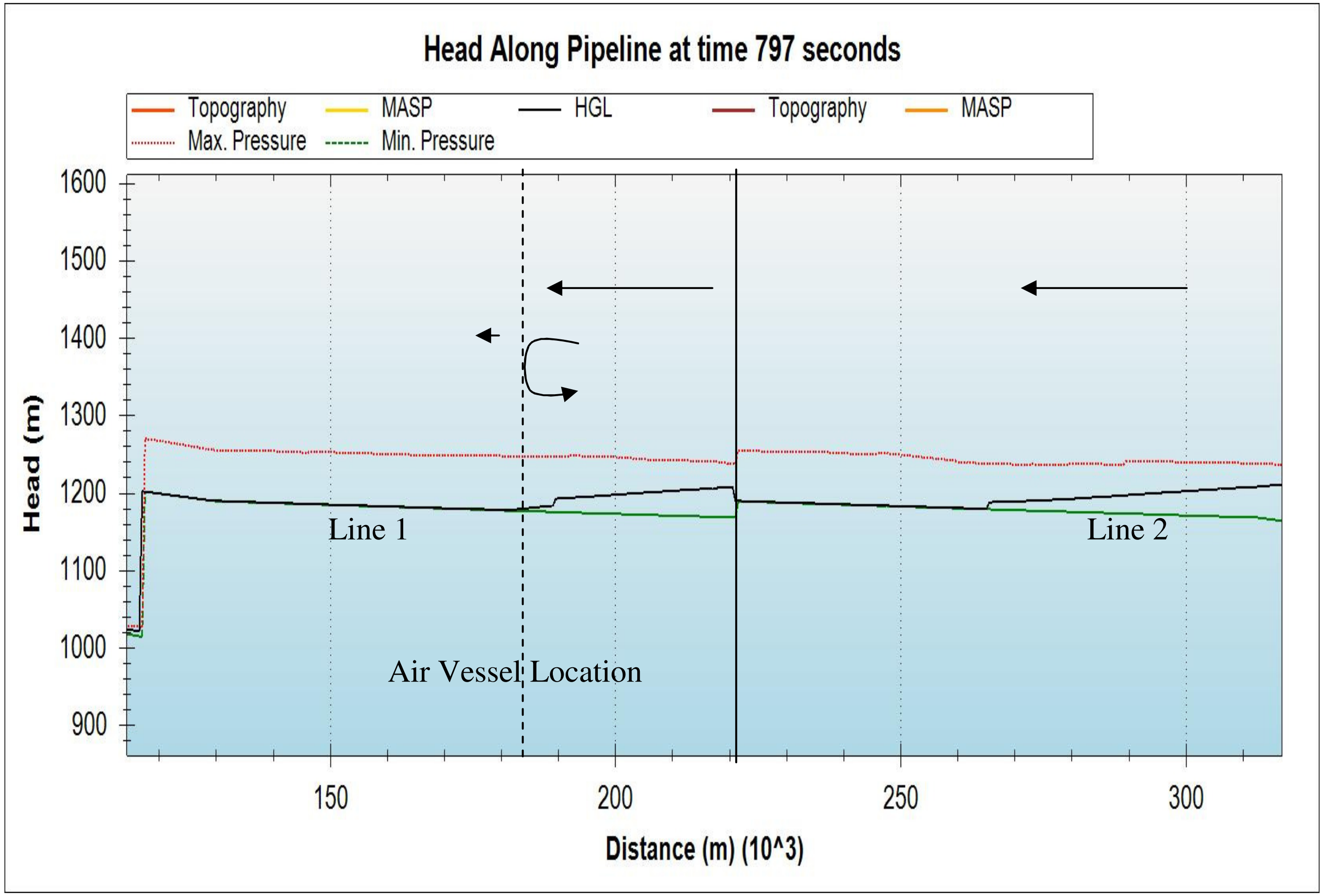


Figure 5.32 Propagation of Transient Pressure through two Parallel Lines

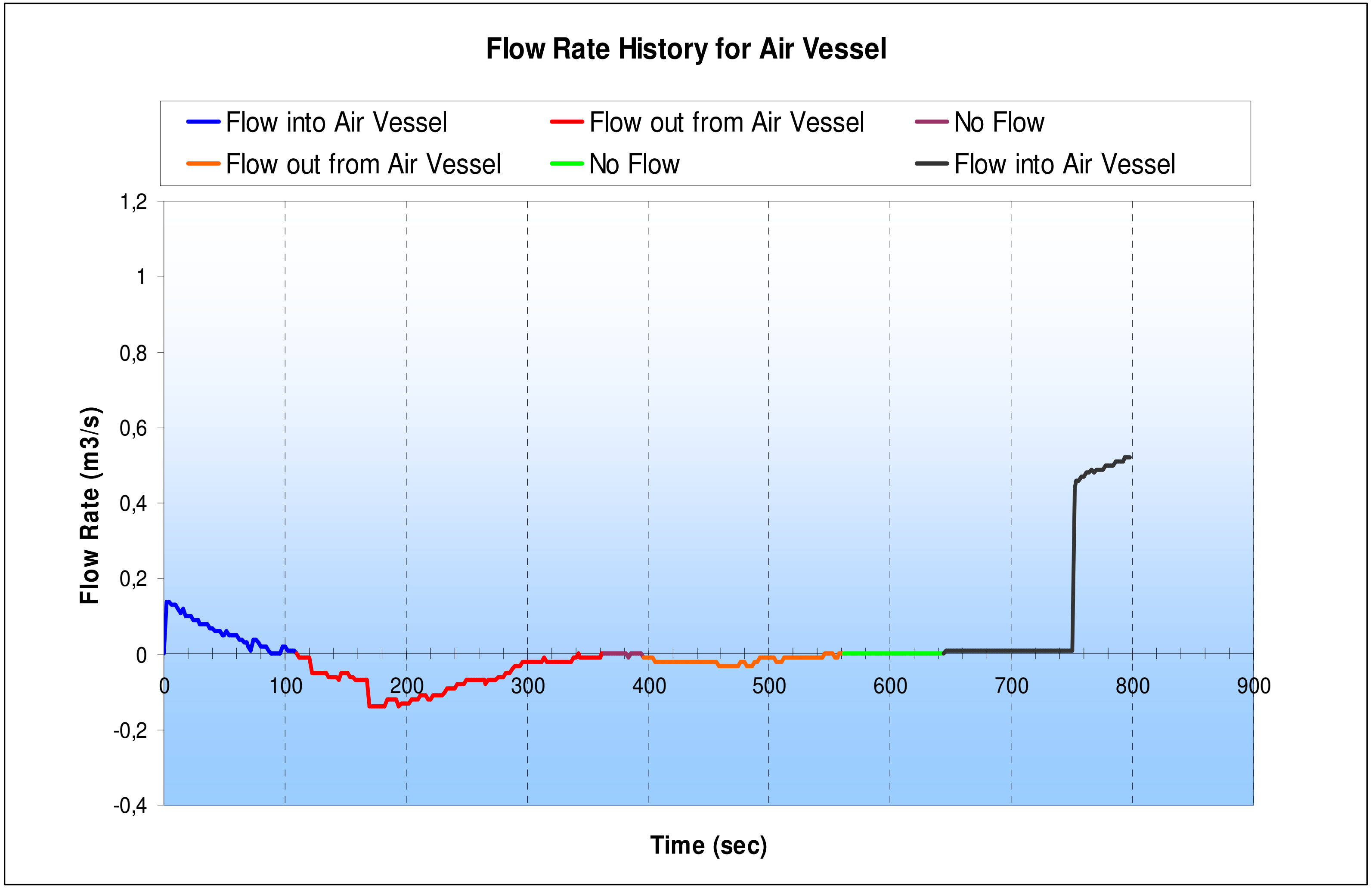


Figure 5.33 Flow Rate vs. Time History at the inlet of the Air Vessel for Scenario-5

5.2 Discussions on the Cases

In all transient scenarios, real system is mathematically modeled by the computer code. All pipeline systems can be represented by three main bodies. First of all, each section of the system should have an upstream boundary that defines the upstream head and discharge conditions throughout the transients.

In all the scenarios, upstream boundary of the system is the very beginning of the route with a constant head reservoir. In fact all pumping stations may be treated as upstream boundaries of the sections as long as the transients do not cross the pump station boundaries. However in the case study, shutting the station pumps down creates transient pressures on the upstream of the pumps so whole system should be considered in a single section.

Another main boundary type to be included into a system is the interior boundaries. Interior boundaries are the points where abrupt steady state changes are imposed to the system by means of pipeline components like pumps, valve in lines, surge tanks etc. These boundaries serve carrying the transient data from upstream of the boundary to downstream and from downstream of the boundary to upstream.

All scenarios have identical interior boundaries which consist of pumping stations and associated valves.

In all scenarios of the case study, pumping stations are treated as lumped systems meaning that they are treated as single pumps equivalent to 3 series pumps. This assumption is reasonable as long as the pumps in the station are identical and driven by the same actuator.

Finally all systems should have a downstream boundary in order to describe the downstream head and discharge during transients. Most of the time downstream boundaries are constant head reservoirs equipped with a valve.

In the scenarios of the case study, downstream of the line is a constant head reservoir that has a height equal to the steady state head of the end of the line.

In Scenario 1 of the case study, valve at the pigging station is closed gradually in 340 seconds. During the closure of the valve, positive surge pressure forms at the upstream of the valve and it propagates towards PS-5.

From the graphs showing pressure values at different times, it is possible to observe the line packing phenomena. In long pipelines or short high friction cases, line packing occurs. In case study, all scenarios are accompanied with line packing. Although the pressure at the upstream of the valve increases, flow is still directed towards the valve because the head of the upper portions of the line keep larger then the lower sections' head. As a result, pressure head continues to increase until the head values of the line get equal at each section.

It can also be observed from the graphs that, during the closure of the valve, there are no considerably high surge pressures. As soon as the valve is totally closed, since the flow is still into the valve, an abrupt pressure increase is observed at time 340 seconds. One can see that the pressure change at time 340 seconds is very similar to that of a downstream dead-end. A fully closed valve is in deed a downstream dead-end but with a reduced flow rate as in this case.

Pigging station valve is an interior boundary element rather then a downstream boundary element until it is totally closed. Downstream of the pig station valve is also effected by the closure of the valve. From the graphs presented for Scenario 1, it is possible to observe the effect of negative transient pressure.

After some time, high pressure waves reach to the downstream of PS-5 and increase the pressure up to the set point of the station. After the set point is reached, PS-5 pumps are shut down and associated valves are closed in the mean time. Red arrows on the graphs for suction and discharge side of PS-5 illustrates the time of station failure and the trend of transient pressures at failure instance.

After the closure of the pigging station valve and PS-5 valves, pipe segment between the pigging station and PS-5 becomes a two dead end pipe. Pressure waves keep traveling up and down in this section until all the wave magnitude is attenuated by friction.

In Scenario 2, the effect of valve closure on the line pressure is intended to be damped out by use of an air vessel. From the graphs, it can be seen that, an amount of positive pressures at the upstream of the pig station valve and negative pressures at the downstream of the valve are damped out slightly. However, it can be observed that the use of an air vessel at the downstream of the pump station PS-5, is not sufficient to cancel out all the transient pressure. For Scenario 2 also, red arrows on the graphs for suction and discharge side of PS-5 illustrate the time of station failure and the trend of transient pressures at failure instance.

In Scenario 3, an additional air vessel is utilized in order to damp out the effect of negative transient pressures at the downstream of the pig station. An air vessel with a volume of 4000 m^3 is simulated at the downstream of the pig station and it is observed that the air vessel well prevented negative pressures and line separation. Discharge at the downstream of the pig station and at the downstream of the air vessel are also compared in order to capture the flow rate variation into or out from the air vessel during transients.

In Scenario 4 and Scenario 5, a virtual parallel line of 85 km. is added to the system between PS-4 and PS-5. In these scenarios, wave propagation in parallel lines is simulated and the results are presented.

In Scenario 4, none of the parallel lines are protected by means of air vessel against transient pressures. From the pressure vs. time graphs for Scenario 4, it can be seen that no difference in line pressures for parallel sections occurred. Transient pressure wave initiated by the pump station travels upstream to the junction connecting two parallel lines and evenly propagates through both lines. This is the general situation that occurs in case of similar parallel pipelines as long as there are no abrupt pressure changes in any of the parallel lines.

In Scenario 5, on the other hand, an air vessel is utilized in one of the parallel lines, Line 1 called for the case, and the effect of air vessel on the line pressure for Line 1 and Line 2 is observed. Although the pressure values are not initially similar for two lines, by the time being they tend to converge to the same pressure level because of the effect of junctions that connect two parallel lines. When the pressure waves reach the junctions, pressure values at the junction converge to same levels. Form the graph showing flow rate variations at the air vessel junction, air vessel regulates the line pressure by rejecting liquid to the system and accepting liquid from the system which is seen as the negative and positive flow rate values on the graph.

In all scenarios of the case study, it is observed that the upstream section of the pump station PS-5 is a critical section at which pressure values exceed MASP. Although use of air vessels at discharge side of the pump stations protects pump stations, high pressures due to a possible pump trip must also be considered and larger thickness values, thus greater MASP values should be considered.

Volume and air content of air vessels are also important parameters for selecting transient prevention systems. Air vessel volume is directly related with the transient pressure values and flow rate values of the system.

In addition to using auxiliary pipeline elements, some operational precautions may be taken in order to cope with possible transient pressures. Selection of suitable valves, pumps and pipe materials, effects of transient events can be reduced and possible blasts can be prevented.

One of the common applications in case of valve closing events is intentionally tripping pumps at the upstream of the closing valve thus canceling out the positive pressures by the negative pressures initiated by the pump trip.

CHAPTER 6

DISCUSSIONS, CONCLUSIONS AND RECCOMENDATIONS

6.1 DISCUSSIONS

In this thesis, transient events in a pipe line are simulated based on user defined scenarios. These scenarios are generated with knowledge on pipeline operations. The simulation starts from a steady flow operating condition, calculated with pipeline and operating flow conditions. The pipeline is defined piecewise composed of pipe-sections, valves, pumps or pumping stations, storage or surge tanks, junctions to generate loops or branches, etc. behaviors of all these components are expressed in transient regime and solved together with the unsteady flow solution coming from pipe sections. Matching all these components available in a pipeline together with the generated scenario a complete transient solution is obtained by a special time-marching technique called "The Method of Characteristics".

Generated computer code and finally compiled computer program can hold a large number of components as long as the system is designed and modeled accurately. It is easier to handle the scenarios and the whole system by using an open code and interfere when necessary. So it is not wrong to say that transient scenarios should be simulated and handled rather in debug mode of an open code instead of a stand alone application. In this thesis, all the computer code is written by both MATLAB and C#. In MATLAB, there is not any user interface integrated and code is run in debug mode thus gives the opportunity for user interference. On the other hand, in C#, stand alone application does not allow user interference until the simulation is completed by the program.

One of the most critical points during transient simulation by help of a computer code is the stability. As long as the system parameters and the user defined mesh properties are not properly selected, it is very likely to have inaccurate results. By a crude assumption, the smaller the time increment, the more precise the results but it should be noted that for large number of meshes, computer time for simulation increases to unreasonable values.

Time profile of the code for different mesh sizes is given in the appendix. Scenario 2 of the case is profiled by using both 2.5 seconds time increments and 5 seconds increments, result a minimum recommended 3 meshes per pipe with 5 seconds increments and more meshes per pipe with 2.5 seconds time increments.

In both "time increment" cases, the smallest number of meshes recommended to be present in the system is 3, thus enough transient information is obtained from each pipe. Both solutions give nearly identical results but the run with 2.5 seconds time increments costs much more CPU time then the 5 second time increment case. CPU time profiles of two different time increment cases are presented in Appendix B.

Another critical point while simulating transient flow in liquid pipeline systems is the minor changes in pipeline. Effect of a diameter change is easily predictable as it causes a considerable large change in the flow velocity thus in the transient pressures. On the other hand small changes in the pipeline properties like friction factor and thickness also causes small changes in the transient parameters that leads to a continuously fluctuating head pattern in the system. As long as the pipeline does not have a constant diameter, a constant friction factor and a constant thickness throughout, it is impossible to observe smooth transient pressures. All graphs related to scenarios show that there are always small fluctuations in the transient pressure head values.

An interior boundary element called "series junction" is modeled between each pipe which creates a common node for two connected pipes. It should be noted that it is better to use a single pipe whenever possible in order to decrease the number of series junction in the system. It is only possible when two pipes have a series connection at a junction have nearly same geometric and hydraulic properties. In addition, connection of more then two pipes in a junction, result a branch or a loop, is modeled by “Branching Connection” boundary condition. This boundary condition can handle different number of pipes incoming to and outgoing form the junction.

Wave speed is another important parameter in transient situations as it caries all the information. It is a function of fluid and pipe properties and it is rarely known exactly. In order to have integer values for number of meshes, relaxation can be applied on the wave speed and an average wave speed can be used throughout the pipeline. In the computer program developed in this thesis, it is possible to define speed of sound for each pipe or use an average speed of sound for all the pipes.

Pump stations are also important boundary elements and should be modeled accurately. Simulation of a transient scenario with a tripping pump requires enough characteristics data for minimum possible linearization assumption between data intervals. This data consist of torque and head characteristics values in nondimensional form. Most of the time it is impossible to obtain the correct data for a pump and test data or generic data about pumps is used. In this thesis pump stations are modeled as lumped elements consisting of pumps and related valves. It is a good approach to model identical pumps going through same transients as single units with modifying their discharge or head data in parallel and series pump configuration respectively.

Piping networks are also considered in the thesis. Although steady state solution of complex networks cannot be obtained by the code, as long as steady state values of loops in the network are supplied to the program, transient solution of the loops can be simulated for networks of any complexity.

Transient flow in networks can be modeled easily by using branching junctions consisting of any number of pipes into or out from the junction as long as the steady state values of all loop elements are obtained accurately. These pipes and junctions are handled by the program with a different procedure and mapped into the remaining system values.

6.2 CONCLUSIONS

In pipeline design it is always necessary to analyze the system for unsteady flow conditions. It is generally hard to predict possible transient events but a pipeline operations experience can give ideas about possible surge events. These possibilities should be considered during design and operation phases of the pipelines.

People generally tend to use some auxiliary pipeline components in order to cope with the transient situations and their consequences. Another approach to transients should be parametric studies on main pipeline components like pipes, pumps and valves. By choosing proper valve and pump types, effects of transients may be damped and security of the operations can be provided without the necessity of auxiliary pipeline components. On the other hand one should keep in mind that, parametric studies on pumps, pipes and valves strongly requires energy and operation cost optimizations. After necessary optimization is done for the design, one can decide on the component properties to be used in the pipeline.

Simulating any dynamic, static or hydraulic system before design and operation is an invincible necessity for the last few years because simulation helps save time and money. A virtual system with compatible properties to the actual system can be constructed and modeled by the help of computer software and possible scenarios can be considered before the construction of the real system.

On the other hand, experimentations conducted on different actual pipeline systems provide a very important amount of knowledge that verifies the theoretical studies and numerical methods applied for simulating transients.

In the appendix, two verification studies are presented, results of which are compared with the results of two example codes in literature.

By the computer program developed in this thesis, one can simulate different situations that may cause transient flow in the system.

6.3 RECOMMENDATIONS

There are different theses related to pipeline engineering in the Department of Mechanical Engineering in METU. These theses are about computer aided design optimization of pipelines, computer aided energy optimization on steady state operation of an existing pipeline and simulation of unsteady flow in crude oil pipelines [11]. All these theses can be combined under a computer program that would have the capability of solving complex networks, steady state design and unsteady flow check of a design.

One of the most frequent flow situations in pipelines is slack line operation in which the liquid flows in the pipeline freely. Many times, an amount of excess head is allowed at high points of the route in order to prevent slack line. In transient situations there is also a possibility of slack line flow so special attention should be given to slack line possibilities. Slack line in transient analysis can be considered in detail and a procedure may be developed to analyze and handle slack line flow situations.

In addition to the above stated capabilities, an RF system can be designed and integrated to the developed computer program that communicates with the sensors located on the pipeline and holds the necessary operational precautions.

A data acquisition study would help developing a complete set of a computer program that designs, simulates and even controls the operations of a pipeline.

All studies carried out for liquid pipeline systems can also be carried out for natural gas pipeline systems.

As a final recommendation, case studies about energy centrals and pumping stations may be carried out in order to get familiar with the movement of waves in short conduits and the effects of these movements. Different valve operations and transient events may be helpful in understanding the physics of pressure waves in shorter distances then the speed travels in a unit of time.

REFERENCES

1. WYLIE, E.B. and STREETER, V.L., "Fluid Transients", McGraw Hill Book Co., New York, 1978
2. Hadj-Taieb, E. and Lili, T., "Transient flow of homogenous gas-liquid mixtures in pipelines", *International Journal of Numerical Methods for Heat & Fluid Flow, Vol.8, No.3, 1998, pp.350-368*
3. Chaudry, M.H., "Applied Hydraulic Transients", Van Nostrand Reinhold Company Inc., 1986
4. Parmakian, J., "Waterhammer Analysis", Dover Publications Inc., 1963
5. Adamkowski, A., "Analysis of Transient Flow in Pipes With Expanding or Contracting Sections", *Institute of Fluid Machinery, Polish Academy of Sciences*, Vol.125, 2003, pp. 716-722
6. Wang, K., Shen, Q., Zhang, B., "Modeling Propagation of Pressure Surges with Formation of an Air Pocket in Pipelines", *Computers & Fluids, 32,* 2003, pp. 1179-1194
7. Bergant, A., Simpson, A.R., Tijsseling, A.S., "Water Hammer with Column Separation : A Historical Review", *Journal of Fluids and Structures, No: 22, 2006, pp.135-171*
8. Yang, K., "Practical Method to Prevent Liquid-Column Separation", *Journal of Hydraulic Engineering, July 2001*
9. Tijsseling, A.S., "Water Hammer with Fluid-structure Interaction in Thick-walled Cylinders", *Computers & Structures, January 2007*
10. Abhulimen, K.E., and Susu, A.A., "Liquid Pipeline Leak Detection System: Model development and Numerical Simulation", *Chemical Engineering Journal, No:97, 2004, pp.47-67*
11. Aksel, E.A., "Simulation of Unsteady Flow in Liquid Pipelines", M. Sc. Thesis, Middle east Technical University, Ankara, May 1991

12. Shimada, M., Brown, J., Vardy, A., "Estimating Friction Errors in MOC Analyses of Unsteady pipe Flows", *Computers & Fluids, No:36, 2007, pp.1235-1246*
13. Oakleigh Software, "Pipe Flow Software", www.pipeflow.co.uk, June 2007, last accessed on June 2007.
14. Fletcher, C.A.J., "Computational Techniques For Fluid Dynamics *2",*2006
15. ERALP, O.C., "Pipeline Engineering Class Notes", 2006
16. American Water Works Associations (AWWA) Manual, M11, 1982
17. Larock, B.E., Jeppson, R.W., Watters, G.Z., "hydraulics of Pipeline Systems", *CRC Press, New York, 2000*
18. Help Documentation of MATLAB 2006a, Mathworks Inc.
19. Help Documentation of Visual Studio 2005, Microsoft Corp.
20. Adamkowski, A., "Case Study : Lapino Powerplant Penstock failure", *Journal of Hydraulic Engineering, July 2001, pp.555*

APPENDIX A

Code Verification

Two example problems are solved with the computer program developed in this thesis. These example problems simulate closing of a downstream valve in two different pipeline systems.

Problem 1

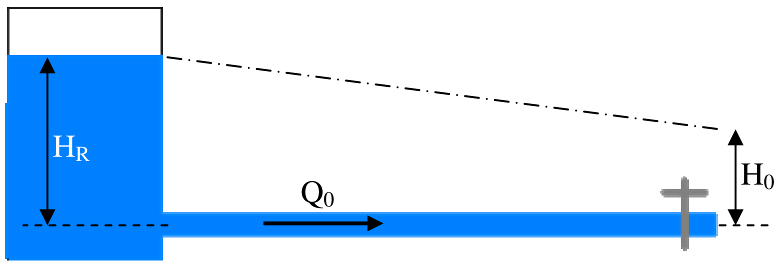


Figure A1 Schematic of Example 1

System data

Length of the Line: 600 m

Diameter of the Line: 0.5 m

Speed of Sound: 1200 m/s

Upstream Reservoir Head: 150 m

Friction Factor: 0.018

Transient Duration: 4.3 s

Valve Closure Time: 2.1 s

Steady State Discharge of Valve: 0.4773 m^3/s

Initial Valve Opening: %100

E_M: 1.5

Valve Opening vs. Time Function: $tau = \left(1 - \frac{t}{t_c}\right)^{E_M}$

Computer Model of the Problem in Developed Computer Program

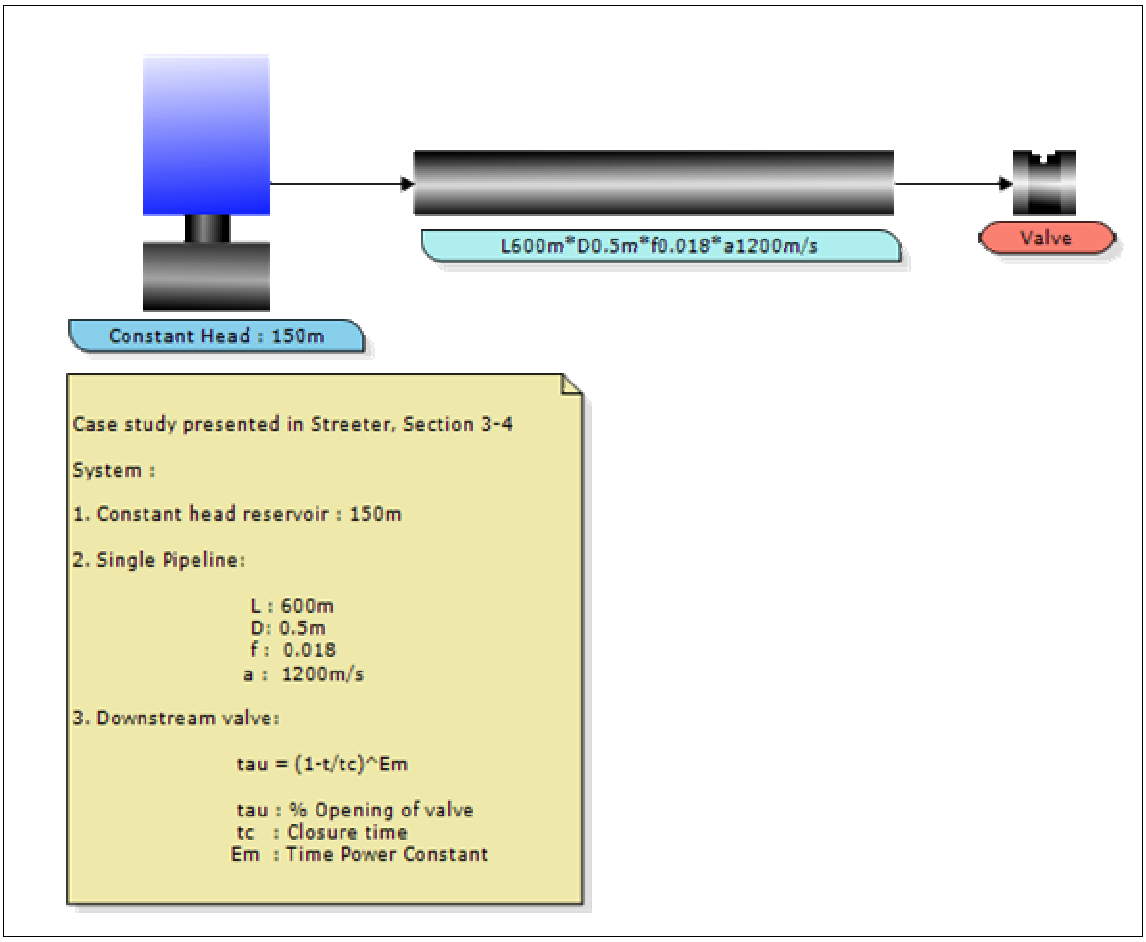


Figure A2 Computer Model of Verification Example 1

Obtained results are tabulated below.

Table A1 Code Verification Results by Problem 1

Koç					
150	148,7	147,4	146,1	144,8	143,5
150	148,7	147,4	146,1	144,8	154,29
150	148,7	147,4	146,1	155,54	165,79
150	148,7	147,4	156,79	166,99	178,07
150	148,7	158,05	168,2	179,23	191,09
150	159,3	169,41	180,39	192,2	204,89
150	170,61	181,54	193,31	205,95	219,41
150	172,19	194,42	207,01	220,42	234,67
150	173,79	197,61	221,43	235,63	250,55
150	175,4	200,79	226,16	251,47	267,07
150	176,99	203,94	230,8	257,54	284,06
150	178,53	206,98	235,29	263,36	284,72
150	179,99	209,87	239,52	262,47	283,35
150	181,34	212,52	237,04	259,52	279,73
150	182,53	208,51	232,53	254,32	273,56
150	177,18	202,55	225,8	246,58	264,62
150	170,03	194,47	216,61	236,11	252,63
150	167,3	184,09	204,79	222,67	237,38
150	164,06	177,61	190,15	206,07	218,67
150	160,32	170,13	178,9	186,16	196,3
150	156,07	161,62	166,15	169,14	170,09
150	151,3	152,1	151,87	150,09	152,19
150	146,04	141,57	136,05	134,93	133,45
150	140,27	130	124,64	119,42	117,67
150	133,97	123,35	113,38	107,39	105,39
150	133,09	117,36	106,11	99,36	97,1
150	133,38	115,84	103,33	95,82	93,32

streeter					
150	148,7	147,4	146,09	144,79	143,49
150	148,7	147,4	146,09	144,79	154,28
150	148,7	147,4	146,09	155,53	165,79
150	148,7	147,4	156,79	167	178,08
150	148,7	158,05	168,2	179,24	191,11
150	159,3	169,41	180,4	192,22	204,93
150	170,62	181,56	193,33	205,99	219,46
150	172,21	194,45	207,05	220,47	234,73
150	173,81	197,64	221,49	235,7	250,64
150	175,42	200,83	226,22	251,56	267,17
150	177,01	203,99	230,87	257,54	284,19
150	178,56	207,04	235,38	263,47	284,87
150	180,02	209,94	239,52	262,6	283,51
150	181,37	212,59	237,15	259,57	279,9
150	182,57	208,59	232,65	254,47	273,74
150	177,22	202,63	225,92	246,74	264,8
150	170,07	194,56	216,73	236,27	252,81
150	167,34	184,17	204,91	222,82	237,56
150	164,11	177,69	190,26	206,22	218,84
150	160,36	170,2	178,9	186,29	196,45
150	156,1	161,68	166,23	169,24	170,2
150	151,32	152,14	151,93	150,16	152,27
150	146,05	141,59	136,08	134,96	133,48
150	140,27	130,01	124,64	119,41	117,66
150	133,96	123,33	113,34	107,34	105,35
150	133,06	117,31	106,04	99,28	97,02
150	133,34	115,77	103,25	95,72	93,22

Problem 2

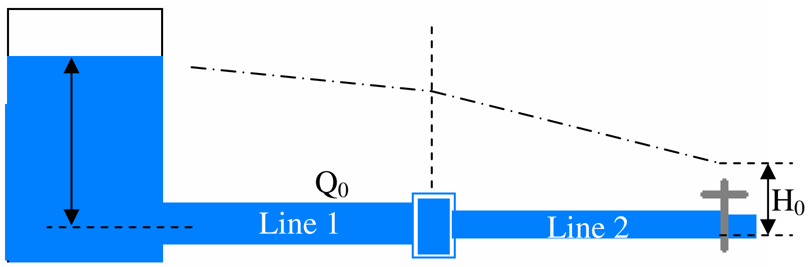


Figure A3 Schematic of Example 2

Length of the Line 1: 550 m

Diameter of the Line 1: 0.75 m

Speed of Sound in Line 1: 1100 m/s

Friction Factor of Line 1: 0.010

Length of the Line 2: 450 m

Diameter of the Line 2: 0.6 m

Speed of Sound in Line 2: 900 m/s

Friction Factor of Line 2: 0.012

Upstream Reservoir Head: 67.7 m

Steady State Head loss Across the Valve: 60 m

Transient Duration: 10 s

Steady State Discharge of Valve: 1 m^3/s

Initial Valve Opening: %100

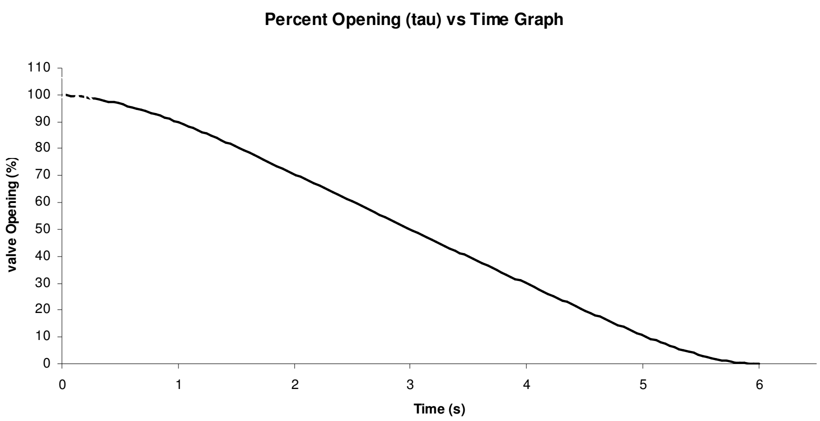


Figure A4 Closure Function of Downstream Valve – Example 2

Computer Model of The Problem in Developed Computer Program

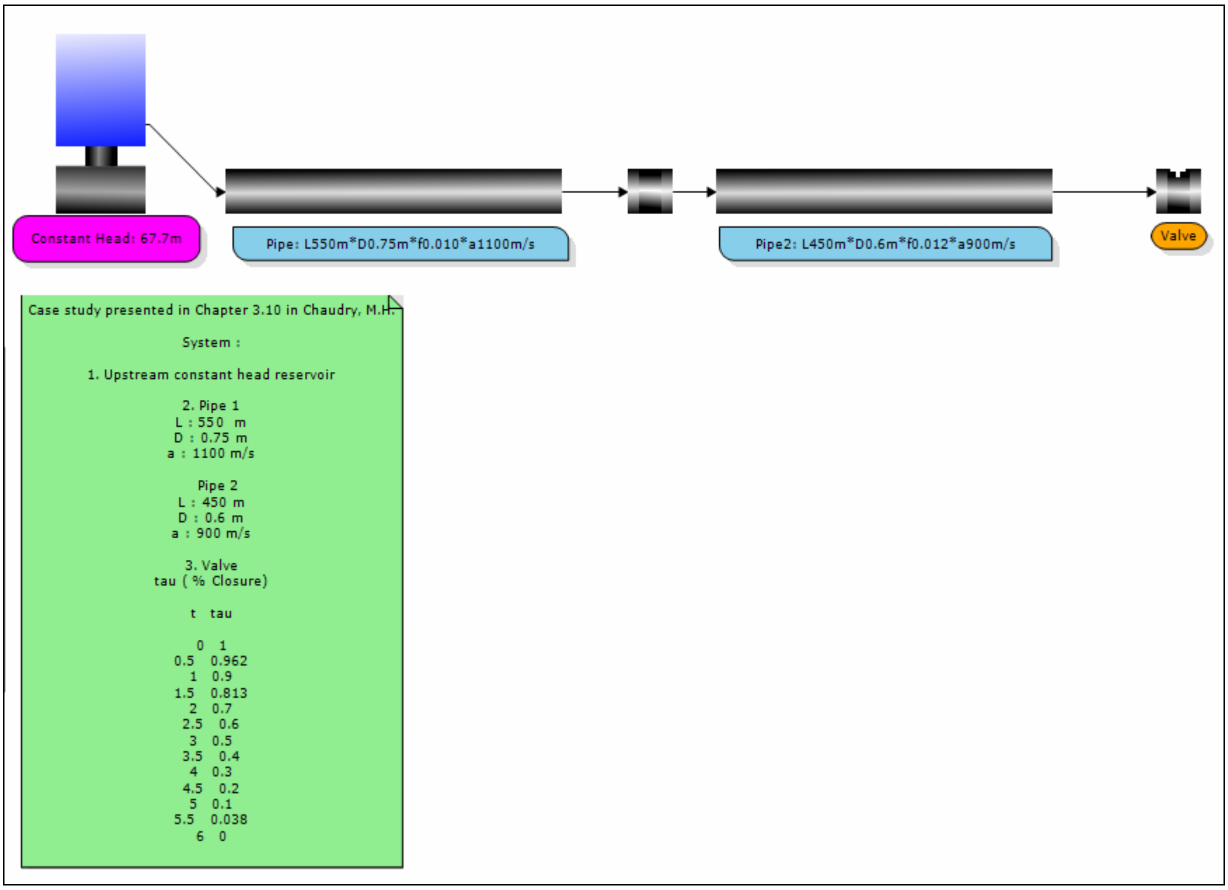


Figure A5 Computer Model of Verification Example 2

Obtained results are tabulated below,

Table A2 Code Verification Results by Problem 2

Chaudry				Koç			
Node1	**Node3**	**Node1**	**Node3**	**Node1**	**Node 3**	**Node1**	**Node3**
67,7	65,78	65,78	60,05	67,7	65,78	65,78	60,05
67,7	65,78	65,78	63,46	67,7	65,79	65,79	63,51
67,7	68,73	68,73	69,78	67,7	68,78	68,78	69,78
67,7	74,16	74,16	79,88	67,7	74,16	74,16	79,81
67,7	79,93	79,93	95,83	67,7	79,83	79,83	95,83
67,7	88,25	88,25	110,41	67,7	88,25	88,25	110,37
67,7	94,96	94,96	125,13	67,7	95,03	95,03	125,13
67,7	99,19	99,19	139,2	67,7	99,19	99,19	139,28
67,7	104,41	104,41	149,14	67,7	104,4	104,4	149,14
67,7	108,47	108,47	158,61	67,7	108,47	108,47	158,59
67,7	111,2	111,2	165,65	67,7	111,18	111,18	165,65
67,7	113,07	113,07	149,46	67,7	113,06	113,06	149,2
67,7	96,01	96,01	114,27	67,7	95,79	95,79	114,27
67,7	63,25	63,25	61,79	67,7	63,25	63,25	61,86
67,7	34,25	34,25	12,33	67,7	34,52	34,52	12,33
67,7	23,55	23,55	6,74	67,7	23,55	23,55	7,22
67,7	47,63	47,63	34,76	67,7	47,77	47,77	34,76
67,7	82,89	82,89	88,45	67,7	82,89	82,89	88,26
67,7	105,95	105,95	130,93	67,7	105,64	105,64	130,93
67,7	108,02	108,02	123,44	67,7	108,01	108,01	123,01
67,7	78,39	78,39	85,13	67,7	78,32	78,32	85,13

APPENDIX B

Time Profiling

Profile Summary

Generated 24-Aug-2007 14:34:21 using cpu time.

Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
SCENARIO_EDITOR	1	282.546 s	31.345 s	
fncInteriorNodes	15120	115.872 s	115.872 s	
fncSeriesJunction	12960	97.439 s	97.439 s	
xlsread	10	16.652 s	2.611 s	
xlsread>parse_data	10	10.174 s	10.120 s	
fncSinglePumpNoFailure	1151	8.319 s	8.319 s	
fncSteadyState	1	8.191 s	0.072 s	
tblWB	2	5.544 s	0.134 s	
actxserver	10	3.652 s	3.603 s	
tblWH	2	3.139 s	0.015 s	
fncDownstreamConstantHeadReservoir	360	2.753 s	2.753 s	
fncValveInLine	360	2.691 s	2.691 s	
fncSinglePumpFailure	289	2.673 s	2.673 s	
fncUpstreamConstantHeadReservoir	360	2.640 s	2.640 s	
newplot	360	1.912 s	0.085 s	
newplot>ObserveAxesNextPlot	360	1.775 s	0.051 s	
graphics\private\clo	360	1.724 s	1.084 s	
setdiff	720	0.573 s	0.448 s	
xlsread>activate_sheet	10	0.165 s	0.165 s	
ismember	360	0.092 s	0.092 s	
findall	360	0.058 s	0.058 s	
xlsread>trim_arrays	10	0.054 s	0.054 s	

Figure A6 Time Profile for dt = 2.5 seconds (Output of MATLAB)

Profile Summary

Generated 24-Aug-2007 14:43:16 using cpu time.

Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
SCENARIO_EDITOR	1	40.051 s	3.593 s	
xlsread	10	14.039 s	1.608 s	
xlsread>parse_data	10	10.129 s	10.114 s	
fncSeriesJunction	6480	10.052 s	10.052 s	
fncInteriorNodes	7560	9.574 s	9.574 s	
fncSteadyState	1	7.948 s	0.060 s	
tblWB	2	3.163 s	0.019 s	
tblWH	2	3.022 s	0.015 s	
actxserver	10	2.157 s	2.156 s	
fncSinglePumpNoFailure	575	0.930 s	0.930 s	
newplot	180	0.573 s	0.020 s	
newplot>ObserveAxesNextPlot	180	0.532 s	0.014 s	
graphics\private\clo	180	0.518 s	0.351 s	
fncSinglePumpFailure	145	0.347 s	0.347 s	
fncValveInLine	180	0.299 s	0.299 s	
fncDownstreamConstantHeadReservoir	180	0.279 s	0.279 s	
fncUpstreamConstantHeadReservoir	180	0.273 s	0.273 s	
setdiff	360	0.141 s	0.084 s	
xlsread>activate_sheet	10	0.095 s	0.095 s	
iofun\private\validpath	10	0.049 s	0.009 s	
ismember	180	0.034 s	0.034 s	
fileparts	10	0.029 s	0.026 s	
findall	180	0.024 s	0.024 s	

Figure A7 Time Profile for dt = 5.0 seconds (Output of MATLAB)