Water Hammer: An Analysis of Plumbing Systems, Intrusion, and Pump Operation

Shawn Batterton

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Civil Engineering

Dr. G.V. Loganathan
Dr. Vinod Lohani
Dr. David F. Kibler

July 7 2006
Blacksburg Virginia

Keywords: Water Hammer, Plumbing, Intrusion, Pump Operation

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Abstract

This thesis provides a comprehensive look at water hammer with an emphasis on home plumbing systems. The mathematics of water hammer are explained, including the momentum and continuity equations for conduits, system construction, and the four-point implicit finite difference scheme to numerically solve the problem. This paper also shows how the unsteady momentum and continuity equations can be used to solve water distribution problems instead of the steady-state energy and continuity equations, along with the examples problems which show that an unsteady approach is more suitable than the standard Hardy-Cross method. Residential plumbing systems are examined in this paper, household fixtures are modeled for their hydraulic functions, and several water hammer simulations are run using the Water Hammer and Mass Oscillation program (WHAMO). It is determined from these simulations that the amount of air volume in the system is a key factor in controlling water hammer. Abnormal pump operation is clearly explained including a description of the four quadrants and eight zones of operation as well as the mathematics and a numerical scheme for computation. Low pressures caused by transients can lead to intrusion and contamination of the drinking water supply. Several scenarios are simulated using the WHAMO program and cases are provided in which intrusion occurs. From the intrusion scenarios, key factors for intrusion to occur during transients include the starting energy in the system, the magnitude of the transient, the hydraulics of the intrusion opening, and the external energy on the pipe (the level of the groundwater table). A primer for using WHAMO is provided as an appendix as well.

Acknowledgements

I heard once before that when you reach a significant achievement in your life, you should stop and take time to thank the people who helped along the way. I don't remember where I heard this but I feel it is a wise saying, and as I conclude this thesis I have many people to thank. First I would like to thank my advisor, Dr. Loganathan. The time, effort, and care he put into this work were amazing and very much appreciated. I'd also like to thank the other members of my thesis committee, Dr. Lohani and Dr. Kibler for their guidance and support. I'd like to say thanks my fellow classmates and colleagues here in the hydro-systems program including Jonathan Ladd, Ecroc Larocque, and Junesok Lee for all their help. Last but not least, I'd like to say thanks to my family and Mary-Kate for all their love and support throughout the entire process.

Table of Contents

List of Figures

List of Tables

Chapter 1 – Introduction

Transient flow is the transition from one steady state to another steady state in a fluid flow system. Transient flow occurs in all fluids, confined and unconfined. A transition is caused by a disturbance to the flow. In a confined system, such as a water pipeline, an abrupt change to the flow that causes large pressure fluctuations is called water hammer. The name comes from the hammering sound the sometimes occurs during the phenomenon. (Parmakian 1963)

The water hammer phenomenon is an important consideration in design in many hydraulic structures due to extreme variations in pressure it causes. For example, the dramatic pressure rise can cause pipes to rupture. Accompanying the high pressure wave, there is a negative wave, which is often overlooked, can cause very low pressures leading to the possibility of contaminant intrusion. Water hammer is a common but serious problem in residential plumbing systems. It puts potentially damaging extra stress and strain on pipes, joints, and fixtures. The noise associated with water hammer can be a nuisance as well.

In order to model the water hammer phenomenon in conduits it is required to solve a set of momentum and continuity equations. The momentum and continuity equations form a set of non-linear, hyperbolic, partial differential equations which cannot be solved by hand. A numerical method with an initial condition and two boundary conditions are needed. For a water distribution system, there are many more parameters needed for solving the water hammer problem. In a water distribution system, every branch of the system requires an additional boundary condition. External boundary conditions take on the form of a driving head, or a flow leaving the system. Internal boundary conditions arise in the form of nodal continuity, energy loss between points, head across valves, pumps, and more. The complexity of the problem requires the use of modeling software. The United States Army Corp of Engineers has developed a program to analyze hydraulic transients in systems such as hydropower plants and pumping stations. The program is called Water Hammer And Mass Oscillation and is referred to as WHAMO and available to the public for free, downloadable online (www.usace.mil)

When modeling the problem of water hammer in a complex system, an understanding of the mathematics of the fundamental equations, the numerical method, and the computer model is needed. This thesis explains the derivations of the momentum and continuity equations, the development of the four-point implicit finite difference scheme and system construction. This work provides the methods for analyzing water hammer on the smaller scale home plumbing systems. Several features of interest arose during in the process which will be discussed in this paper. The method of handling the boundary that is programmed in WHAMO is inadequate for the analysis of small scale systems. However a simple trick is developed that allows WHAMO to accurately model the boundary condition of water leaving the system into the free atmosphere. Before transient analysis can begin, steady flow conditions must be generated. Steady flow conditions developed by using the energy equation and the continuity equation matched the steady flow conditions developed by using the momentum equation and the continuity equation. This work shows why this happens. During transient events, pumps can operate in unusual and abnormal manner.

Understanding the behavior of pumps in all the modes of operation is necessary in order to accurately predict the behavior of the system during transients. Chapter 5 explains the pump operation during transients. The low pressure wave of a transient can create an adverse pressure gradient, leading to potential contaminant intrusion into the drinking water system. This problem is examined by creating a model similar to an actual test apparatus used to investigate intrusion in the program WHAMO and running various simulations and analyzing the results.

Overall the goal of this thesis is to provide a comprehensive look at water hammer with an emphasis on home plumbing systems. The specific objectives are: 1) to explain the mathematics of water hammer in a closed system, 2) examine and analyze water hammer in home plumbing systems, 3) investigate the use of the WHAMO, an unsteady model, for both steady and unsteady modeling, 4) explain unsteady flow and abnormal pump operation, and 5) present possible scenarios of intrusion or cavitation during low pressure water hammer events. The sections on the mathematics of water hammer and pump operation are general and are not specific to plumbing systems. The sections on steady-state conditions and intrusion modeling can also be applied to water distribution systems in general. The modeling tool used throughout is the program WHAMO by the United States Army Corp of Engineers, and details on the use of the program are provided throughout the paper. The design examples are specifically chosen to illustrate the key points. A primer for using WHAMO is provided as appendix III.

Chapter 2 - Water Hammer Mathematics

The Momentum Equation

The continuity and momentum equations can be used to describe transient flow in a closed conduit. Consider a segment of a constant diameter conduit in the flow direction (x-axis) of length Δx and cross-sectional area A. For this 1-dimensional element we consider the force balance which yields the necessary momentum equation. In Figure 2.1, the flow direction is to the right and the dashed line labeled HGL is the instantaneous hydraulic grade line. Figure 2.1 represents the moment in time where the shock wave is propagating in the reverse direction to the flow due to a downstream disturbance.

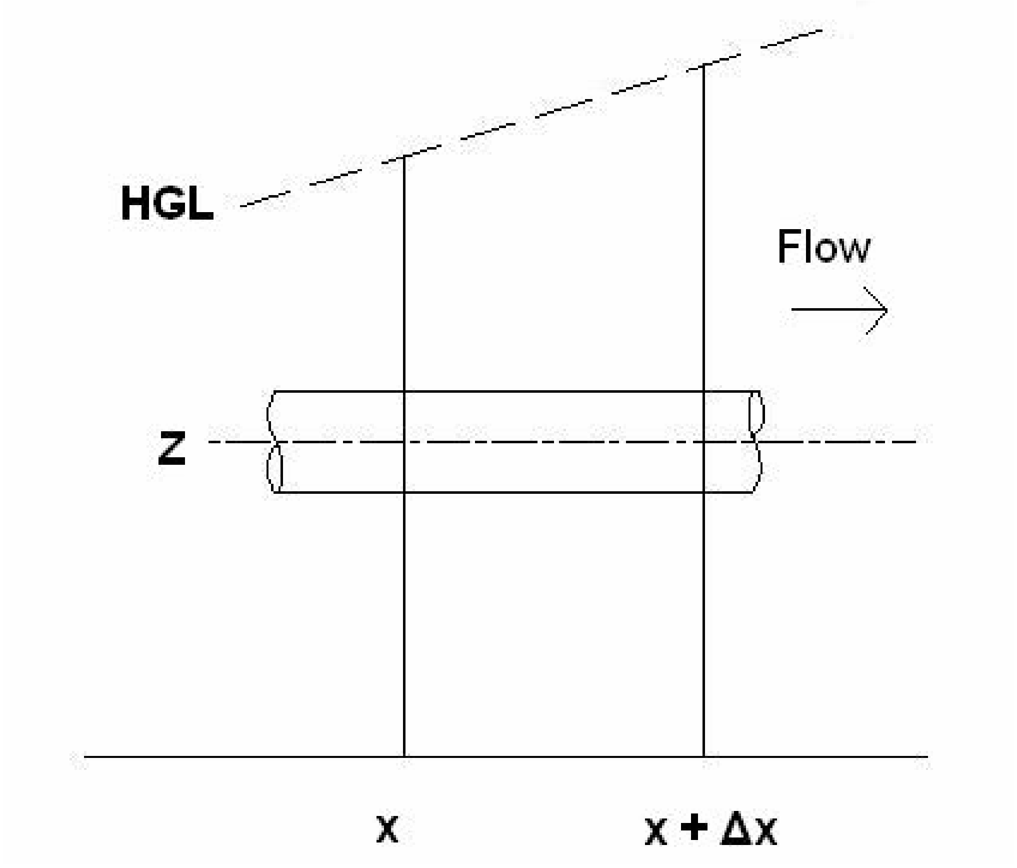


Figure 2.1 Conduit with Instantaneous HGL.

At position x, the flow is Q, and the piezometric head, pressure head plus the elevation head, is H. At the position x + Δx the flow is Q + $\frac{\partial Q}{\partial x}$Δx, and piezometric head is H + $\frac{\partial H}{\partial x}$Δx, where $\frac{\partial Q}{\partial x}$ and $\frac{\partial H}{\partial x}$ are the partial derivatives of Q and H with respect to x and are considered to increase in the positive x-direction. Figure 2-2 shows the forces acting on the fluid element with a free body diagram. The angle of the conduit is unimportant for now because the H term takes into account any change in elevation of the conduit.

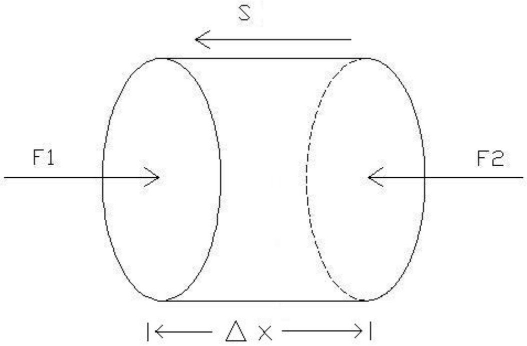


Figure 2.2 Free Body Diagram of a Fluid Element

The forces acting on the fluid element are the pressure forces, F1 and F2, the wall shear force due to friction, S and the body force. The piezometric head H = p/γ + z accounts for both the pressure and weight components.

Using,

$$F_1 = (H - z)\gamma A \tag{2.1}$$

$$F_2 = (H + \frac{\partial H}{\partial x}\Delta x - z)\gamma A \tag{2.2}$$

A is the area on either side of the fluid element.

We use the following steady state, incompressible fluid flow, constant diameter pipe estimate of the shear force

$$S = \frac{\gamma}{8g} f\, V^2 \pi D \Delta x \tag{2.3}$$

in which, g is the acceleration due to gravity, f is the Darcy-Weisbach friction factor, V is the average velocity of the fluid in the pipe, and D is the diameter of the conduit. The term $\frac{\gamma}{8g} f\, V^2$ is the wall shear stress, τ_o, and the $\pi D \Delta x$ is the area that the shear is acting on. According to Parmakian's Water Hammer Analysis (1963), $\frac{\partial A}{\partial x} \Delta x\, \gamma A$ is always very small compared to $\frac{\partial H}{\partial x} \Delta x\, \gamma A$ and it can be neglected. Summing up the forces in the flow direction

$$\sum F = F1 - F2 - S \tag{2.4}$$

Substituting eqs. (2.1, 2.2, and 2.3) into eq. (2.4),

$$F = ((H - z)\gamma A) - ((H + \frac{\partial H}{\partial x} \Delta x - z)\gamma A) - \frac{\gamma}{8g} f\, V^2 \pi D \Delta x$$

This simplifies to:

$$F = -\gamma A \frac{\partial H}{\partial x} \Delta x - \frac{\gamma}{8g} f\, V^2 \pi D \Delta x \tag{2.5}$$

From Newton's second law of motion,

$$F = m \frac{dV}{dt} \tag{2.6}$$

Where, m, is the mass of the fluid element, and $\frac{dV}{dt}$ is the acceleration of the fluid element. In this case the mass of the fluid element can be given by

$$\text{Mass} = \frac{\gamma}{g} A\Delta x. \tag{2.7}$$

Substituting eqs. (2.6 and 2.7) into eq.(2.5) and dividing by mass results in:

$$\frac{dV}{dt} = -g\frac{\partial H}{\partial x} - \frac{fV^2}{2D} \tag{2.8}$$

The total derivative dV/dt is given by the partial derivative of velocity

$$\frac{dV}{dt} = \frac{\partial V}{\partial t} + \frac{dx}{dt}\frac{\partial V}{\partial x} \tag{2.9}$$

Replacing $\frac{dx}{dt} = V$ we obtain

$$\frac{dV}{dt} = \frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} \tag{2.10}$$

Since the velocity change term due to position is much smaller than the velocity change with time term, $V\frac{\partial V}{\partial x}$ may be neglected (Parmakian 1963). Using eq. (2.10) with the $V\frac{\partial V}{\partial x}$ term neglected back into eq. (2.8), along with changing V^2 to V|V| yields

$$\frac{\partial V}{\partial t} + g\frac{\partial H}{\partial x} + \frac{f|V|V}{2D} = 0 \tag{2.11}$$

The V^2 term is changed to V|V| so that the sign of the velocity can be considered. Eq. (2.11) is the commonly used water hammer momentum equation for one dimensional pipe flow in terms of velocity and piezometric head. It can also be expressed in terms of discharge Q by multiplying the entire equation by A as below:

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + \frac{f|Q|Q}{2DA} = 0 \tag{2.12}$$

This equation is good for a flat conduit or a sloped conduit because the elevation change of the pipe with respect to x is taken into consideration in H. The derivation was done in the style used by Chaudhry in his book Applied Hydraulic Transients (Chaudhry 1987), and common simplifying assumptions were made (Parmakian 1963) in order to produce the momentum equation in the same form as the computer program WHAMO uses. This equation paired with the continuity equation is the basis for solving the water hammer problem in the program WHAMO. The full form of the equation and is shown below.

$$\frac{\partial V}{\partial t} + \mathrm{V}\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \mathrm{g}\frac{\partial z}{\partial x} + \frac{f|V|V}{2D} = 0 \tag{2.13}$$

The Continuity Equation

As the water hammer pressure wave moves through a pipe, we like to account for the following: (1) Continuity of the flow (2) the pipe wall extension and expansion due to pipe wall elasticity and compressibility of the fluid. Hansen (1967) has derived the most general form of the control volume equation that considers both the movement and the deformation of the control volume. White (2003) also contains a good description. Based on Hansen (1967) and White (2003) the continuity equation for a moving, deforming control volume is written as

$$\int_{C.V} \frac{\partial \rho}{\partial t} d\forall + \int_{C.S.} \rho \vec{V}_b d\vec{A} + \int_{C.S.} \rho \vec{V}_r \vec{n} dA = 0 \tag{2.14}$$

in which: C.V. = control volume

C.S. = control surface

ρ = density of the fluid

$d\forall$ = elemental volume

$\vec{V}_b$ = boundary velocity of C.V.

$\vec{V}_r$ = relative velocity of the fluid with respect to the control volume boundary velocity

$= \vec{V} - \vec{V}_b$

$\vec{V}$ = actual fluid velocity as referred to the reference coordinates

$\vec{n}$ = outward drawn normal for the area dA

Equation (2.14) is rewritten as

$$\frac{d}{\partial t}\int_{C.V,}\rho d\forall + \int_{C.S.}\rho V_{rn} dA = 0 \tag{2.15}$$

in which: $V_{rn} = V_r \cos\theta$ and θ = angle between $\vec{V}_r$ and $\vec{n}$

Following White (2003) eq.(2.14) is written in differential form as

$$\frac{\partial \rho}{\partial t}(AdL) + \rho\ \frac{\delta\forall}{\delta t} + \frac{\partial}{\partial x}(\rho V)dL\ A = 0 \tag{2.16}$$

in which: A = pipe cross-sectional area

$\delta\forall$ = incremental volume due to pipe expansion

dL = elemental pipe length

V = V_{rn} = water velocity

According to Sheet, Watters, and Vennard (1996), the term $\delta\forall$ can be written as (also see Parmakian, 1963)

$$\delta\forall = A\ dL(\frac{1-\nu^2}{E})(\frac{\delta p\ d}{e}) \tag{2.17}$$

In which: ν = Poisson ratio

E = Young's modulus of elasticity

δp = pressure increment

d = pipe inner diameter

e = pipe wall thickness

Using eq. (2.17) in eq. (2.16) we obtain

$$\frac{\partial \rho}{\partial t}(AdL) + \rho AdL(\frac{1-\nu^2}{E})\ \frac{dp}{dt}\ \frac{d}{e} + \frac{\partial}{\partial x}(\rho V)dL\ A = 0 \tag{2.18}$$

Equation (2.18) reduces to

$$\frac{1}{\rho}\ \frac{\partial \rho}{\partial t} + (\frac{1-\nu^2}{E})\ \frac{dp}{dt}\ \frac{d}{e} + \frac{\partial V}{\partial x} + \frac{V}{\rho}\ \frac{\partial \rho}{\partial x} = 0 \tag{2.19}$$

In eq. (2.19) we replace $\frac{1}{\rho}[\frac{\partial\rho}{\partial t}+\frac{\partial\rho}{\partial x}\mathrm{V}] = \frac{1}{\rho}\frac{d\rho}{dt}$ (2.20)

where V = $\frac{dx}{dt}$ (2.21)

Also, $\frac{d\rho}{dt} = \frac{\rho}{K}\frac{dp}{dt}$ (2.22)

in which: K = bulk modulus of the fluid

Therefore, we have

$$\frac{dp}{dt}[\frac{1}{K}+(\frac{1-\nu^2}{E})\frac{d}{e}]+\frac{\partial V}{\partial x}=0 \qquad (2.23)$$

Putting $\frac{1}{\rho c^2}=[\frac{1}{K}+(\frac{1-\nu^2}{E})\frac{d}{e}] = \frac{1}{K}[1+\frac{Kc_1d}{Ee}]$ (2.24)

where: c = wavespeed and $c_1 = (1-\nu^2)$

we have

$$[\frac{\partial p}{\partial t}+\frac{\partial p}{\partial x}\mathrm{V}]+\rho c^2\frac{\partial V}{\partial x}=0 \qquad (2.25)$$

Dividing eq. (2.25) by γ yields

$$[\frac{\partial H}{\partial t}+\frac{\partial H}{\partial x}\mathrm{V}]+\frac{c^2}{g}\frac{\partial V}{\partial x}=0 \qquad (2.26)$$

The term $\frac{\partial H}{\partial x}$V is small compared to $\frac{\partial H}{\partial t}$ and it is often neglected. In terms of discharge, eq. (2.26) becomes

$$\frac{\partial H}{\partial t}+\frac{\partial \mathrm{Q}}{\partial x}\frac{\mathrm{c}^2}{\mathrm{gA}}=0 \qquad (2.27)$$

Implicit Finite Difference Method

The continuity and momentum equations form a pair of hyperbolic, partial differential for which an exact solution can not be obtained analytically. However other methods have been developed to solve the water hammer equations. If the equations are hyperbolic it means the solutions follow certain characteristic pathways. For the water hammer equation the wave speed is the characteristic. This leads to the development of the method of characteristics to solve this set of equations. This is a popular method of solving hyperbolic equations. It entails converting the two partial differential equations to ordinary differential equations then solving using an explicit finite difference method. One drawback to the method of characteristics is that the time step must be small to satisfy the Courant condition for stability.

Another numerical method for solving the water hammer equations is the implicit finite difference method. The implicit method replaces the partial derivatives with finite differences and provides a set of equations that can then be solved simultaneously. The advantage of this method that is unconditionally stable so large time steps can be used. The disadvantage of this method is that for large systems, it is necessary to solve a large number of non-linear equations simultaneously. The computer program WHAMO uses the implicit finite-difference technique but converts its equations to a linear form before it solves the set of equations (Fitzgerald and Van Blaricum, 1998).

The solution space is discretized into the x-t plane so that at any point on the grid (x,t) there is a certain H and Q for the that point, H(x,t) and Q(x,t).

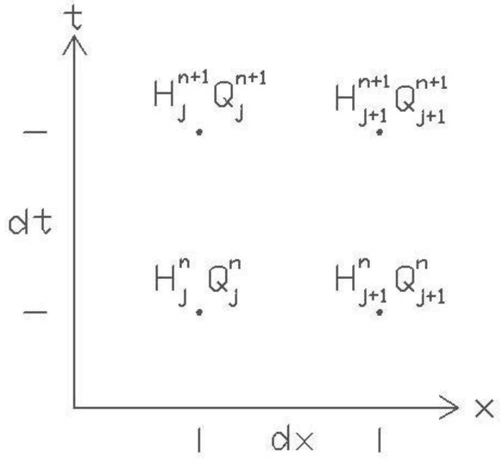


Figure 2.3 Finite Difference Grid

Each node in the solution grid would be a node in the system or computational node within a conduit. The most common link between two nodes on the computational grid is the conduit and the two water hammer equations form the relationships of head and flow in the x and t directions. There are other elements that link the nodes together such as valves and pumps and will be examined further as well. The scheme for the finite difference approximation is the same for all elements and the process of transforming the governing equations to finite difference from is shown for the conduit elements.

To approximate H_t, the partial derivative of H with respect to time, the average of H(j) and H(j+1) at the future time step minus the average of H(j) and H(j+1) at the current time step all divided by the time step.

$$\frac{\partial H}{\partial t} = (H_{n+1,j+1} + H_{n+1,j} - H_{n,j+1} - H_{n,j})/\,(2\Delta t) \tag{28}$$

And similarly, for the partial derivative of Q

$$\frac{\partial Q}{\partial t} = (Q_{n+1,j+1} + Q_{n+1,j} - Q_{n,j+1} - Q_{n,j})/\,(2\Delta t) \tag{29}$$

The approximation of the partial derivatives with respect to is the average of the next position step minus the average of the current position step.

$$\frac{\partial H}{\partial x} = (H_{n+1,j+1} + H_{n,j+1} - H_{n+1,j} - H_{n,j})/\,(2\Delta x) \tag{30}$$

$$\frac{\partial Q}{\partial x} = (Q_{n+1,j+1} + Q_{n,j+1} - Q_{n+1,j} - Q_{n,j})\,/\,(2\Delta x) \tag{31}$$

The two equations for the approximations of $\frac{\partial H}{\partial x}$ and $\frac{\partial Q}{\partial x}$ are useful as they are above; however, the finite difference scheme that WHAMO uses includes a weighting factor for computational stability, θ, and a value of .6 is used. With the weighting factor, the equations become

$$\frac{\partial H}{\partial x} = \frac{\theta}{\Delta x}(H_{n+1,j+1} - H_{n+1,j}) + \frac{(1-\theta)}{\Delta x}(H_{n,j+1} - H_{n,j}) \tag{32}$$

$$\frac{\partial Q}{\partial x} = \frac{\theta}{\Delta x}(Q_{n+1,j+1} - Q_{n+1,j}) + \frac{(1-\theta)}{\Delta x}(Q_{n,j+1} - Q_{n,j}) \tag{33}$$

Now, with the approximations for the partial derivatives can be substituted in to the momentum and continuity equations. After the substitution and the two equations are no longer differential equations but are algebraic equations.

The momentum equation is as follows:

$$\frac{\Delta x_j}{2g\theta A_j \Delta t}(Q_{n+1,j+1} + Q_{n+1,j} - Q_{n,j+1} - Q_{n,j}) + (H_{n+1,j+1} - H_{n+1,j}) + \frac{(1-\theta)}{\theta}(H_{n,j+1} - H_{n,j})$$

$$+ \frac{\Delta x_j f_j}{4g\theta D_j A^2{}_j}(Q_{n,j}|Q_{n,j}| + Q_{n,j+1}|Q_{n,j+1}|) = 0 \tag{34}$$

Where $Q|Q|$ is approximated $(Q_{n,j}|Q_{n,j}| + Q_{n,j+1}|Q_{n,j+1}|)/2$, thus linearizing the equation, greatly reducing the computational cost of solving it.

The continuity equation is as follows:

$$(H_{n+1,j+1} + H_{n+1,j} - H_{n,j+1} - H_{n,j}) + \frac{2\Delta t c_j^2 \theta}{gA_j \Delta x_j}(Q_{n+1,j+1} - Q_{n+1,j})$$

$$+ \frac{2\Delta t c_j^2 (1-\theta)}{gA_j \Delta x_j}(Q_{n,j+1} - Q_{n,j}) = 0 \tag{35}$$

These equations can represented in a shorter form by introducing the following coefficients for the known values in a system. Using the same notation as the WHAMO program the coefficients are as follows:

$$\alpha_j = \frac{2\Delta t c_j^2 \theta}{g A_j \Delta x_j} \tag{2.36a}$$

$$\beta_j = (\mathrm{H}_{n,j+1} - \mathrm{H}_{n,j}) + \frac{(1-\theta)}{\theta} \alpha_j (\mathrm{Q}_{n,j} - \mathrm{Q}_{n,j+1}) \tag{2.36b}$$

$$\gamma_j = \frac{\Delta x_j}{2 g \theta A_j \Delta t} \tag{2.36c}$$

$$\delta_j = \frac{(1-\theta)}{\theta} (\mathrm{H}_{n,j} - \mathrm{H}_{n,j+1}) - \frac{\Delta x_j f_j}{4 g \theta D_j A^2{}_j} (\, \mathrm{Q}_{n,j} |\, \mathrm{Q}_{n,j}| + \mathrm{Q}_{n,j+1} |\, \mathrm{Q}_{n,j+1}|) \tag{2.36d}$$

All the parameters for the coefficient should be known from the properties of the pipe or the values of head and flow at the previous time step. With the coefficients the momentum and continuity equations of the jth segment of the pipe become:

$$\text{Momentum: } - \mathrm{H}_{n,j+1} + \mathrm{H}_{n+1,j+1} + \gamma_j (\mathrm{Q}_{n+1,j} + \mathrm{Q}_{n+1,j+1}) = \delta_j \tag{2.37}$$

$$\text{Continuity: } \mathrm{H}_{n,j+1} + \mathrm{H}_{n+1,j+1} + \alpha_j (\, \mathrm{Q}_{n+1,j+1} - \mathrm{Q}_{n+1,j}\,) = \beta_j \tag{2.38}$$

The initial conditions provide the head and flow at locations in the system. Now, there are four unknowns for the head and flow at the next time step and two equations. This is where the boundary conditions are needed. A boundary condition at every end of a branch is necessary in order to have as many equations as unknowns to solve the system. The three external boundary conditions WHAMO uses are a fixed head reservoir, where $H_i = H_{res}$ – loss, at fixed flow where Q_i = QBC, and a surge tank. There are internal boundary conditions as well at every node in the system. The energy equation and continuity equation must be satisfied at each junction. The junction equations are as follows:

Energy: $H_i = H_j - \mathrm{loss}_{ij}$

$H_i = H_k - \mathrm{loss}_{ik}$

Continuity: $Q_i + Q_j + Q_k \ldots = 0$

The energy equation states that the energy at node *i* is equal to that at node *j* minus the energy loss between the nodes. The continuity equation is stating the sum of the flows in and out of a junction is equal to zero. Other important features or elements in the system are minor losses, valves, and pumps. The mathematics of representing a pump in the system are complicated and will be covered in a separate chapter specifically about pump operation. Minor losses in a conduit are represented by the term $C_{add}\frac{|Q|Q}{2gA^2}$ and are simply added to the loss terms in the momentum equation, where C_{add} is the minor loss coefficient. The total head loss term in the momentum equation is

$$\left(\frac{\Delta x_j f_j + C_{add}}{4g\theta D_j A^2{}_j}\right)\left(Q_{n,j}| Q_{n,j}| + Q_{n,j+1}| Q_{n,j+1}|\right) \tag{2.39}$$

For a valve, the flow through the value is based on the formula

$$Q = C_q D^2 \sqrt{g\Delta H} \tag{2.40}$$

Rearranging the formula into finite difference form

$$H_{n+1,j} - H_{n+1,j+1} = \frac{1}{C_q^2 D^4 g}\ Q_{n+1,j}|\ Q_{n+1,j}| \tag{2.41}$$

The notation $Q_{n+1,j}|\ Q_{n+1,j}|$ is used instead of $(Q_{n+1,j})^2$ to allow for sign change. Linearizing the equation, it then becomes

$$H_{n+1,j} - H_{n+1,j+1} = \frac{2|Q_{n,j}|}{C_q^2 D^4 g}\ Q_{n+1,j} - \frac{1}{C_q^2 D^4 g}\ Q_{n,j}|\ Q_{n,j}| \tag{2.42}$$

The continuity equation for valves is simply that the flow on one side of the valve is equal to the flow on the opposite side of the valve.

$$Q_{,j+1} = Q_j \tag{2.43}$$

The discharge coefficient, C_q, can be related to the head loss coefficient by the following expression

$$C_q, = \frac{\pi}{\sqrt{8}\sqrt{C_h}} \tag{2.44}$$

And

$$C_h = \frac{\Delta h}{V^2/2g} \tag{2.45}$$

Now, with equations for the all the links and nodes in the system, the initial and boundary conditions, a matrix of the linear system of equations can be set up to solve for head and flow everywhere, simultaneously, for the first time step. The process is repeated for the next time step, and again for the next step until the specified end of the simulation.

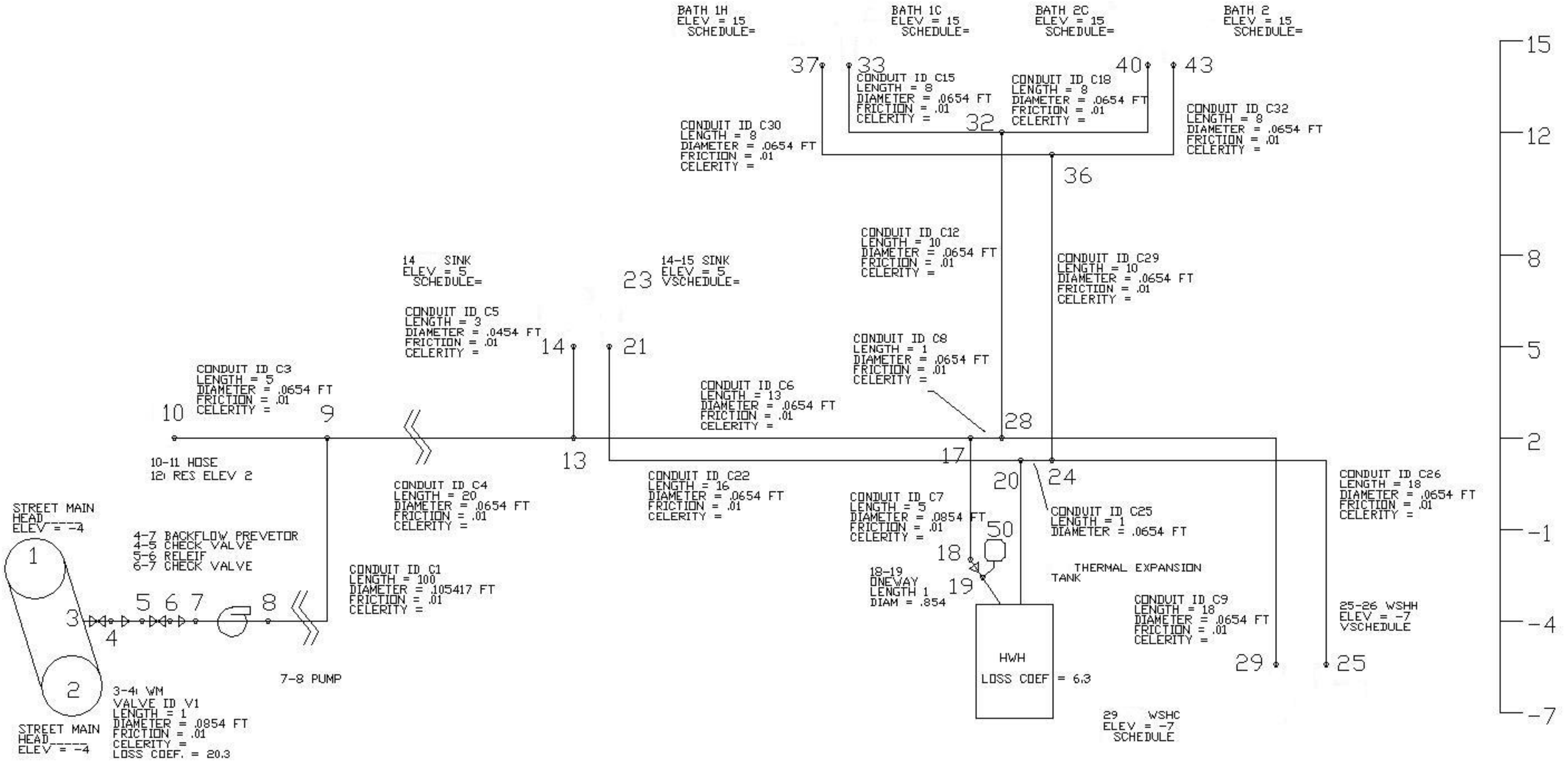
In the next chapter, a home plumbing system is examined. Various real physical features are converted into mathematical modeling blocks and then the system is put together and simulated under different scenarios using the WHAMO computer program.

Chapter 3 - Design of Plumbing Systems

Modeling is used for two main purposes: i) understanding the system being modeled, and ii) to predict outcomes of various what if scenarios created by changing model parameters (Woolhiser 1996). The use of modeling to predict future outcomes needs to be done with care. All models are simplification of reality and always have some errors in predicting outcomes of different modeling scenarios. Therefore, complete reliance on modeling results can lead to disastrous consequences. Model results need to be examined thoroughly to make sure the solution is reasonable. To do this a complete understanding of the model is needed. The goal of this chapter is to explain how the Water Hammer And Mass Oscillation (WHAMO) program can be applied to model minor water distribution systems, a scope different than the one originally intended, and analyze a home plumbing system under transient conditions.

WHAMO Application to a Home Plumbing System

To illustrate the idea of applying WHAMO to a home plumbing system let's examine a typical house system. The typical house system used for this simulation is a two story house with fixtures including two hose bibs, three bathrooms, a dishwashing machine, a hot water heater, and a washing machine in the basement. Inside a typical house, there are only three rooms where plumbing features go. The rooms are the kitchen, bathrooms, and laundry room. The other elements include the street main, which provides water to the house, the water meter valve, various other internal valves, tee junctions, and bends. The example system schematic is given in Figure 3.1. The individual elements of the plumbing system and their connectivity are given in Tables 3.1-3.4



Legend – See Tables 3.1-3.4

Figure 3.1 Plumbing System Schematic

Table 3.1 Cold Water Element List

Element ID	Type	Node Location	Upstream Node	Downstream Node	Comment
Res1	Head Boundary	100	-	-	Represents the Street Main
Dumy	Dummy Conduit	-	100	1	Connect Head Boundary to the System
Res2	Head Boundary	200	-	-	Represents the Street Main
Dum1	Dummy Conduit	-	200	2	Connect Head Boundary to the System
W1	Conduit	-	1	3	Water Main
W2	Conduit	-	2	3	Water Main
-	Junction	3	-	-	
Metr	Conduit	-	3	4	Water Meter
Chk1	Oneway	-	4	5	Back Flow Preventor
C1	Conduit	-	5	7	
P1	Pump	-	7	8	Pump
C2	Conduit	-	8	9	
Tee2	T-Junction	9	-	-	
C3	Conduit	-	9	10	
C4	Conduit	-	9	13	
Fbc1	Flow Boundary	10	-	-	Hose Bibb
Tee3	T-Junction	13			
C5	Conduit		13	14	
Fbc2	Flow Boundary	14			Kitchen
C6	Conduit		13	17	
Tee4	T-Junction	17			
C8	Conduit		17	28	
Tee1	T-Junction	28			
C9	Conduit		28	29	
Fbc3	Flow Boundary	**29**			**Washing Machine***
C12	Conduit		28	32	
Tee5	T-Junction	32			
C15	Conduit		32	33	
Fbc4	Flow Boundary	33			Bathroom1 Cold water
C18	Conduit		32	40	
Fbc5	Flow Boundary	40			Bathroom2 Cold water
C7	Conduit		17	18	
ONWY	Oneway		18	19	Feed into Hot water line

*Location where the transient is triggered

Table 3.2 Hot Water Element List

Element ID	Type	Node Location	Upstream Node	Downstream Node	Comment
ONWY	Oneway		18	19	Feed from cold water line
	Junction	19			
Dum2	Dummy Conduit		19	50	
Tnk1	Surge Tank	50			Hot water heater and expansion tank
HWH	Conduit		19	190	Hot water heater head loss
Hwp	Oneway		190	191	Check valve to prevent backflow to water heater
Hwp2	Dummy Conduit		191	20	To link a valve to a junction
Tee6	T-Junction	20			
C22	Conduit		20	21	
Fbc6	Flow Boundary	21			Kitchen
C25	Conduit		20	24	
Tee7	T-Junction	24			
C26	Conduit		24	25	
Fbc7	Flow Boundary	25			Washing Machine
C29	Conduit		24	36	
Tee8	T-Junction	36			
C30	Conduit		36	37	
Fbc9	Flow Boundary	37			Bathroom1 Hot water
C32	Conduit		36	43	
Fbc8	Flow Boundary	43			Bathroom2 Hot water

Table 3.3 Conduit Properties

ID	Length (ft)	Diameter (ft)	Celerity (ft/s)	Darcy Weisbach Friction Factor	Minor Loss, k
W1	10	0.5	4000	0.01	
W2	10	0.5	4000	0.01	
METR	1	0.0854	4100	0.01	20.3
C1	100	0.1054	4000	0.01	
C2	5	0.1054	4000	0.01	
C3	5	0.0654	4200	0.01	
C4	20	0.0654	4200	0.01	
C5	3	0.0654	4200	0.01	
C6	13	0.0654	4200	0.01	
C7	5	0.0654	4200	0.01	
C8	1	0.0654	4200	0.01	
C9	5	0.0654	4200	0.01	0.9
C12	10	0.0654	4200	0.01	
C15	8	0.0654	4200	0.01	
C18	8	0.0654	4200	0.01	
C22	16	0.0654	4200	0.01	
C25	1	0.0654	4200	0.01	
C26	18	0.0654	4200	0.01	
C29	10	0.0654	4200	0.01	
C30	8	0.0654	4200	0.01	
C32	8	0.0654	4200	0.01	
CHWH	7	0.0854	4100	0.01	6.3

Table 3.4 System Nodes and Elevations

Node Location	Node ID	Type	Elev. (feet)	Description
100	Res1	Head Boundary	-4	Water Main
200	Res2	Head Boundary	-4	Water Main
1			-4	
2			-4	
3		Junction	-4	
4			2	
5			2	
6			2	
7			5	
8			2	
9	Tee2	T-Junction	-3	
14	Fbc2	Flow Boundary	5	Kitchen, Cold
17	Tee4	T-Junction	2	
18			2	
19		Junction	2	
20	Tee6	T-Junction	2	
21	Fbc6	Flow Boundary	-7	Kitchen, Hot
24	Tee7	T-Junction	2	
25	Fbc7	Flow Boundary	-7	Washing Machine, Hot
28	Tee1	T-Junction	2	
29	Fbc3	Flow Boundary	-7	Washing Machine, Cold
32	Tee5	T-Junction	12	
33	Fbc4	Flow Boundary	15	Bathroom, Cold
36	Tee8	T-Junction	12	
37	Fbc9	Flow Boundary	15	Bathroom, Hot
40	Fbc5	Flow Boundary	15	Bathroom, Cold
43	Fbc8	Flow Boundary	15	Bathroom, Hot

Simulation of Street Main

The water supply system for a house starts with a connection to street water main. In Figure 1 RES1 and RES2 are used to represent street water main. The street main acts as a reservoir and is modeled as a reservoir in WHAMO with an elevation head equivalent to the pressure head of the street main. A street main with a pressure of 80 psi is modeled as a reservoir with a head water elevation of 180.3 feet corresponding to the conversion from pressure to pressure head. The conversion from static head to an equivalent water height is as follows:

80 (lbs/in^2) * 144 (in^2/ft^2) / * 1/62.4 (lbs/ft^3) = 180.3 ft

The WHAMO element code for simulating this reservoir would be as follows:

RESE ID RES1 ELEV 180.3 FINI

The reservoir acts as a constant head boundary condition. A boundary condition is needed at each end of a branch in the system to provide enough mathematical equations to solve the simulation.

Simulation of Water Meter

As water flows from the street water main to a house it must pass the water meter. The water meter measures how much flow is entering the house and incurs a head loss. It can be modeled simply as a conduit of short length with a head loss coefficient. From the example in Harris (1990) the water meter is rated for a loss of 6 psi at a flow rate of 25.9 gpm so that is equivalent to a valve with a minor loss coefficient of 20.3. The calculations used to figure this loss coefficient are as follows:

- The first step is to convert the units from gallons per minute to cubic feet per second.

(25.9 gallons/ minute)(1 ft^3/ gallon)(1min/60 seconds) = .057705 c.f.s.

- The next step is to find the velocity for the flow. The inner diameter of the water meter is 1.265 inches so the area, is equal to (1.265/12)^2*pi/4 = .008727 ft^2. Now since the velocity is equal to flow divided by area the velocity can be computed as:

V = Q/A = .057705 cfs/ .008727 ft^2 = 6.61157

- The third step is to find the head loss that is equivalent to the 6 psi pressure loss

6 (lbs/in^2) * 144 (lbs/ft^2) / 1(lbs/in^2) * 1/62.4 (lbs/ft^3) = 13.8 ft

- The equation for a minor loss is:

Hloss = k*(V^2/(2g).

Rearranging for k, the loss coefficient is:

k = Hloss(2g)/V^2, and all the variables needed to solve for the loss coefficient are known.

k = 13.8 (2g)/(6.61157^2) = 20.3

Solving, results in value of 20.3 for the loss coefficient for the water meter. The loss coefficient is more useful than an equivalent pressure loss for a certain flow which is often how it is specified in plumbing handbooks. The loss coefficient is good for all flows. For other elements of a plumbing system where losses are specified by a certain pressure loss the same procedure is undertaken, as with the water meter, to find the minor loss coefficient.

Since the water meter never changes position it is unnecessary to use the valve command and valve characteristics commands. The system command, which describes the elements location and connectivity is

```
EL METR LINK 3 4
```

And the element command, which provides the element properties is

```
COND ID METR LENG 1 DIAM .0854 CELE 4100 FRIC .01
ADDEDLOSS AT .05 CPLUS 20.3 CMINUS 20.3 FINI
```

Booster Pump Simulation

In situations where the street main pressure is low or more energy is needed to raise the water in a tall building a booster pump is used to supply additional head to the system. The pump would be placed after the water meter and can be modeled by the PUMP, PCHAR and OPPUMP commands in WHAMO. The pump command includes the identifier, type and specifications. The specifications needed are the rated head in feet, rated discharge in cubic feet per second, rated pump speed in rpm, rated torque in lb-ft and rotational inertia in lb-ft^2. The rated characteristics are the characteristics at the point of maximum efficiency. An example PUMP command taken from table 3.12 is as follows:

```
Pump id p1 type 1 RQ .2027 Rhead 100 Rspeed 2900 rtorque 18.11
 wr2 1.03 fini
```

The TYPE 1 in the pump is the identifier of the pump characteristics. The pump characteristics are in accordance to the four quadrant characteristic table which includes the abnormal behavior that occurs during transient events. Up to six different sets of pump characteristics can be specified for a system. Complete pump characteristics are usually unknown; however, the known characteristics of a pump with a similar specific speed can be used. The moment of inertia can be estimated if it is unknown as well. Wylie and Streeter (1978) provide the equation for estimating the pump rotational inertia as

$$I = 3550(HP/N)\hat{}1.435 \qquad (3.1)$$

in which, HP is horse power and N is the rotational speed in Rpm. Thorley (1991) presents a set of empirical functions for the inertia of the pump and motor.

$$Ipump = 1.5(10^7)(P/N^3)^{.9956} \qquad (3.2)$$

$$Imotor = 118(P/N)^{1.48} \qquad (3.3)$$

Thorley's expressions are in SI units where inertia is in (kg)m^2, P is the brake horsepower in kilowatts at the best efficiency point and N is in Rpm.

The pump characteristics are input as two tables of ratios. In Table 3.12, the WHAMO input file, the speed ratios and flow ratios form the row and column headers and the corresponding characteristics are supplied as the body of the table. The speed ratio, SRATIO, is the actual pump speed divided by the rated pump speed. This ratio is the first row of the pump characteristic tables, which can be seen in table 3.5. A minimum of 3 speed ratios is needed and the maximum number allowable is 50. A negative speed ratio indicates that the pump is rotating in the reverse direction. The constant speed of the pump during operation is specified when inputting the OPPUMP command that signifies operation of a pump. The tables are needed during the abnormal operation of the pump that accompanies water hammer events. The QRATIO is the ratio of discharge to rated discharge and it forms the columns. The head ratio fills out the table and a similar table is filled out of the torque ratio (TRATIO). So, a given column in the HRATIO table gives the head-discharge curve for that columns speed and the same can be said if for the TRATIO table and torque-discharge curve. Table 3.5 shows how the pump characteristics tables are set up for the HRATIO.

Table 3.5 HRATIO characteristics

	speed ratios										
	-1.5	**-1.25**	**-1**	**-0.75**	**-0.5**	**-0.25**	**0**	**0.25**	**0.5**	**0.75**	**1**
Flow Ratio	Head ratio										
-1.1	0.95	0.9	0.93	1	1.25	1.4	1.55	1.75	2.1	2.76	3.6
-0.9	0.79	0.64	0.6	0.65	0.73	0.88	1.07	1.3	1.6	2.2	2.8
-0.7	0.76	0.54	0.4	0.36	0.4	0.5	0.65	0.85	1.2	1.75	2.35
-0.5	0.74	0.52	0.35	0.23	0.2	0.25	0.34	0.5	0.64	1.34	2
-0.25	0.74	0.52	0.34	0.18	0.12	0.12	0.12	0.27	0.53	1.1	1.7
0	0.74	0.52	0.33	0.18	0.06	0.02	0	0.13	0.4	0.94	1.55
0.25	0.65	0.41	0.22	0.04	0	-0.1	-0.12	0.06	0.35	0.83	1.48
0.5	0.44	0.2	0	-0.2	-0.32	-0.4	-0.33	-0.08	0.25	0.74	1.37
0.75	0	-0.3	-0.5	-0.7	-0.85	-0.87	-0.7	-0.4	0.05	0.6	1.25
1	-0.65	-1	-1.3	-1.4	-1.45	-1.38	-1.2	-0.8	-0.3	0.3	1
1.25	-1.5	-1.85	-2.1	-2.3	-2.3	-2	-1.7	-1.2	-0.74	-0.11	0.64
1.5	-2.55	-2.85	-2.9	-3.4	-3.4	-2.73	-2.2	-1.6	-1.3	-0.6	0.25

The pump that is used in the simulation example has a rated speed of 2900 Rpm, a rated discharge of .2027 cubic feet per second, and a rated head of 100 ft. For the first column of the table, where the speed ratio is -1.5, the speed is -4350 Rmp. At this speed, for a flow ratio of 1.1, the head ratio is .95 (See table 3.5), so the head would be 95 ft. The characteristics in this example are from Knapp (1937). The complete operation of a pump during transient events is a complex phenomenon. Chapter 5 goes into the subject in more details.

The pump operation specifications are also needed when modeling pumps and they can be inputted using the OPPUMP command. The first part of the command is to identify the pump whose operation is being specified. Then there are the operation specifics where the user specifies the constant pump speed with the PUMP command or the constant speed until pump shutoff with the SHUTOFF command and using the TOFF command to specify when the pump is shut off. The default TOFF is 0.0 seconds. The OFF command is used when the pump is not operated and it has no impact on the head calculations of the system. An example for the pump operation command is as follows:

```
OPPUMP ID P1 SHUTOFF 500 TOFF 1.5 FINISH
```

This is an example of the pump shutting down. The input file in table 3.12 has the pump turned off for the entire simulation.

Simulation of Pressure Reducing Valve

In cases where the water pressure exceeds 80 psi a pressure reducing valve is installed to lower the water pressure. This is modeled in WHAMO using the PCVALVE command. The PCVALVE command differs from the VALVE command because the valve opening and closing schedule is not a function of the user input but a function of the pressure at a certain reference node. The secondary commands include ID which is followed by a user-defined identifier, DIAMETER, the flow characteristics, the reference node, and the pressure control. The flow characteristics refer to the type of valve it is and the valves characteristics. The different valve options are GATE, BUTTERFLY, HOWELL, and SPHERICAL or the user could specify this using the VCHAR command. The REFERNCE NODE command identifies the node at which the pressure will be referenced. PTARG is the desired downstream pressure, and in the case of home plumbing systems this is 80 psi. At this target pressure the valve will neither open nor close. At some specified PMAX, a pressure higher than the PTARG, the valve will close at its maximum rate, also specified by the MAXRATE command. The number after the MAXRATE command is the number of seconds in which it takes for the valve to go from fully open to fully close. For a pressure reducing valve, the further the valve is closed the more energy loss it incurs in the system. For the case where the pressure is lower than the target pressure that valve will open. Similarly, there is an OPENING MAXRATE command with a PMAX lower that target pressure. After the target pressure is specified, the user can instruct WHAMO to use a linear or square root interpolation to determine the valve rate when the pressure is in between PMAX and PTARG. The default is linear. An example of this command would be as follows:

```
PCVALVE ID REDU BUTTERFLY DIAM 1
REFERENCE NODE 200     PTARG 80
OPENING MAXRATE 10     PMAX  60     LINEAR
CLOSING MAXRATE 20     PMAX 120     ROOT
```

Simulation of Junctions and Minor Losses

Along the way, from the street main to the house fixtures, there are bends, expansions, contractions, and various other minor losses. WHAMO has commands for two types of junctions. The simple JUNC command links the elements together but has no hydraulic significance. The tee-junctions command calculates all the losses automatically. This command is called TJUCTION with secondary commands of FILLET, which specifies the fillet radius between the pipes and CRISER, which is the minor loss coefficient when there is no flow in the riser pipe. The default is .95 and this corresponds to Gardel's formula which WHAMO uses to calculate losses (Gardel 1955). For other minor losses, such as bends, orifices, or simple junctions, the ADDEDLOSS command can be in used. The ADDEDLOSS command includes the following subcommands. The AT command is the location of the loss measured in feet downstream from the upstream end of the conduit. CPLUS is the minor loss coefficient for flow in the assumed positive direction and CMIMUS is the minor loss coefficient for flow in the assumed negative direction. The application of these commands is shown with examples from table 3.12

Tee Junction:

```
EL TEE2 at 9 riser 13 (System command)
TJUNCTION id TEE2 fillet 0 fini  (Properties command)
```

Minor loss:

```
COND ID C9 AS C3
 addedloss at 9 cplus .9 cminus .9 LENG 18 FINI
```

Simulation of Conduits

The pipes of a home plumbing system are typically type L copper. The inside diameters, which are used in the model are different from the nominal diameters of the copper pipe. The celerity for each pipe varies with pipe diameter, anchoring conditions and Modulus of elasticity for the pipe material. Table 3.6 shows the differences in celerity for various conditions.

Table 3.6 Celerity in Copper Pipes

Copper pipe, Nominal Size	Inner Radius	Condition A	Condition B	Condition C	Modulus of Elasticity	Condition A	Condition B	Condition C

	Ri, ft	ψ (a)	Ψ (b)	ψ (c)	E, Gpa	Celerity, a, fps		
1.25"	0.052709	28.47079	22.7395	24.72341	107	3861.153	4012.718	3958.253
	0.052709	28.47079	22.7395	24.72341	131	3998.356	4134.815	4086.011
1"	0.042709	25.55047	20.46814	22.22741	107	3936.193	4077.923	4027.145
	0.042709	25.55047	20.46814	22.22741	131	4066.170	4192.896	4147.699
.75"	0.032709	21.98354	17.69386	19.17875	107	4034.071	4162.050	4116.382
	0.032709	21.98354	17.69386	19.17875	131	4153.877	4267.273	4226.976

Condition A: Conduit anchored against longitudinal movement throughout its length

Condition B: Conduits achored against longitudinal movement through out is length

Condition C: Conduits with frequent expansion joints

The equation for celerity used was presented by Chaudhry (1979).

$$a = \surd(K/(\rho[1+(K/E)\psi) \qquad (3.4)$$

Where: a = celerity in feet per second
K = is the bulk modulus of elasticity of the fluid = 2.19 Gpa at 15º C
ρ = is the density of the fluid
E = Youngs modulus of elasticity of the conduit wall
$\psi = 2(1+\nu)((Ro^2+Ri^2)/(Ro^2-Ri^2)) - 2\nu Ri^2/(Ro^2-Ri^2)$ (3.5)
when the conduit is anchored against longitudinal movement throughout its length
$\psi = 2[(Ro^2-1.5Ri^2)/(Ro^2-Ri^2) + \nu\,(Ro^2-3Ri^2)/(Ro^2-Ri^2)]$ (3.6)
when the conduit is anchored against longitudinal movement through out is length
$\psi = 2[(Ro^2+Ri^2)/(Ro^2-Ri^2)+ \nu]$ (3.7)
when the conduit has frequent expansion joints
Ro and Ri = the outer and inner radii, respectively
ν = Poisson's Ratio

The 1.25", 1" and .75" are the typical sizes of pipes in a plumbing system. For the CONDUIT command which represents the pipes, a LENGTH, DIAMETER, CELERITY, and FRICTION input are needed as well. The FRICTION input is the Darcy-Weisbach friction factor. In addition for computational purposes the NUMSEG command breaks the conduit into x number of computational segments. An example of the conduit command from table 3.12 is as follows:

```
COND ID C3 LENG 5 DIAM .0654 CELE 4200 FRIC .01 numseg 10 FINI
```

The default amount of computational segments is 1. WHAMO has a maximum of 450 computational segments and 65 branches. This limit can easily be exceeded even in simple systems so care must be taken to not to make the model overly complex. It is good practice to simplify where possible without compromising the accuracy of the model.

Water Heater Simulation

An interesting feature in the model of the home system is the water heater. The first step in modeling a water heater is to identify how it works. There are different types of water heaters, ranging from solar to tankless heaters. The most common types are gas and electric and they both work in the same manner. The cold water line enters the tank near the bottom, and then it is heated by either burning gas or electric coils. As water is heated, the water becomes less dense and rises to the top of the tank and exits when a fixture on the hot water line is opened. Table 3.7 lists the typical elements of a hot water heater.

Table 3.7 Elements of a Water Heater

A	Cold In
B	Hot Out
C	Shutoff Valve
D	Temperature/Pressure Relief
E	Insulations
F	Outer Case
G	Anode Rod
H	Thermostat
I	Electric Heating Elements
J	Drain Valve
K	Burner Control
L	Dip Tube
M	Overflow
N	Steel Tank
O	Burner

Taking a closer look at the plumbing specifications of a standard water heater, the first feature encountered is a one-way valve to prevent any backflow situations. When water gets hot it expands. If the inlet is not blocked by a check valve or some other one-way device, the increased (due to expansion) volume travels back into the inlet pipe. If the inlet pipe is blocked, the increase in volume has to be accommodated safely. When a one-way valve is installed, a thermal expansion tank is always installed on the hot water side of the valve to ease pressure build up. Another check valve is installed after the hot water line leaves the tank to prevent any from coming in back into the tank from the hot water line. When the water is heated, the water expands, and with the valves that prevent any hot water from re-entering the cold water side there is no place for the water to go unless there is an expansion tank. The thermal expansion tank protects against tank explosion due to the expansion of the heated water. The expansion tank is an air chamber connected to the water line. The air chamber can be modeled in WHAMO as an air chamber surge tank. The command is SURGETANK and then after the element ID it is then distinguished as an air chamber by adding AIR to the command string. The other pieces of data needed are the top and bottom elevations, the celerity, friction factor, diameter, ambient air temperature, and the ambient air pressure. The input commands are ELTOP, ELBOTTOM, CELERITY, FRICTION, DIAMETER, TEMP and PBAR. The temperature is in degrees Fahrenheit and the pressure is absolute pressure in psi. The tank also needs to be initialized by setting the initial pressure, the initial water surface elevation, and the initial air mass in terms of cubic feet at standard temperature and pressure. The surgetank command used in the simulation from table 3.12 is shown below.

```
surgetank id tnk1 air elbottom 2 eltop 8
cele 4100 fric .02 diam 1.5 temp 100
pbar 14.5 N 1.25 wsinit 7 fini
```

There is a fluid density command in WHAMO; however it applies universally through out the system, not to specified parts of the system so WHAMO can not model the effects of heating the water. Since the flow can not go in the reverse direction the flow pattern is not affected by the inability to model the fluid expansion.

Water heaters also require a pressure relief valve to handle extremely high pressure situations. At a certain rated pressure, usually 300 psi, (www.howstuffworks.com accessed on April 17 2006) the valve opens and water is released from the tank. This is modeled similarly to the pressure reducing valve except the reference node for the target pressure is located upstream of the valve instead of downstream. The one-way valve that prevents the hot water from flowing back into the cold water system is simply modeled in WHAMO using the ONEWAY command. It is a valve in WHAMO that allows no flow in the reverse direction.

Simulation of Plumbing Fixtures

The plumbing fixtures, such as sinks, showers, and washing machines, are modeled using the flow boundary condition (FBC). This is consistent with the current practice of designing plumbing systems, where a fixed demand for each fixture is specified. Example flow rates of various fixtures are given in table 3.8.

Table 3.8 Minimum Design Capacities at Fixture Supply Pipe Outlets (Woodson 2000)

FIXTURE	FLOW RATE	PRESSURE
	(gpm)	(psi)
Bathtub	4	8
Bidet	2	4
Combination fixture	4	8
Dishwashing, residential	2.75	8
Drinking fountain	0.75	8
Laundry tray	4	8
Lavatory	2	8
Shower	3	8
Shower, temperature controlled	3	20
Sillcock, hose bibb	5	8
Sink, residential	2.5	8
Water closet, flushometer tank	1.6	15
Water closet, tank, close coupled	3	8
Water closet, tank, one piece	6	15

For each FBC there is either a constant flow or a flow schedule. The flow schedule is one way to trigger transient conditions. In the simulations, the washing machine is used to trigger the transient and the command is shown below. The demand shown is the cfs equivalent of 2.5 gpm and at time .5 seconds the valve starts to close and is fully shut at time .6 seconds.

```
FBC ID FBC3 QSCHED 2 FINI
SCHED QSCHED 2 TIME 0 Q .00557 T 0.5 Q .00557 t 0.6 q 0
```

The first line in the command sequence is part of the element properties, where FBC would be the flow boundary condition as identified in the system command.

Like all models, WHAMO has limitations in modeling various components of a plumbing system. Some examples were discussed in previous sections. However, for many systems WHAMO can provide valuable insight into the transient flow conditions. In the next part of this chapter, a WHAMO model of an example residential plumbing system is built, and simulation results of a number of scenarios are discussed.

Simulations of a Plumbing System in which Transients are Triggered by a Washing Machine

The scenarios are presented in text example problem format for the sake of clarity to the reader.

Problem Statement:

A typical residential plumbing system is to be analyzed to determine the potential water hammer effects. A sketch of the plumbing system is given as figure 3.1. The system connectivity, element, and node properties are given in tables 3.1 - 3.4. The input code for the computer program WHAMO is given in table 3.12. Node 29 represents the washing machine which is where the transients are triggered. The washing machine valve is an automatic valve. The flow spins a coil of wire which sends a signal to automatically shut off the valve stopping water from entering the washing machine. These closure times have become extremely small. The closure times range from 10 -60 milliseconds for small direct acting valves to 105-200 milliseconds for the large piston type valves (www.ascovalve.com). For this reason, the washing machine will be the key fixture for analysis. Small air chambers are typically installed above fast acting valves to control water hammer but over time they can become full of water and lose their effectiveness (Time-Life Books, 1975). The washing machine valve in this problem has a closure time of .1 seconds. The pump is not in operation and the street water main has a pressure of 80 psi. Analyze the following scenarios:

1) The washing machine with a 2.5 gpm flow rate is turned off .5 seconds into the simulation; all other fixtures are not operated; the hot water heater has a tank with an air column 2 feet in depth, and a check valve prevents flow from exiting the plumbing system to the street main.

2) The washing machine with a 7.5 gpm flow rate is turned off; all other fixtures are not operated; the hot water heater has a tank with 2 feet of air in it and a check valve prevents flow from exiting the plumbing system to the street main. This scenario represents a higher than normal flow rate which would create a large water hammer effect.

3) The washing machine with a 7.5 gpm flow rate is turned off; all other fixtures are not operated; the hot water heater has a tank with .01 feet of air in it and a check valve prevents flow from exiting the plumbing system to the street main. This scenario now takes into consideration the problem of the air chambers filling with water over the course of time.

4) The washing machine with a 7.5 gpm flow rate is turned off; all other fixtures are not operated; the hot water heater has a tank with .01 feet of air in it and there is no check valve to prevent flow from exiting the plumbing system to the street main. This problem examines the influence the backflow preventor imparts on the transient.

5) The washing machine with a 7.5 gpm flow rate is turned off; all other fixtures are not operated; the system has no tank associated with heating the water and there is no check valve to prevent flow from exiting the plumbing system to the street main. Scenarios 5 and 6 are examined to determine the effects of having a water heater tank and the influence of another fixture in operation.

6) The washing machine with a 7.5 gpm flow rate is turned off; the upstairs shower, node 43, is operated at 3 gpm; the system has no tank associated with heating the water and there is no check valve to prevent flow from exiting the plumbing system to the street main. Table 3.7 summarized the different conditions simulated.

Table 3.9 Summary of Simulation Scenarios

	Washing machine demand	Air Chamber	Check Valve	Shower Fixture
Simulation 1	2.5 gpm	W/H with expansion tank	yes	off
Simulation 2	7.5 gpm	W/H with expansion tank	yes	off
Simulation 3	7.5 gpm	W/H with small air volume	yes	off
Simulation 4	7.5 gpm	W/H with small air volume	no	off
Simulation 5	7.5 gpm	None	no	off
Simulation 6	7.5 gpm	None	no	on

Results of Simulation

Simulation 1

The cold water washing machine fixture, node 29, where the transient is triggered, is the most sensitive node. The largest head value at this node is 190.5 feet and the smallest head value is 179.0 feet. Figure 3.2 shows a plot of discharge and head versus time for node 29. The water hammer impact for this situation is mild in that it produces a brief rise in head but not to a dangerous level and there is no oscillation of the wave. The thermal expansion tank dampens the water hammer wave. The expansion tank is modeled by adding its air volume to the top of the tank of the water heater. The tank is 6 feet tall and has two feet of air volume to account for the thermal expansion tank. The behavior of the tank is shown in figure 3.4. A snapshot of the system at time of .6 is shown in table 3.6. The fact that at all energy values are approximately the same shows that there is no large wave traveling through the system at the time of .6 seconds.

The pressure at node 29 before the washing machine stops the flow of water is nearly 80 psi. The scheduled flow is only 2.5 gallons per minute. For these numbers to be accurate a very large loss must occur as the water exits the system through the fixture, otherwise the large pressure gradient across the fixture would force the flow rate to be extremely high. A simple test was performed in the bottom floor of Patton Hall that examines the pressure discharge relationship.

The writer used a pressure gage in the hydraulics laboratory faucet and found that the water pressure ranged from 80-90 psi. The procedure in determining the flow rate was to measure the amount of time needed to fill a 5.7 liter bucket. This procedure was repeated for accuracy and the average time to fill the bucket was 15.8 seconds which is equals a flow rate of 5.71 gallons per minute. This pressure discharge relationship is of the same order or magnitude as the scheduled 2.5 gpm discharge in scenario 1. There is large variety of different fixtures used throughout and each type has its own discharge coefficient. With this uncertainty, it is better to use a range of demands to analyze the home plumbing system.

Simulation 2

Figure 3.5 shows the time history of node 29. Simulation 2 has the same pattern as simulation 1 as expected. The maximum head rises to 222.5. There is no negative pressure wave in this simulation and compared to the following simulation where the air volume in the system is greatly reduced, it appears the volume of air in the thermal expansion tank eliminates the negative pressure wave.

Simulation 3

Figure 3.6 shows the results of node 29, the washing machine, node 19, the base of the hot water heater, and node 40, a fixture on the second floor bathroom. The initial behavior of node 29 is the same as the first two simulations, however, the head increases and begins to oscillate and comes to a steady state near 200 feet. Node 19 has a gentle rise in head and comes to a steady state near 230 feet. The steady state pressures that are greater than the street main pressures are due to the back flow valves. Once the valve is completely shut, triggering the water hammer, the water has no place to go, and the energy of the valve closing is added to the water in the system.

Simulation 4

Figure 3.7 summarizes the results of the simulation. Node 29 is the most sensitive. Data on the behavior of the water heater tank is plotted as well to see its influence on the transient. Figure 3.8 shows at a time of approximately .9 seconds the system loses dampening effects of the air volume in the water heater and the head begins to oscillate. With the check valve removed, the head in the cold water line returns to the street main pressure. It also oscillates with a greater amplitude and period. The lowest head experienced during the transient is 147.7.

Simulation 5

Without the water heater tank, the water hammer effect is large. The head at node 29 rises from 173.4 feet to 450.7 feet, then drops to -22 feet and the pressure at that moment is -6 psi. At this point we have hit a scenario where many adverse impacts may be observed. The high pressures may break the pipes, the low pressure may cause cavitation or provide intrusion potential and the large oscillations may create loud hammering sounds. Since we are scheduling the out flow and it is not a function of the water main head, for scenarios where the initial water street main pressure is different from 80psi as in the simulations, the plots can be simply shifted up or down depending on street main pressure. So, if simulation 5 was run with a street main head of 150.3 instead of the 180.3, the maximum head at node 29 would be 420.7 feet and the minimum head would be -52 feet. The WHAMO program doesn't consider cavitation; it does print a warning statement though if the minimum head drops below -20 feet.

Simulation 6 Results

Table 3.13 shows the maximum and minimum energy heads for all nodes. With the increased in flow in simulation 6 creates a larger energy in the steady state conditions, so the head before water hammer is triggered is lower than in simulation 6. The head at node 29 is 168.3 in simulation 6, and is 173.4 in simulation 5. In simulation 6 the head at node 29 rises to a 446.6 feet and drops to -48.1 feet. Overall the high heads for simulation 6 are about the same or slightly lower that those of simulation 5. The low heads, however, are lower for the cold water line, and much lower in the hot water line, where there were no negative heads before.

From these simulations, it can be concluded that an air chamber of sufficient size can eliminate water hammer problems from a home plumbing system. Air chambers are used to control water hammer and typically are installed above fast acting valves like a washing machine. Over time, their air volume can be filled with water making them less effective. Simulation 3 can represent this situation and as the results show, the pressure wave occurs and oscillates, and this may cause the water hammer noise that gives the phenomenon its name, but it isn't severe to cause major damage. The backflow preventor does two good things to prevent the intrusion contamination of the drinking water supply. Along with preventing flow from leaving the home plumbing system and going into the water main, the back flow preventor reduces the low pressure spikes that could potentially cause intrusion. Simulation 5 shows that without any measures to control water hammer, a washing machine shutting off could potentially cause major damage to a plumbing system. We also see that having other fixtures operating while the water hammer is triggered adds to the adverse effects of the transient.

Chapter 3 Tables and Figures

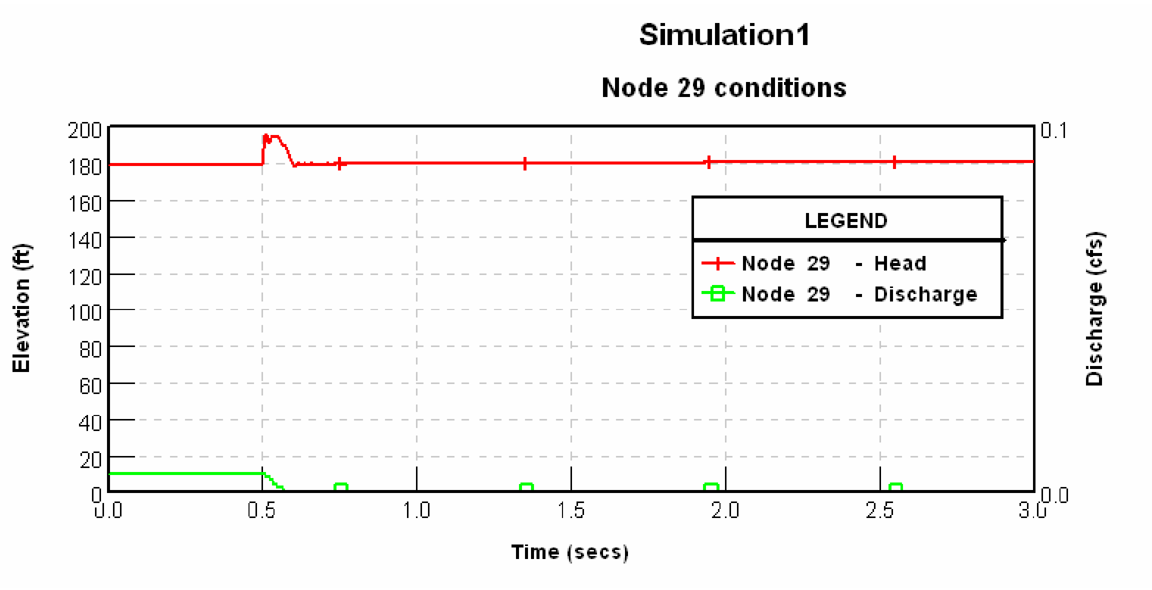


Figure 3.2 Simulation1 Node 29 Results

Table 3.10, System Snapshot at t = .6 seconds

TIME	.60			TOTAL	
=	SECONDS			HEAD	DISCHARGE
	TOTAL				
	HEAD	DISCHARGE	NODE	(FEET)	(CFS)
NODE	(FEET)	(CFS)	----	----------	---------
----	----------	---------	19	179.68	0
100	180.3	0	50	179.68	0
1	180.3	0		179.68	0
	TOTAL			TOTAL	
	HEAD	DISCHARGE		HEAD	DISCHARGE
NODE	(FEET)	(CFS)	NODE	(FEET)	(CFS)
----	----------	---------	----	----------	---------
1	180.3	0	19	179.68	0
3	180.3	0	190	179.68	0
	TOTAL			TOTAL	
	HEAD	DISCHARGE		HEAD	DISCHARGE
NODE	(FEET)	(CFS)	NODE	(FEET)	(CFS)
----	----------	---------	----	----------	---------
3	180.3	0	190	179.68	0
4	180.02	0	191	179.68	0
	TOTAL				
	HEAD	DISCHARGE	20	179.68	0
				TOTAL	
NODE	(FEET)	(CFS)		HEAD	DISCHARGE
----	----------	---------	NODE	(FEET)	(CFS)

```
  4      180.02       0            ----   ----------   ---------
  5      180.01       0             20     179.68          0
         TOTAL
          HEAD     DISCHARGE               179.68          0
NODE     (FEET)      (CFS)          21     179.68          0
                                           TOTAL
----   ----------  ---------                HEAD      DISCHARGE
  5      180.01       0            NODE    (FEET)       (CFS)
         180.01       0            ----   ----------   ---------
         179.93       0             20     179.68          0
         179.81       0                    179.68          0
         179.69       0             24     179.68          0
                                           TOTAL
  7      179.64       0                     HEAD      DISCHARGE
         TOTAL
          HEAD     DISCHARGE       NODE    (FEET)       (CFS)
NODE     (FEET)      (CFS)         ----   ----------   ---------
----   ----------  ---------        24     179.68          0
  7      179.64       0                    179.68          0
  8      179.64       0             25     179.68          0
         TOTAL                             TOTAL
          HEAD     DISCHARGE                HEAD      DISCHARGE
NODE     (FEET)      (CFS)         NODE    (FEET)       (CFS)
----   ----------  ---------       ----   ----------   ---------
  8      179.64       0             24     179.68          0
  9      179.64       0                    179.68          0
         TOTAL
          HEAD     DISCHARGE        36     179.68          0
                                           TOTAL
NODE     (FEET)      (CFS)                  HEAD      DISCHARGE
----   ----------  ---------       NODE    (FEET)       (CFS)
  9      179.63       0            ----   ----------   ---------
         179.63       0             36     179.68          0
 10      179.63       0                    179.68          0
         TOTAL
          HEAD     DISCHARGE        43     179.68          0
                                           TOTAL
NODE     (FEET)      (CFS)                  HEAD      DISCHARGE
----   ----------  ---------       NODE    (FEET)       (CFS)
  9      179.61       0            ----   ----------   ---------
         179.61       0             36     179.68          0
 13      179.6        0                    179.68          0
         TOTAL
          HEAD     DISCHARGE        37     179.68          0
                                           TOTAL
NODE     (FEET)      (CFS)                  HEAD      DISCHARGE
----   ----------  ---------       NODE    (FEET)       (CFS)
 13      179.57       0            ----   ----------   ---------
         179.57       0             28     179.55          0
 14      179.57       0                    179.12          0
         TOTAL
          HEAD     DISCHARGE        29     178.89          0
NODE     (FEET)      (CFS)                 TOTAL      DISCHARGE
```

```
 ----     ----------     ---------
  13        179.6            0
            179.6            0
  17        179.61           0
            TOTAL
            HEAD         DISCHARGE

 NODE       (FEET)         (CFS)
 ----     ----------     ---------
  17        179.59           0
            179.57           0
  28        179.55           0
            TOTAL
            HEAD         DISCHARGE

 NODE       (FEET)         (CFS)
 ----     ----------     ---------
  17        179.56           0
            179.63           0
  18        179.7            0
            TOTAL
            HEAD         DISCHARGE
 NODE       (FEET)         (CFS)
 ----     ----------     ---------
  18        179.7            0
  19        179.68           0
```

```
            HEAD
 NODE       (FEET)         (CFS)
 ----     ----------     ---------
  28        179.55           0
            179.62           0

  32        179.67           0
            TOTAL
            HEAD         DISCHARGE
 NODE       (FEET)         (CFS)
 ----     ----------     ---------
  32        179.67           0
            179.69           0

  40        179.69           0
            TOTAL
            HEAD         DISCHARGE
 NODE       (FEET)         (CFS)
 ----     ----------     ---------
 200        180.3            0
  2         180.3            0
            TOTAL
            HEAD         DISCHARGE
 NODE       (FEET)         (CFS)
 ----     ----------     ---------
  2         180.3            0
  3         180.3            0
            TOTAL
            HEAD         DISCHARGE
 NODE       (FEET)         (CFS)
 ----     ----------     ---------
  32        179.67           0
            179.69           0
  33        179.69           0
```

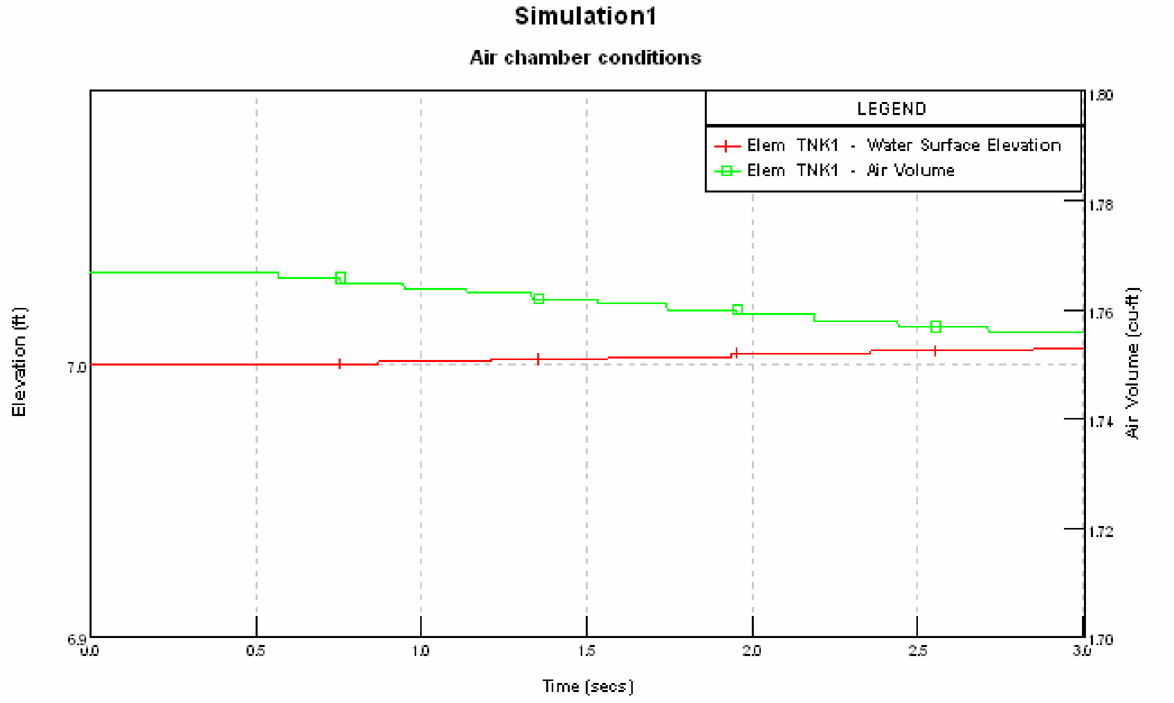


Figure 3.3 Simulation1 Air Chamber Results

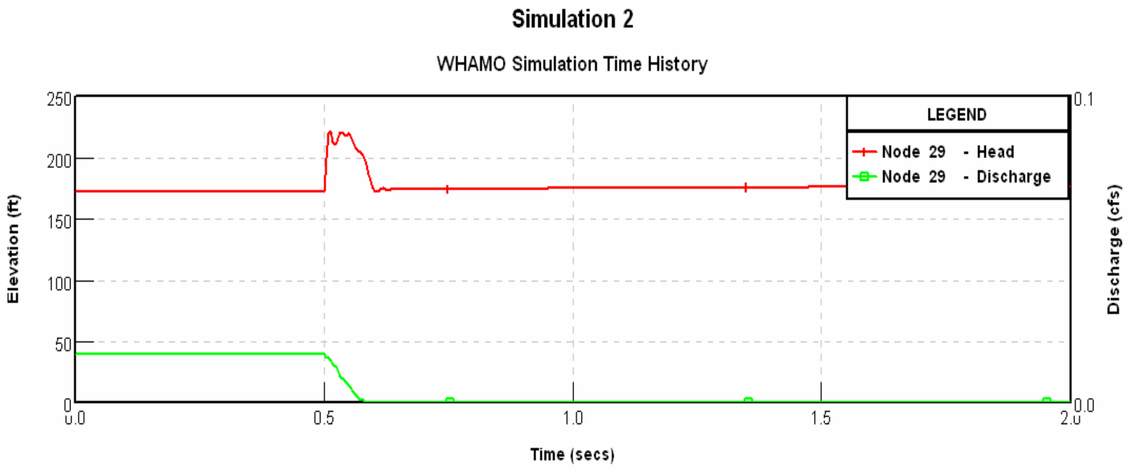


Figure 3.4 Simulation2 Node 29 Results

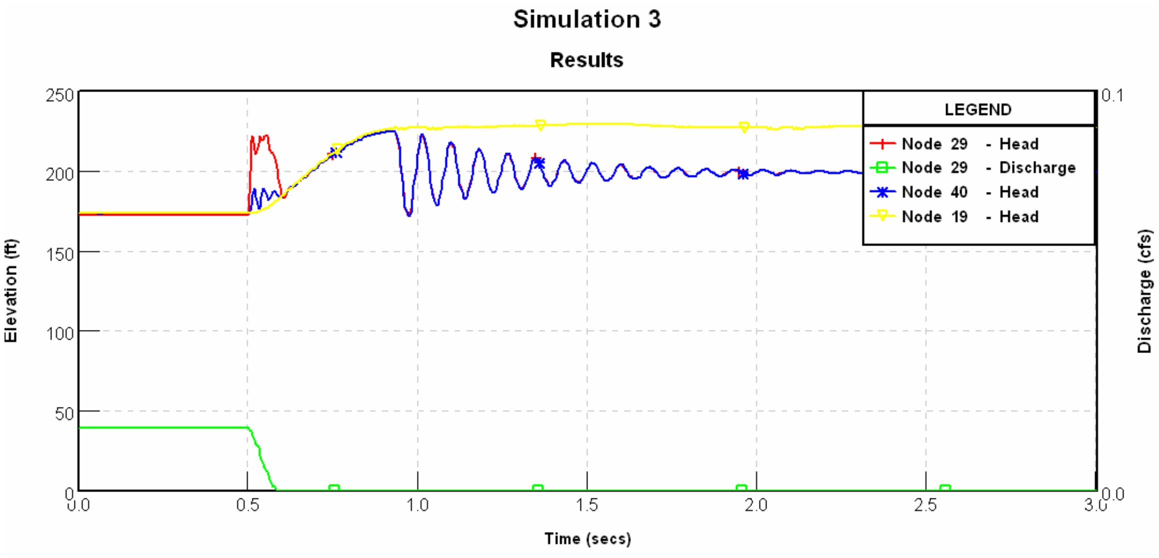


Figure 3.5 Simulation 3 Results

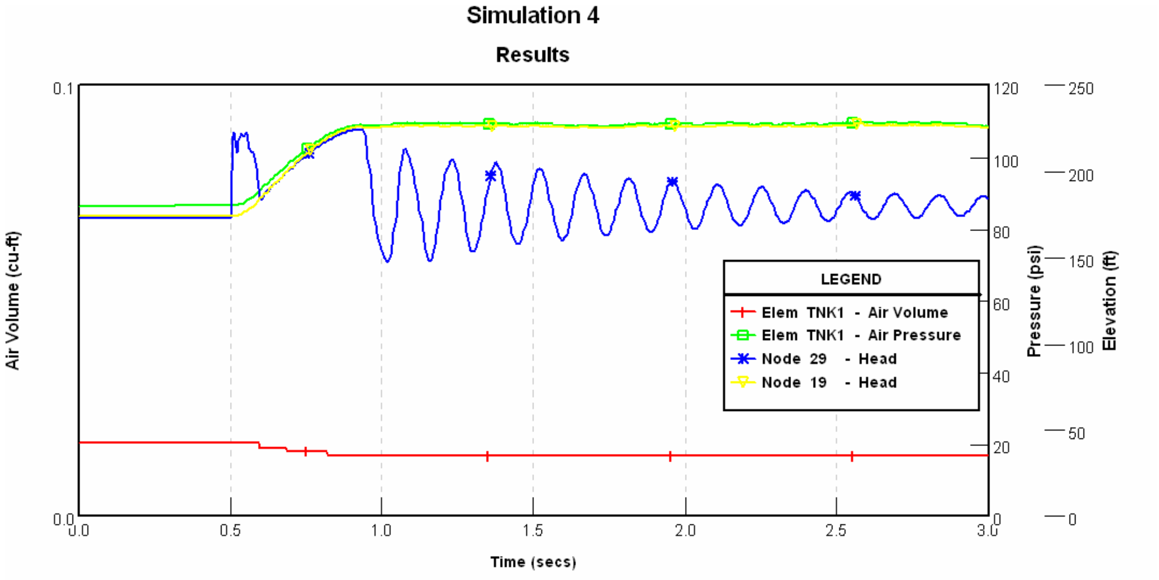


Figure 3.6 Simulation 4 results.

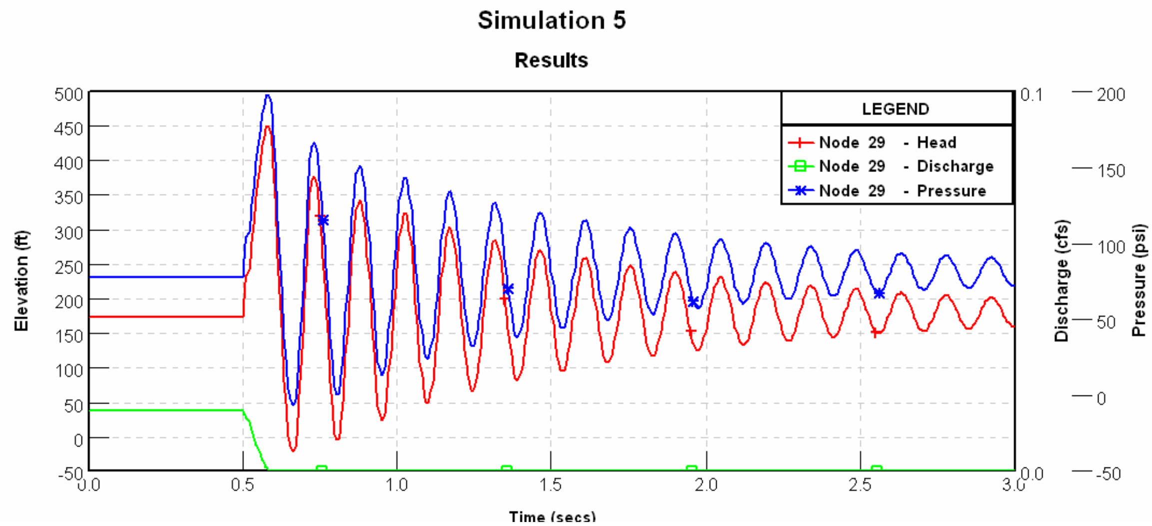


Figure 3.7 Simulation 5 results

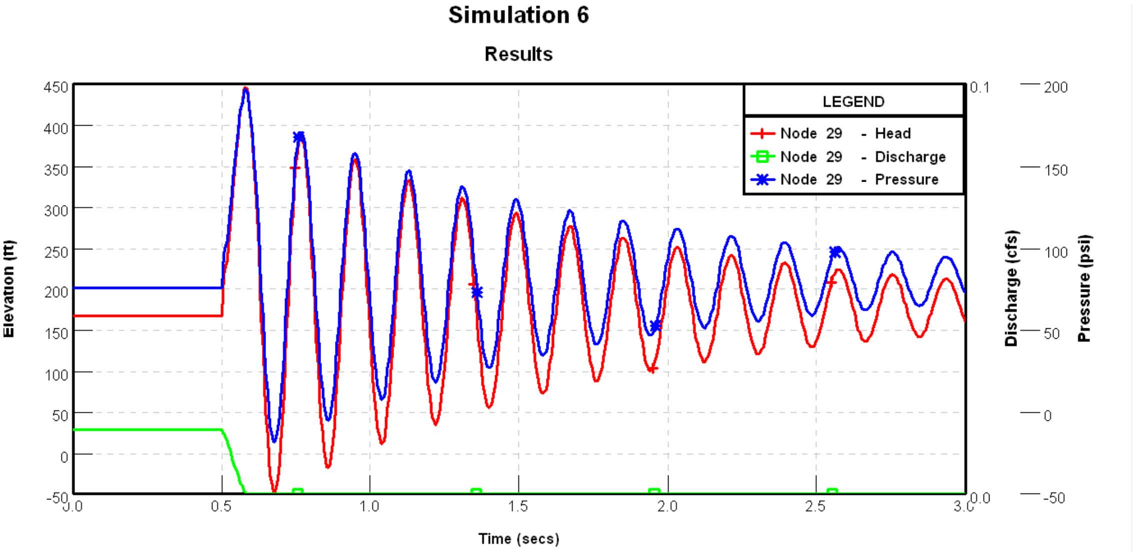


Figure 3.8 Simulation 6 results

Table 3.11 Node Comparison of Simulations 5 and 6

SIMULATION 5					SIMULATION 6				
	MAXIMUM		MINIMUM			MAXIMUM		MINIMUM	
NODE	HEAD	TIME	HEAD	TIME	NODE	HEAD	TIME	HEAD	TIME
	(FEET)	(SEC)	(FEET)	(SEC)		(FEET)	(SEC)	(FEET)	(SEC)
------	--------	------	--------	------	------	--------	------	--------	------
100	180.3	0	180.3	0	100	180.3	0	180.3	0
200	180.3	0	180.3	0	200	180.3	0	180.3	0
1	180.3	0	180.3	0	1	180.3	0	180.3	0
2	180.3	0	180.3	0	2	180.3	0	180.3	0
3	180.7	0.6	179.8	0.7	3	180.7	0.6	179.9	0.7
5	183.4	0.6	176.8	0.7	5	183	0.6	175	0.3
7	337.3	0.6	23.2	0.7	7	334.6	0.6	33	0.7
8	337.3	0.6	23.2	0.7	8	334.6	0.6	33	0.7
9	342.9	0.6	20	0.7	9	340.2	0.6	28.1	0.7
10	343	0.6	19.8	0.7	10	340.3	0.6	27.9	0.7
13	396.5	0.6	-5	0.7	13	393.1	0.6	-18.1	0.7
14	396.6	0.6	-5.1	0.7	14	393.1	0.6	-18.2	0.7
17	428.5	0.6	-17.5	0.7	17	424.7	0.6	-45	0.7
18	430.9	0.6	-17.8	0.7	18	426.9	0.6	-48.6	0.7
19	431.8	0.6	174.4	0	19	426.9	0.6	-48.6	0.7
190	433.6	0.6	174.4	0	190	429.4	0.6	-53.1	0.7
191	435.8	0.6	174.4	0	191	429.4	0.6	-53.1	0.7
20	435.8	0.6	174.4	0	20	429.4	0.6	-53.1	0.7
21	435	0.6	174.4	0	21	430.8	0.6	-55.2	0.7
24	435.2	0.6	174.4	0	24	429.8	0.6	-53.9	0.7
25	435.6	0.6	174.4	0	25	431.7	0.6	-56.4	0.7
28	430.1	0.6	-18.3	0.7	28	426.2	0.6	-45.6	0.7
29	450.7	0.6	-21	0.7	29	446.6	0.6	-48.1	0.7
32	432.8	0.6	-22.2	0.7	32	429	0.6	-48.8	0.7
33	433.3	0.6	-22.7	0.7	33	429.4	0.6	-49.2	0.7
36	436	0.6	174.4	0	36	431.9	0.6	-57.4	0.7
37	436.4	0.6	174.4	0	37	432.2	0.6	-57.9	0.7
40	433.3	0.6	-22.7	0.7	40	429.4	0.6	-49.2	0.7
43	436.4	0.6	174.4	0	43	432.2	0.6	-58	0.7

Table 3.12 WHAMO input file

```
Home Plumbing system model

C BC-All flow boundary conditions
C Valve- 1 check for back flow
C HWH- small pipe with loss and check valve, air chamber surge tank for the fluid expansion
C STREET MAIN IS REPRESENTED AS A RESERVOIR HW WITH APPROPRIATE HEAD
C REFER TO ELEMENT LIST AND SCHEMATIC DRAWING FOR CLARITY

SYSTEM
EL RES1 AT 100
el res2 at 200
el dumy link 100 1
el dum1 link 200 2
EL w1 LINK 1 3
el w2 link 2 3
junc at 3
EL METR LINK 3 4
EL CHK1 LINK 4 5                    (Back flow preventor to water main)
EL C1 LINK 5 7
el p1 link 7 8                      (Pump element)
el c2 link 8 9
el tee2 at 9 riser 13
EL C3 LINK 9 10
EL fbc1 at 10
EL C4 LINK 9 13
el tee3 at 13 riser 14
EL C5 LINK 13 14
EL fbc2 at 14
EL C6 LINK 13 17
el tee4 at 17 riser 18
EL C8 LINK 17 28
EL TEE1 AT 28 RISER 32
EL C9 LINK 28 29
EL fbc3 at 29                       (Washing machine flow boundary)
EL C12 LINK 28 32
el tee5 AT 32 riser 40
EL C15 LINK 32 33
EL fbc4 at 33
EL C18 LINK 32 40
EL fbc5 at 40
EL C7 LINK 17 18
EL ONWY LINK 18 19
junc at 19
el dum2 link 19 50
el tnk1 at 50                       (Water heater tank element)
EL HWH LINK 19 190
el hwp link 190 191
el hwp2 link 191 20
el tee6 AT 20 riser 21
EL C22 LINK 20 21
EL fbc6 at 21
EL C25 LINK 20 24
el tee7 at 24 riser 36
EL C26 LINK 24 25
EL fbc7 at 25
```

```
EL C29 LINK 24 36
el tee8 AT 36 riser 37
EL C32 LINK 36 43
EL fbc8 at 43
EL C30 LINK 36 37
EL fbc9 at 37
Node 100 elev -4
Node 200 elev -4
node 1 elev -4
node 2 elev -4
node 3 elev -4
node 4 elev 2
node 5 elev 2
node 6 elev 2
node 7 elev 5
node 8 elev 2
node 14 elev 5
node 19 elev 2
node 20 elev 2
node 21 elev -7
node 24 elev 2
node 25 elev -7
node 28 elev 2
NODE 29 ELEV -7
NODE 9  ELEV -3
NODE 12 ELEV 2
NODE 17 ELEV 2
NODE 15 ELEV 5
NODE 18 ELEV -2
node 37 elev 12
NODE 40 ELEV 15
node 43 elev 15
node 32 elev 12
node 36 elev 12
node 33 elev 15
node 40 elev 15
fini
```

C element properties

```
 RESE ID RES1 ELEV 180.3 FINI (Initial starting pressure of the street water main)
 rese id res2 elev 180.3 fini           (180.3 feet represents 80psi, will vary initial pressure)
 cond id dumy dummy fini
 cond id dum1 dummy fini
 cond id dum2 dummy fini
 coND ID W1 LENG 10 DIAM .5 CELE 4000 FRIC .01 FINI
 coND ID W2 LENG 10 DIAM .5 CELE 4000 FRIC .01 FINI
 CONDUIT ID C1 LENG 100 DIAM .1054 CELE 4000 FRIC .01 numseg 10 FINI
 Pump id p1 type 1 RQ .2027 Rhead 100 Rspeed 2900 rtorque 18.11
 wr2 1.03 fini
 Cond id c2 leng 5 diam .1054 cele 4000 fric .01 fini
 COND ID C3 LENG 5 DIAM .0654 CELE 4200 FRIC .01 numseg 10 FINI
 COND ID C4 AS C3 LENG 20 FINI
 COND ID C5 AS C3 LENG 3 DIAM .0454 FINI
 COND ID C6 AS C3 LENG 13 FINI
 COND ID C7 AS C3 LENG 5 DIAM .0854 FINI
```

```
 COND ID C8 AS C3 LENG 1 FINI
 tjunction id tee1 fillet 0 fini
 tjunction id tee2 fillet 0 fini
 tjunction id tee3 fillet 0 fini
 tjunction id tee4 fillet 0 fini
 tjunction id tee5 fillet 0 fini
 tjunction id tee6 fillet 0 fini
 tjunction id tee7 fillet 0 fini
 tjunction id tee8 fillet 0 fini
 COND ID C9 AS C3
 addedloss at 9 cplus .9 cminus .9 LENG 18 FINI
 COND ID C12 As c3 LENG 10 FINI
 COND ID C15 AS C3 LENG 8 FINI
 COND ID C18 AS C3 LENG 8 FINI
 COND ID C22 AS C3 LENG 16 FINI
 COND ID C25 AS C3 LENG 1 FINI
 COND ID C26 AS C3 LENG 18 FINI
 COND ID C29 AS C3 LENG 10 FINI
 COND ID C30 AS C3 LENG 8 FINI
 COND ID C32 AS C3 LENG 8 FINI
 COND ID METR LENG 1 DIAM .0854 CELE 4100 FRIC .01
 ADDEDLOSS AT .05 CPLUS 20.3 CMINUS 20.3 FINI
 ONEWAY ID CHK1 DIAM .0854 CLOSS 1 FINI
 ONEWAY ID onwy DIAM .0854 CLOSS 1 FINI
 COND ID HWH LENG 7 DIAM .0854 CELE 4100 FRIC .01
 ADDEDLOSS AT 1 CPLUS 6.3 CMINUS 6.3 FINI
 oneway id hwp diam .0854 CLOSS 1 FINI
 cond id hwp2 diam .0854 dummy fini
 surgetank id tnk1 air
 elbottom 2 eltop 8
 cele 4100 fric .02
 diam 1.5 temp 100
 pbar 14.5 N 1.25
 wsinit 7 fini                    (Water heater element, will change the wsinit for the case of no thermal
expansion tank)
 flowbc id fbc1 q 0 fini
 flowbc id fbc2 q 0 fini
 flowbc id fbc3 qsched 2 fini                (Flow schedule for the washing machine)
 flowbc id fbc4 q 0 fini
 flowbc id fbc5 q 0 fini
 flowbc id fbc6 q 0 fini
 flowbc id fbc7 q 0 fini
 flowbc id fbc8 q 0.00001 fini
 flowbc id fbc9 q 0 fini
```

```
PcharACTERISTICS type 1
Sratio
-1.5 -1.25 -1  -.75 -.5  -.25  0.00 .25 .5   .75  1
Qratio
-1.1 -.9   -.7 -.5  -.25 0.00  .25  .5  .75  1    1.25  1.5
Hratio
1.903  1.441  1.149  0.957   0.846  0.827   0.859   1.043  1.299   1.701   2.298
1.744  1.304  0.941  0.727   0.583  0.532   0.575   0.741  0.964   1.358   1.972
1.616  1.169  0.819  0.547   0.392  0.337   0.347   0.469  0.732   1.147   1.743
```

```
1.525  1.069  0.712  0.446   0.26   0.171   0.177   0.284  0.52    0.950   1.525
1.48   1.023  0.669  0.381   0.178  0.065   0.044   0.13   0.381   0.818   1.423
1.485  1.031  0.66   0.371   0.165  0.041   0.0     0.0843 0.337   0.759   1.35
1.179  0.828  0.541  0.2     0.034  -0.05   -0.0343 0.0625 0.284   0.706   1.285
0.675  0.416  0.137  -0.16   -0.23  -0.2    -0.137  -0.028 0.25    0.633   1.137
0.140  -0.42  -0.48  -0.52   -0.48  -0.42   -0.309  -0.168 0.487   0.562   1
-0.91  -0.79  -0.94  -0.82   -0.8   -0.71   -0.55   -0.403 -0.112  0.343   1
-1.48  -1.46  -1.35  -1.25   -1.19  -1.088  -0.859  -0.617 -0.308  1.275   0.563
-2.11  -2.02  -1.91  -1.8    -1.7   -1.526   -1.23  -1.11  -0.675  -0.253  1.95
Tratio
0.208   0.665   0.729   0.886   0.978   1.043  1.065  1.133  1.197  1.241  1.193
0.031   0.142   0.434   0.576   0.625   0.646  0.713  0.750  0.816  0.851  0.851
-0.329  0.021   0.089   0.253   0.311   0.409  0.431  0.475  0.459  0.495  0.536
-0.525  -0.218  0.013   0.049   0.120   0.184  0.220  0.241  0.270  0.293  0.425
-0.809  -0.358  -0.234  -0.131  0.003   0.030  0.055  0.068  0.106  0.219  0.393
-1.530  -1.063  -0.680  -0.383  -0.170  -0.043 0.000  0.028  0.110  0.248  0.440
-2.359  -1.658  -1.084  -0.756  -0.450  -0.209 -0.027 0.063  0.191  0.375  0.616
-3.225  -2.411  -1.800  -1.268  -0.835  -0.450 -0.108 0.044  0.250  0.479  0.763
-4.106  -3.315  -2.578  -1.879  -1.268  -0.738 -0.242 -0.031 0.203  0.563  0.859
-5.070  -4.228  -3.340  -2.547  -1.800  -1.063 -0.430 -0.117 0.175  0.531  1.000
-6.291  -5.219  -4.177  -3.315  -2.411  -1.625 -0.672 -0.179 0.073  0.531  0.871
-7.515  -6.214  -5.070  -4.050  -2.950  -1.919 -0.968 -0.601 -0.125 0.394  0.813
fini

OPPUMP
ID P1 OFF
FINI


C WSHC IS THE WASHING MACHINE AND IS QUICK CLOSING VALVE IN THIS SIMULATION

SCHEDULE
VSCHED 1 T 0.0 G 0
VSCHED 2 T 0.0 G 100 T 0.5 G 100 T .6 G 0
QSCHED 2 TIME 0 Q .00557 T 0.5 Q .00557 t 0.6 q 0          (Flow schedule, will vary flow and closure
times)
QSCHED 1 t 0 q 0 t .5 q 0
FINI


C OUTPUT REQUESTS

noecho

HISTORY
NODE 19 HEAD Q psi decimal 3 lines 50
node 1 head psi Q gpm
node 14 head psi q
node 3 head psi q gpm
node 4 head psi q gpm
node 29 head psi q
node 19 head psi q
node 43 head psi q
node 18 psi q
node 24 q gpm
node 43 q gpm
```

```
node 25 q
node 36 q gpm
node 37 q gpm

FINISH

PLOT
elem tnk1 elev volume pressure
node 29 head q psi
node 1 head  q
NODE 3 HEAd psi Q
node 13 head q
node 40 psi q head
node 14 head psi q
node 19 head psi q
FINISH

C COMPUTATIONAL PARAMETERS
CONTROL
DTCOMP 0.005 DTOUT .1 TMAX 3
 FINI

c check
GO
GOODBYE
```

Chapter 4 - WHAMO: Steady State Simulation and Boundary Conditions

In the previous chapter, usage scenarios of a residential plumbing system were modeled using WHAMO. The initial steady state conditions of the system before the transient is triggered and the boundary conditions are of great influence on the results of the simulation. This chapter aims to show how boundary conditions are handled in WHAMO, as well as comparing the steady state solutions of EPANET, a steady flow model, and WHAMO an unsteady model.

WHAMO Boundary Conditions

Three types of external boundary conditions are used in simulating fluid flow conditions in WHAMO. They are a fixed head reservoir, a fixed flow condition and a surge tank, which relates flow to head. The obvious choice for modeling discharge from a faucet is the flow boundary condition (FBC). However, the flow boundary condition requires the specification of the quantity of flow. The extent of the present discussion is how to model pressure head controlled flow normally called pressure driven flow. It is generally recommended that in pipe networks flows at nodes should be determined as a function of head at that node corresponding to the outlet device. To address this issue fully, we present simulations of the following problem (Finnemore and Franzini 2002) using WHAMO. Figure 4.1 shows the problem configuration.

Problem Statement:

Water at 60 °F flows from a reservoir through a cast iron pipe of 10 inch diameter, and 5000 ft length. The roughness, e, for cast iron is .00085 ft, and the relative roughness, e/D, is .00102. The elevation difference from the water surface elevation of the reservoir to the discharge point of the pipe is 260 ft. The pipe entrance is sharp-cornered but non-projecting with a loss coefficient of .5. What is the flow rate?

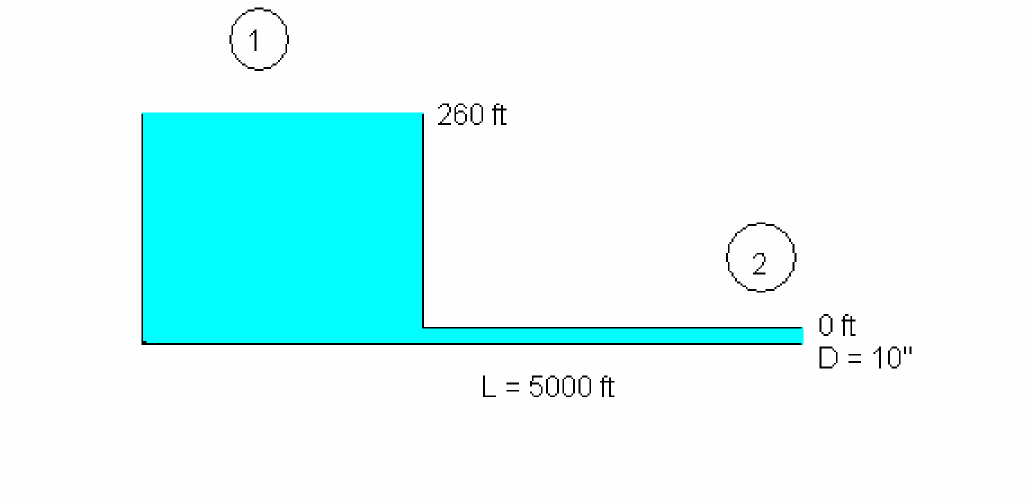


Figure 4.1 Problem Sketch

Solution by Hand

Because flow rate is the unknown, we cannot use the flow boundary condition. That leaves only two choices, either a reservoir or a surge tank should be at the downstream end. Because a surge tank is meant for a fluctuating water surface with finite tank size, the only possible boundary condition is the reservoir. Based on the fixed elevation for the reservoir, a zero head reservoir is adopted. The friction loss is absorbed in the conduit. To model the velocity head at the free end, an exit loss with a loss coefficient of 1 is applied. This configuration is shown in figure 4.2

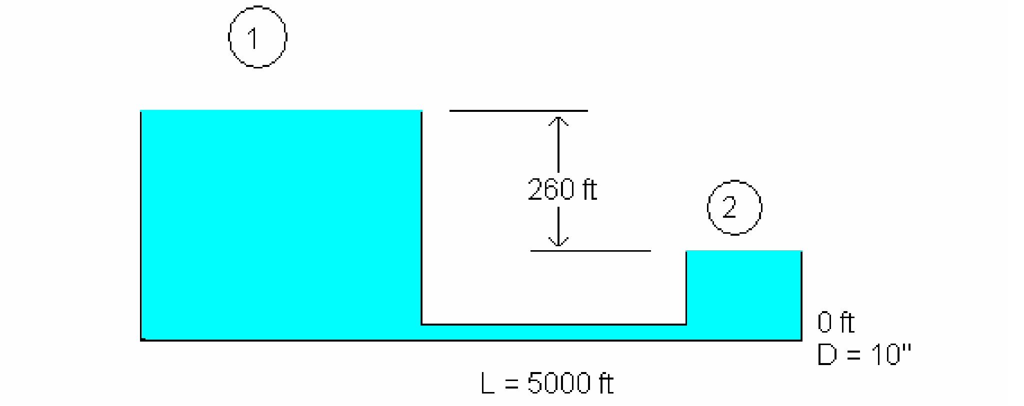


Figure 4.2 Equivalent Representation of the Free Flow Condition in WHAMO

Applying the energy eq. between 1 and 2 we obtain

$$Z_1 - h_{entrance} - h_{friction} - h_{exit} = Z_2 \qquad (4.1)$$

The application of the energy equation in figure 4.1 yields

$$Z1 - - h_{entrance} - h_{friction} = V_2^2/(2g) \qquad (4.2)$$

It is clear that for eqs. (4.1) and (4.2) to be identical, $Z_2 + h_{exit}$ must be equal to $V_2^2/(2g)$.

The friction factor, *f*, is a function of the Reynolds number, **R**, which is equal to (DV)/ν, where D is the diameter of the pipe, V is the velocity of the fluid, and ν is the kinematic viscosity of the fluid. There are equations to represent the friction factor that approximate the friction factor as a function of the relative roughness, but for a more accurate solution an iterative method is used. The iterative methods procedure involves estimating an approximate friction factor, solving the equation for velocity, calculating the Reynolds number and then recalculating the friction factor. If the calculated friction factor agrees with the estimated friction factor then the problem is done, but if is different, the process is repeated using the newly calculated friction factor as the estimated friction factor.

In the process of solving this sample problem by hand the friction factor converges to a value of .020. Rearranging the energy equation, eq. (4.2) to isolate the velocity and substituting the value of .020 for the friction factor yields

$$V_2 = (2(g)260/(1.5+6000(.020)))^{.5} \qquad (4.3)$$

$$V_2 = 11.74 \text{ ft/sec}$$

Now, solving for flow from the area and velocity

$$Q = \text{Area(Velocity)} = .25\pi(10/12)^2(11.74) = 6.40 \text{ cfs}$$

<u>Solution by WHAMO</u>

We now show use of WHAMO for solving the problem stated earlier. Note that in this problem we are seeking only a steady state solution. In the first run, we use a zero head for the second reservoir but omit the exit loss. Table 4.1 contains the WHAMO input commands.

Table 4.1 WHAMO input commands

```
SYSTEM
 EL HW AT 1
 EL C1 LINK 1 5
 EL C2 LINK 5 6
 EL TW AT 6
 NODE 1 ELEV 0
 NODE 5 ELEV 0
 NODE 6 ELEV 0
FINI

C ELEMENT PROPERTIES

 RESERVOIR ID HW ELEV 260 FINI
 CONDUIT ID C1 LENG 5000 NUMSEG 50 DIAM .833 CELE 4720 FRIC .02
 ENDLOSS AT HW CPLUS .5 CMINUS .5 FINI
 CONDUIT ID C2 DUMMY DIAM .833 CELE 4720 FRIC .02
 RESERVOIR ID TW ELEV 0 FINI
```

Items in bold in table 4.1 are the two reservoirs in figure 4.2. Reservoir HW is location 1 and TW is location 2. The input file structure has two parts. First is the system connectivity, second is the system properties. Appendix III provides a detailed explanation of the commands and input file (see table 4.1) structure for the WHAMO program. One difference between Figure 4.2 and the input file is the second conduit, which is a dummy conduit, and is there only to provide another node point before the reservoir to examine the solution results. The results of the simulation show that the flow through the system is 6.423 cfs, which is close to the hand solution computations presented earlier. A closer look at the output, however, reveals some discrepancies in the solution. *The energy head at node 5 is 0 and it is not the velocity head as it should be.* For proper accounting of the velocity head we use a coefficient of k = 1. The element properties command in the input file is changed to include endloss and is shown below.

CONDUIT ID C2 DUMMY DIAM .833 CELE 4720 FRIC .02
ENDLOSS AT TW CPLUS 1 CMINUS 1 FINI

*Adding the additional loss term in the WHAMO simulation,as shown in bold “**ENDLOSS AT TW CPLUS 1** CMINUS 1 FINI” for conduit 2, the program produces the correct answer, Q = 6.396 cfs. The energy at node 5 is 2.14 feet, which is the velocity head of the water exiting the system.*

The program produces the correct answer but has limitation of not calculating the friction factor as a function of the relative roughness and Reynolds number.

Steady State Pipe Network Analysis: Comparison of WHAMO and EPANET

In this section we would like to examine the steady state pipe network analysis solutions by EPANET and WHAMO. Water distribution systems are designed to operate under the peak hourly demand and the maximum daily demand plus fire flow. Under these worst case scenarios a certain minimum pressure is required. Tables of daily demands, fire flow requirements, and daily and hourly peaking coefficients can be found in Mays (1999). From the tables a single design demand can be calculated for each service location. For example, a single family residential has a fire flow requirement of 500-2000 gal/min. These fixed design demands can be inputted into EPANET and the system can be analyzed to check if the pressures at the service locations are above the minimum and below the maximum.

Water consumption is not static; it varies with the season, day of the week, and time of day. Small systems analyzed over shorter time periods are subject to greatest fluctuations in demand (Mays 1999). The peak hour flow coefficients range from 2 to 7 times greater than the average daily demand for the U.S. range (Mays 1999). In EPANET, the time varying demands are modeled using the extended period simulation procedure. In this method, a series of steady state problems are solved by updating the conditions (tank levels, demands, supplies, pump conditions, and valves) at the end of each time interval. In WHAMO, the unsteady equations are solved including the consideration of pipe expansion and fluid compressibility. This is where the application of the WHAMO program can be extremely useful.

The EPANET map of a hypothetical system is shown below in figure 4.3. Each node is identified with a number and the pipes are listed p1, p2, …, p13. There are eleven nodes and thirteen pipes.

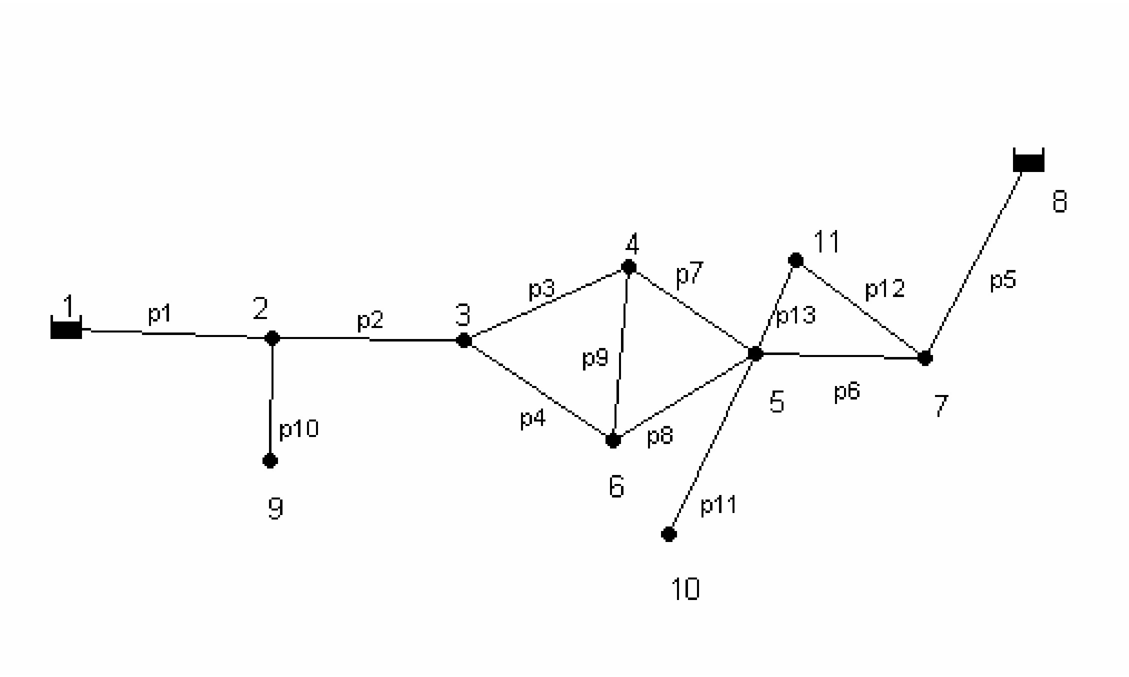


Figure 4.3 EPANET Network Map

Nodes 1 and 8 are reservoirs with 150 and 140 feet of head respectively. At node 5 there is a demand of 5 cfs, and at nodes 6 and 11 there is a demand of 1 cfs. All pipes are 8 inches in diameter, 1000 ft in length, and have a roughness height of .85 milli feet or 0.85(10^-3) ft.. The pipe network shown in figure 4.3 is simulated in both EPANET and WHAMO. Results of the simulation are summarized by nodes in Table 4.2, and by pipes in Table 4.3. The EPANET input data is presented in Table 4.4 and the WHAMO input file is presented in Table 4.5. Both methods use different equations to solve the system. For steady state analysis, EPANET solves the continuity and energy equations. WHAMO uses the continuity and momentum equation to solve for the steady state and transient analysis. WHAMO does have internal boundary conditions where the head at one node must equal the head at the next node plus the head loss between them. It is clear from Tables 4.2 and 4.3 both EPANET and WHAMO yield the same results.

In the following, the steady state momentum eq. is reduced to the steady state energy eq. to explain the identical solutions albeit the discrepancies due to numerical solvers. The unsteady momentum equation is

$$\frac{\partial V}{\partial t} + g\frac{\partial H}{\partial x} + \frac{f|V|V}{2D} = 0 \qquad (4.4)$$

In this equation, the elevation and pressure terms are grouped into a single term H and the $V\frac{\partial V}{\partial x}$ term is neglected because the velocity change with respect to position in a single pipe link is negligible. For steady flow $\frac{dV}{dt} = 0$ and changing the partial derivative into difference form the head loss can be represented as

$$\Delta H = f L V^2/(2gD) \tag{4.5}$$

which is the Darcy-Weisbach equation.

Considering the complete momentum equation

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g\sin\alpha + \frac{f}{2D}V|V| = 0 \tag{4.6}$$

for steady flow we have $\frac{\partial V}{\partial t} = 0$.

Therefore, the steady state momentum eq. is

$$V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g\sin\alpha + \frac{f}{2D}V|V| = 0 \tag{4.7}$$

Because the above eq. involves just one independent variable namely, x, we can write the partial derivatives as total derivatives and we obtain

$$V\frac{dV}{dx} + \frac{1}{\rho}\frac{dp}{dx} + g\sin\alpha + \frac{f}{2D}V|V| = 0 \tag{4.8}$$

which is integrated with respect to x as

$$\int V\frac{dV}{dx}\,dx + \int\frac{1}{\rho}\frac{dp}{dx}dx + \int g\sin\alpha\,dx + \int\frac{f}{2D}V|V|dx = 0 \tag{4.9}$$

Using $\sin \alpha = \dfrac{dZ}{dx}$

we have

$$\int V \frac{dV}{dx}\,dx + \int \frac{1}{\rho}\frac{dp}{dx}dx + \int g \frac{dZ}{dx}dx + \int \frac{f}{2D} V\left|V\right| dx = 0 \qquad (4.10)$$

and the integration between upstream section 1 and downstream section 2 yields

$$(V2^2 - V1^2)/2 + (p2\text{-}p1)/\rho + g(Z2 - Z1) + (fl/2d)V^2 = 0 \qquad (4.11)$$

which is rewritten as

$$p1/\gamma + V1^2/2g + Z1 - (fl/d)V^2/2g = p2/\gamma + V2^2/2g + Z2 \qquad (4.12)$$

which is precisely the steady state incompressible fluid energy eq. However, when external machinery are involved, the momentum eq. cannot be reduced to the steady state energy equation. For friction losses the representation through the shear stress $\tau = (\gamma A h_f)/(\tau_o PL)$ enables equivalence. For external machinery, in the differential form of the momentum eq., the machinery is dismantled into internal boundary conditions. However, the consideration of the machinery separately though the imposed boundary conditions should lead to the same energy considerations.

The small differences between the EPANET results and the WHAMO results are probably due to the roundoff error in friction factor and the different methods each program uses for solving the problem. The friction factor used for the WHAMO simulation was taken from the results of the EPANET simulation. The output of the friction factor is only to three decimal places and for long pipe lengths small rounding errors in friction factor influence the final solution. Also, WHAMO uses an implicit finite difference method while EPANET uses a gradient method to solve the simulation. The WHAMO output file provides the details the WHAMO simulation and results.

The WHAMO program has the capability to specify a schedule for the reservoir head and the flow schedule so it has the power to model a small water distribution system not only for the peak demand but for the all the different demands throughout the day and the transient flow produced by the ever changing demand. To examine the usefulness of an unsteady solver for water distribution systems the hypothetical system shown in figure 4.3 is modeled with a single demand starting at 0 flow, then changing to 1 cfs, then returning to 0 cfs over the course of 2.5 minutes. The system is initially at rest. The program WHAMO encounters computation errors if there is no flow in the system so a flow rate of 0.0000001 cfs is released from node 8. The head at all points in the system is 150 feet while initially at rest so the small amount of flow released for computational purposed has no significant effect on the simulation. Ten seconds into the simulation the demand begins and it reaches 1 cfs 12 seconds into the simulation. After 42 seconds the demand begins to lessen, and after 44 seconds the demand is zero again. The demand is changed using the FBC that connects with node 5. The goal of this simulation is to see the nature of the flow, and how close it is to the steady flow approximation.

Figure 4.4 shows the results of the simulation for node 7, which is indicative of the nodes throughout the system. For this simulation the flow is not steady, and it oscillates throughout the entire simulation and it appears unsteady approach would be preferred. However, it is a single example and every system has its own unique behavior and results from a single example cannot be extrapolated to all systems in general.

The WHAMO program has a feature where the computational and output time steps can be specified allowing for accurate and efficient computing. For WHAMO modeling of water distribution systems in general, during periods of interest or intense water consumption, a short time step can be specified in order to accurately model the transients, and likewise, during less active periods, a larger computation time step can be specified to save computer time. The power of the program is limited in a few ways though. Only 400 elements and 65 branches can be modeled for one simulation, so the size of the water distribution system modeled is limited. Also, as stated earlier, the friction factor is supplied by the user and not calculated by the program so some accuracy is lost there.

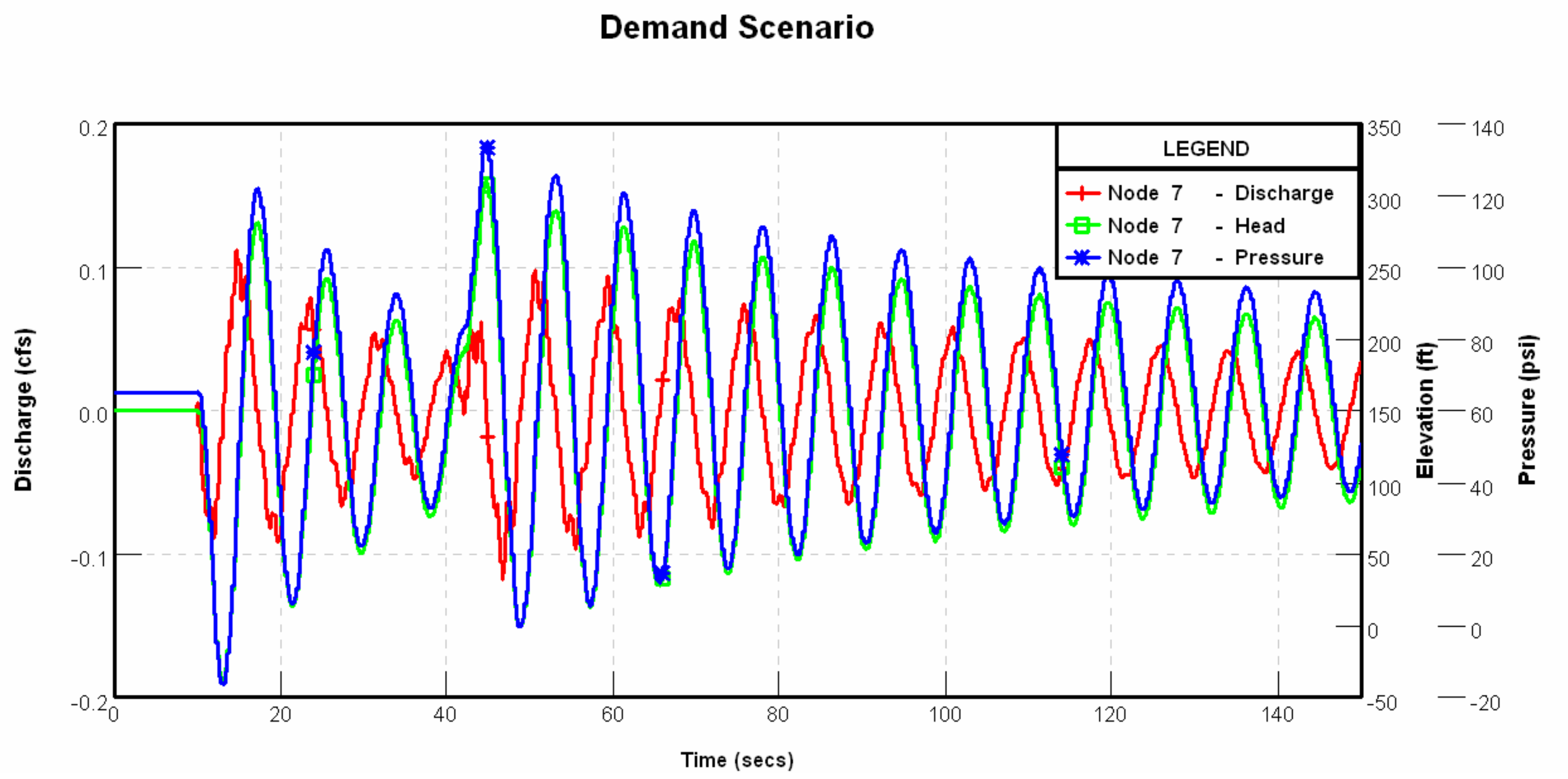


Figure 4.4 Example Demand Scenario

Table 4.2. Results for Nodes

EPANET node results			
Node	Demand	Head	Pressure
ID	CFS	Feet	psi
2	0	112.03	48.54
3	0	74.06	30.79
4	0	64.75	28.06
5	5	59.88	25.94
6	1	63.94	27.71
7	0	76.19	33.01
9	0	112.03	48.54
10	0	59.88	25.94
11	1	63.25	27.4

WHAMO node results			
Node	Demand	Head	Pressure
ID	CFS	Feet	Psi
2	0	112.7	48.84
3	0	75.4	32.67
4	0	66	28.60
5	5	61.2	26.52
6	1	65.2	28.25
7	0	77.3	33.50
9	0	112.7	48.84
10	0	61.2	26.52
11	1	64.4	27.91

Table 4.3. Results for Pipes

EPANET			WHAMO	
Link	Flow		Link	Flow
ID	CFS		ID	CFS
P1	3.04		P1	3
P2	3.04		P2	2
P3	1.49		P3	1.5
P4	1.55		P4	1.6
P5	3.96		P5	-4
P6	1.98		P6	-2
P7	-1.07		P7	1.1
P8	-0.97		P8	1
P9	-0.42		P9	0.4
P10	0		P10	0
P11	0		P11	0
P12	1.97		P12	-2
P13	0.97		P13	-1

Chapter 5 - Abnormal Pump Operation

Pumps are a significant element of a water distribution system, and their impacts on transients are significant as well. Pumps can cause significant transient events, by start up or shut down, and have a major impact. Studies of abnormal pump operation started back in the 1930's and have continued ever since. This chapter is intended to provide a clear explanation of pump operation during transient events, and the impact the pump's characteristics have on a transient event. An example is presented to illustrate a simple case abnormal pump operation. The eight zones of operation and four quadrant representation of the pump characteristics are explained, and a graphical illustration of the pump characteristics is examined to provide clarity to the subject.

A simple example of pump operation is the following. Water in a lower reservoir is lifted by a pump to a reservoir at a higher elevation. In this case, the natural energy grade line slopes upward from the lower reservoir to the higher reservoir so the natural direction of the flow is from the higher reservoir to the lower reservoir. The pump at the lower reservoir provides the head to overcome the elevation difference and head losses between the two reservoirs, and causes the water to flow from the lower reservoir to the upper reservoir. If a sudden power failure happens the electric motor no longer provides any torque to the pump, and the torque on the pump is solely from the flow in the system. Although the power supply to the pump stops suddenly, the impeller does not stop rotating immediately. The inertia of the rotating parts will keep the impeller rotating for some time. Without the electrical power to keep the pump running at full speed, the pump is not able to keep the same flow rate as before the power failure. The higher head on the upstream side of the pump would cause the flow to decrease in the system and this change in flow causes a high pressure wave on the upstream side of the pump and negative pressure wave on the downstream side of the pump. The flow continues to decrease and eventually will reverse direction and flow in its natural direction, from the upper reservoir to the lower reservoir. At this point the pump is still rotating in the positive direction but the flow is moving opposite to the rotation of the pump. The negative total torque on the impeller continues the negative rotational acceleration and at some time the impeller will stop rotating in the positive direction and begin rotating in the negative direction. The pump acts as a turbine and continues to accelerate in the reverse direction until the impeller is rotating at such a speed that the fluid can not apply any more torque on the impeller. At this point, equilibrium is reached and the condition is called a runaway turbine.

An experiment simulating a sudden pump power failure was done by Knapp in 1937 (Knapp 1937). The pump used was a 4-inch double suction pump. The results of the power failure are graphed out in figure 7 (Knapp 1937) showing the path of the transient on the pump characteristics diagram. The complete characteristics diagram for a pump will be explained further later on in this section. From this diagram, one can identify the head, flow, speed, and torque values as the pump passes through its various phases during the power failure. For this case, the head is constant at 150 feet, and the suction and discharge lines are short with large diameters so the effects of friction can be ignored. The pump is operating at a speed of 3200 rpm before the pump trip. The values for speed, torque, and flow can be seen in Table 5.1

Table 5.1 Values of Speed, Torque and Flow for a Sudden Power Failure

Speed, N, Rpm	Torque in ft-lb	Q, cfs
3200	50	1.5
3050	40	1
2900	30	0.65
2850	20	0.2
2750	13.3	-0.35
2450	20	-0.85
2100	30	-1
1500	40	-1.2
600	50	-1.4
0	54	-1.5
-500	55	-1.6
-1300	50	-1.55
-2350	40	-1.5
-3050	30	-1.4
-3350	20	-1.25

The pump reaches runaway conditions, zero torque, at a negative speed of 3600 rpm. The sign convention used for torque in the literature and characteristic diagrams for abnormal pump operation can be a bit confusing. Generally, the term torque is considered the rotational force that the fluid exerts on the pump. Pump torque is the torque that the driving shaft exerts on the pump. In normal steady-state pump operations, the pump torque is positive and in the direction of rotation and the fluid torque is of equal magnitude and of opposite direction so that the sum of both torques is zero and the angular acceleration is zero. In relation to the positive direction of rotation of the pump in normal operations, the fluid torque on the pump would be negative. However, the convention for abnormal operation is to consider the fluid torque as positive. This sign convention is taken care of in the equation for the unbalanced torque to the system. Instead of the general equation for the unbalanced torque, $T_{total} = T_{pump} + T_{fluid}$, the equation $T_{total} = T_{pump} - T_{fluid}$ is used.

Complete Pump Characteristics

The pump characteristics are needed to provide the relationships between flow, head, speed and torque to solve the pump operation problem. The efficiency is a function of the other variables so it can be determined if the other values are known. Pump characteristics can normally be obtained from the manufacturer for the normal conditions. However, during transient conditions, pumps act abnormally and the characteristics of abnormal operation are needed. The first investigation of pumps operated under abnormal conditions was done by Kittredge and Thoma in 1931 (Kittredge and Thoma 1931) where they ran a small pump under conditions of negative head, flow, and speed. A few years later, Knapp, continued this investigation with a larger, more efficient pump that represented a modern installation (Knapp 1937). He used two pumps in a loop to simulate the full range of operated conditions. The results were a set of characteristic curves for all types of operation. Pump characteristic data from the WHAMO user's manual (Fitzgerald and Van Blaricum) illustrate the characteristic curves in figures 5.2-5.5.

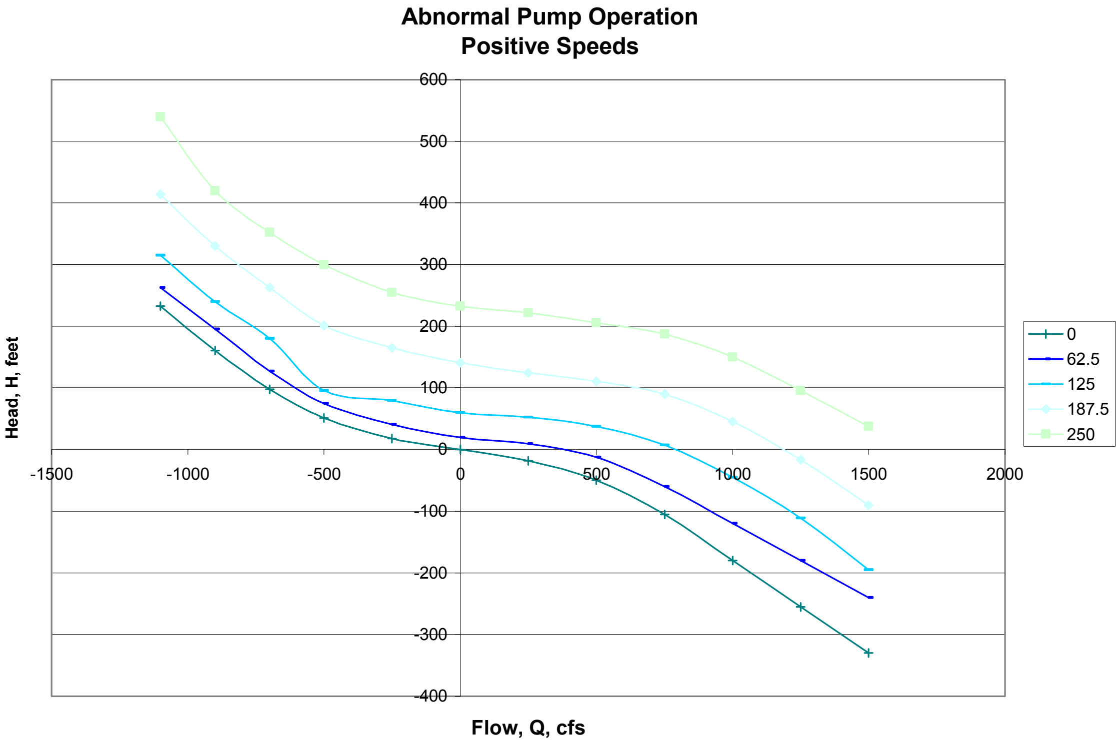


Figure 5.1 Positive-Rotation Head-Discharge Curves

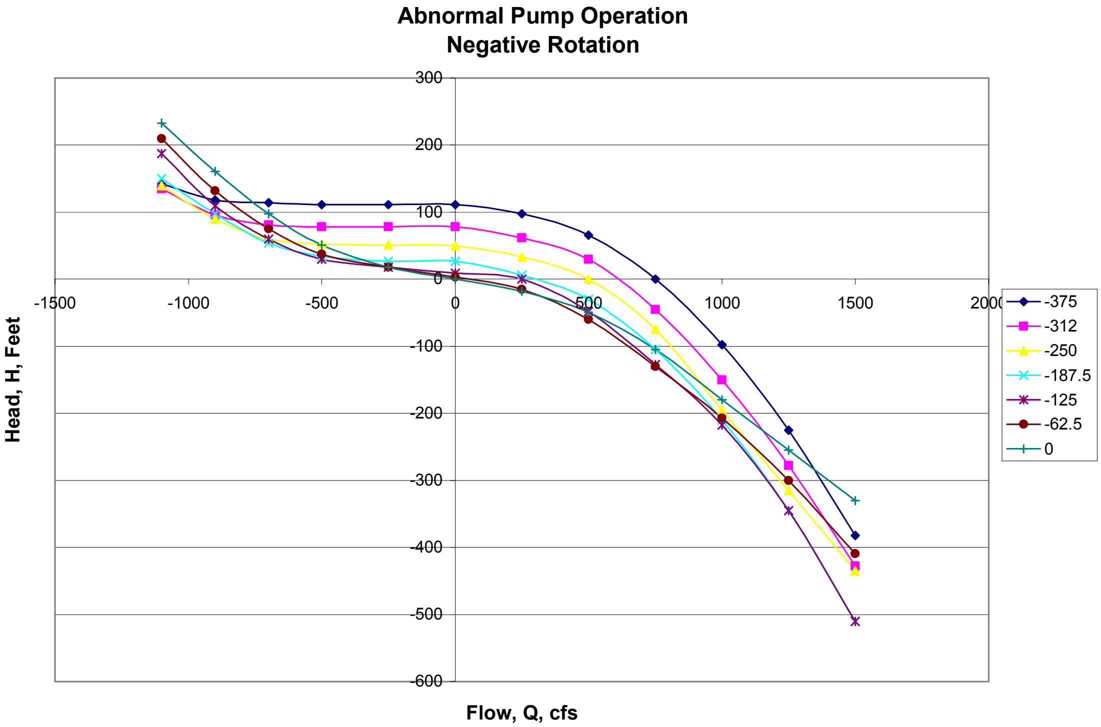


Figure 5.2 Negative-Rotation Head-Discharge Curves

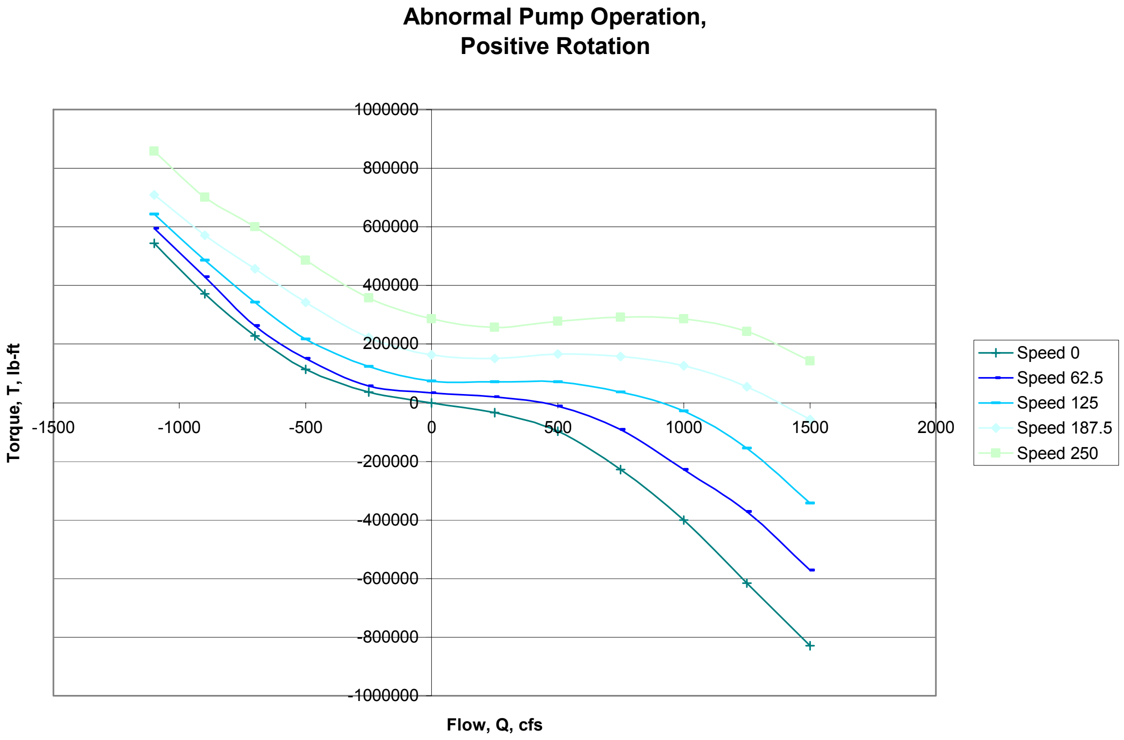


Figure 5.3 Positive-Rotation Torque-Discharge Curves

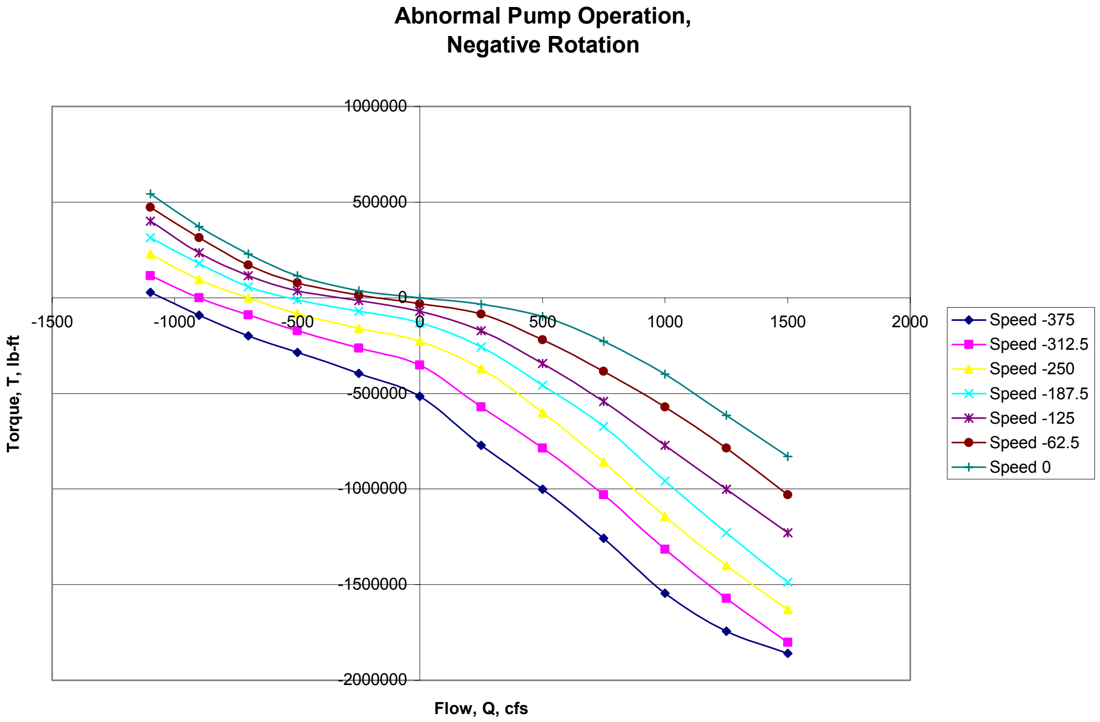


Figure 5.4 Negative-Rotation Torque-Discharge Curves

A normal pump curve provided by a manufacturer would consist of a small part of positive-rotation head-discharge curve. Von Karmen suggested that a comprehensive diagram be presented including all characteristics in a single figure (Knapp 1937). This figure, known as the Karman-Knapp circle diagram, is arranged with speed on the x-axis and flow on the y-axis dividing the figure into four quadrants, and plotting lines of constant head and constant torque. For the characteristics shown in figures 5.2 to 5.5, the torque and head values have a large difference on their magnitude and a single plot would be unable to accurately show both, so this is one reason why the dimensionless values are used. The four quadrants are arranged in a counter-clockwise fashion. Quadrant I, has positive flow and positive rotation. Quadrant II has positive flow and negative rotation. Quadrant III has negative flow and negative rotation, and Quadrant IV has negative flow and positive rotation. In addition to combining four sets of curves into one figure, the Karman-Knapp circle diagram is useful in visualizing and understanding the physical picture as well. Many critical operation points can be obtained directly from the diagram.

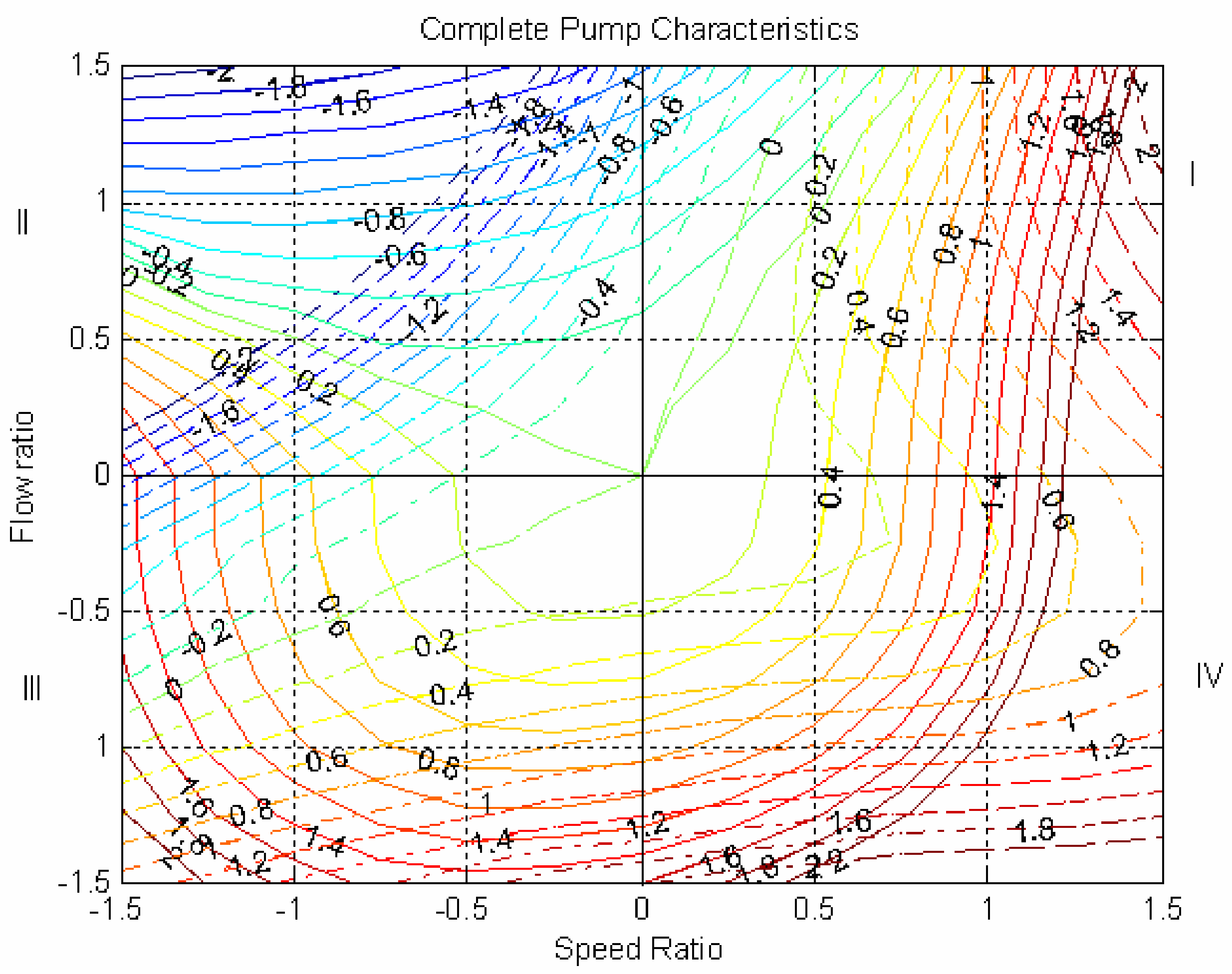


Figure 5.5 **Karman-Knapp Complete Characteristics Diagram**

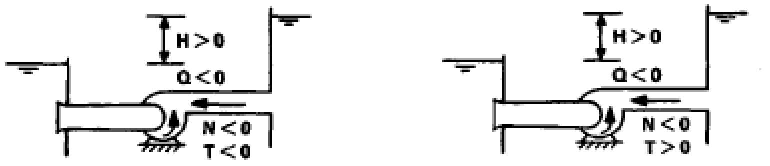
The solid lines are lines of constant head, and the dashed lines are lines of constant torque. Some important features of the diagram are the lines of zero flow, head, speed and torque. The example of pump failure discussed in the beginning of this chapter can be used to show the usefulness of this diagram. At the time of power failure, the pump is operating in quadrant I in the sector of normal pump operation. The example is one where the head is constant so one can follow the constant head line to find the characteristics during the transient event. As the flow slows down the speed at which the flow reverses can be found by finding the intersection of the constant head line with the flow axis. After this point the pump is operating in quadrant IV in the sector of energy dissipation. The point where the pump ceases to rotate in the positive direction and begins to operate as a turbine can be found by where the constant head line intersects with the speed axis. Now the pump is operating in quadrant III in the sector of normal turbine operation. The pump reaches equilibrium at the point where the constant head line intersects the line of zero torque. The speed at the line of zero torque is the runaway speed of the machine.

In each quadrant there can be different modes of operation called sectors or zones. Martin (1983) developed a figure that illustrates the eight zones of possible pump operation in the four quadrants

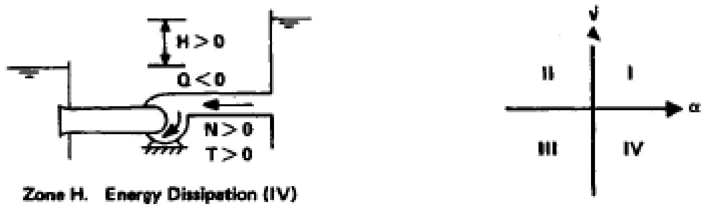
Zone A. Normal Pumping (I)   Zone B. Energy Dissipation (I)

Zone C. Reverse Turbine (I)   Zone D. Energy Dissipation (II)

Zone E. Reverse Rotation Pumping Radial–Flow Machine (II)   Zone E. Reverse Rotation Pumping Mixed-or Axial-Flow Machine (III)



Zone F. Energy Dissipation (III)   Zone G. Normal Turbine (III)



Zone H. Energy Dissipation (IV)

Figure 5.6 4 Quadrants and Zones of Operation (From Martin 1983)

In quadrant I where the flow and speed are positive there are three zones of operation. Zone A is the zone of normal pumping operation, where useful work is being done by the pump and head and torque are positive. The sign convention discussed in the beginning of this chapter is used and the torque is only the fluid torque, not the motor torque. Zones B and C occur when the head across the pump is negative. Zone B is quite an abnormal condition. This condition is an energy dissipation condition and it is similar to a turbine that is rotating faster than the runaway speed so the fluid is acting to slow the rotation of the impeller down to the point where it reaches runaway speed, except that the blade angle is that of a pump and not of a turbine. Zone C is the reverse turbine zone. The impeller acts a turbine and can produce useful energy. The efficiency would be very low though due to the blade angle and exit conditions. The line of zero torque is the boundary between zones B and C.

In quadrant II there are two zones of operation. Zone D is a zone of energy dissipation. In this case flow is traveling from higher head before the pump to a lower head after the pump but the pump is rotating in reverse causing energy to be lost as it passes through the pump. Zone E is where the pump, rotating in the wrong direction, is able to provide enough energy to have a positive gain in head across the pump. The efficiency of zone E would be very low due again to the improper blade angle and poor exit conditions. The occurrence of operation in quadrant II is very infrequent.

Quadrant III contains the zones of normal turbine operation and an energy dissipation zone. Zone G is the zone of normal turbine operation, and as the name of the zone says, a turbine operating under normal conditions would be operating in zone G. This zone is often encountered during a pump power failure as can be seen in the example in this chapter. Useful energy could be produced from this situation. Zone F is case where the turbine is rotating faster than the runaway speed, the fluid produces a braking effect on the impeller and no useful work is done. The boundary between zone F and zone G is the line of zero torque.

Quadrant IV is comprised of a single zone solely of energy dissipation. Zone H is encountered shortly after power failure to a pump. This zone of operation begins where the pump is being overpowered by the head across the pump and flow begins to reverse direction. It ends when the flow of the water has finally stopped the pump from rotating in the positive direction and it starts to rotate in the reverse direction. During this time the action of the pump is only creating an energy loss to the flow as it moves in the opposite direction of the rotating impeller.

Similarity and Specific Speed

Pump curves for a selected pump for normal operation can usually be found but complete characteristics are rare. In situations where there are tests done to determine the complete characteristics it is impossible to test every possible combination of parameters to determine the complete set of characteristics. Homologous relationships overcome these deficiencies. Kinematic similarity can be used assuming a similar relationship of the velocity triangle. This ratio is defined as the flow coefficient.

$$\Phi = V_m/U = V_m/(\omega R) \tag{5.1}$$

Where, V_m is the meridial velocity, which is the component parallel to the stream lines and U is the linear velocity. The ratio of the major forces on the pump, inertia to pressure forces, yields the Euler number. The other forces besides inertia and pressure may be neglected (Martin 1983). The reciprocal of the Euler number is called the flow coefficient and is represented by C_h.

$$C_h = gH/(\omega^2 D^2) \tag{5.2}$$

A third dimensionless coefficient relating the torque to speed can be defined

$$C_T = T/(\rho\omega^2 D^5) \tag{5.3}$$

The importance of these coefficients is that they provide a relationship between flow, head, and torque versus speed. Flow varies with ω and head and torque vary with ω^2. From these relationships a single curve in the Karman-Knapp circle diagram the entire family of curves can be extrapolated. Combining eq (5.1) and eq (5.2) in a manner to eliminate the geometric variable yields the specific speed.

$$\mathrm{Ns} = \frac{N_R Q_R^{.5}}{H_R^{.75}} \tag{5.4}$$

Where, in US units N_R is in Rpm, Q_R is in gpm, and H_R is in feet. For specific speed in SI units, the input units for the equation are rad/s, m3/s, and m. 1 SI unit of specific speed equals 2733 US units. Specific speed is important because it is said that pumps with the same specific speed tend to be geometrically similar (Mays 1999) and pumps of the approximately the same specific speed can use the same set of complete pump characteristics (Chaudhry 1987). Martin (1983) provides a summary table of pumps that have their complete characteristics documented and their references for a wide range of specific speeds.

Work by Benjamin Donsky (1961) examined three different pumps with different specific speeds. The pumps examined were radial flow, mixed flow, and axial flow. Radial flow pumps develop their head by centripetal force and are generally used for large heads. Axial flow pumps develop their head by the lifting of water on the vanes of the pump, and are used for lower heads. Mixed flow pumps displace water in both the radial and axial directions pumps are used for intermediate heads. Radial flow pumps correspond with lower specific speeds an axial flow pumps correspond with higher specific speeds. Donsky (1961) concluded that radial flow pumps, the lowest specific speed, cause a greater change in head and surge during a power failure event than the mixed and axial flow machines, and for design purposes choosing a lower specific speed will produce a more conservative design.

The h curve represents $h/(\alpha^2+v^2)$ and the B curve represents $\beta/(\alpha^2+v^2)$. They are plotted against theta, which equals 180 + $\arctan(v/\alpha)$. Quadrant III is from 0 to 90 degrees, quadrant IV is from 90-180, quadrant I is from 180-270 and quadrant II is from 270-360. This representation of the pump characteristics lacks the physical meaning of the Karman-Knapp circle but it is now the preferred method of representing pump characteristics.

Transient Pump Operation Mathematics

The general equation of motion for a rotating system provides the mathematical relationship between the torque on the pump and the rotational speed.

$$Ttotal = I\, d\omega/dt \qquad (5.5)$$

Where,

T_{total} = unbalanced torque on the system

I = the moment of inertia of the pump's rotative parts and fluid entrained in the pump about the axis of rotation

ω = angular velocity in radians per second

t = time

Converting equation 1 from radians per second to revolutions per minute yields

$$T_{total} = (\pi I/30)\, dN/dt \qquad (5.6)$$

Eq. (5.6) relates the characteristics of the pump operation with time. If a mathematical relationship exists between torque and speed, the equation can be integrated analytically. Normally, this analytical relationship is not available. Separating the variables, equation 2 may be integrated, yielding

$$t_1 - t_2 = (I\pi/30) \int_{N1}^{N2} (1/T)\, dN \qquad (5.7)$$

The procedure to solve equation 3 is to solve it graphically. If the quantity ($I\pi/30T$) is plotted as a function of N, the area under the curve from N_1 to N_2 is the time required for the change in speed. For the power failure example Table 5.2 illustrates the procedure.

Table 5.2 Relation of torque to change in angular velocity

Torque in ft-lb	(Iπ)/30T	Area	Time	dw/dt
50	250.96		0.00	-84.56
40	200.77	1.77	1.77	-65.23
30	150.58	2.30	4.07	-45.66
20	100.38	1.10	5.17	-30.40
13.3	66.76	3.29	8.46	-30.40
20	100.38	9.87	18.33	-45.66
30	150.58	7.67	25.99	-65.23
40	200.77	9.20	35.19	-84.56
50	250.96	10.64	45.84	-98.79
54	271.04	6.07	51.91	-103.68
55	276.05	4.82	56.73	-99.66
50	250.96	8.03	64.76	-84.56
40	200.77	12.42	77.18	-65.23
30	150.58	10.73	87.91	-45.66
20	100.38	6.57	94.48	-0.28

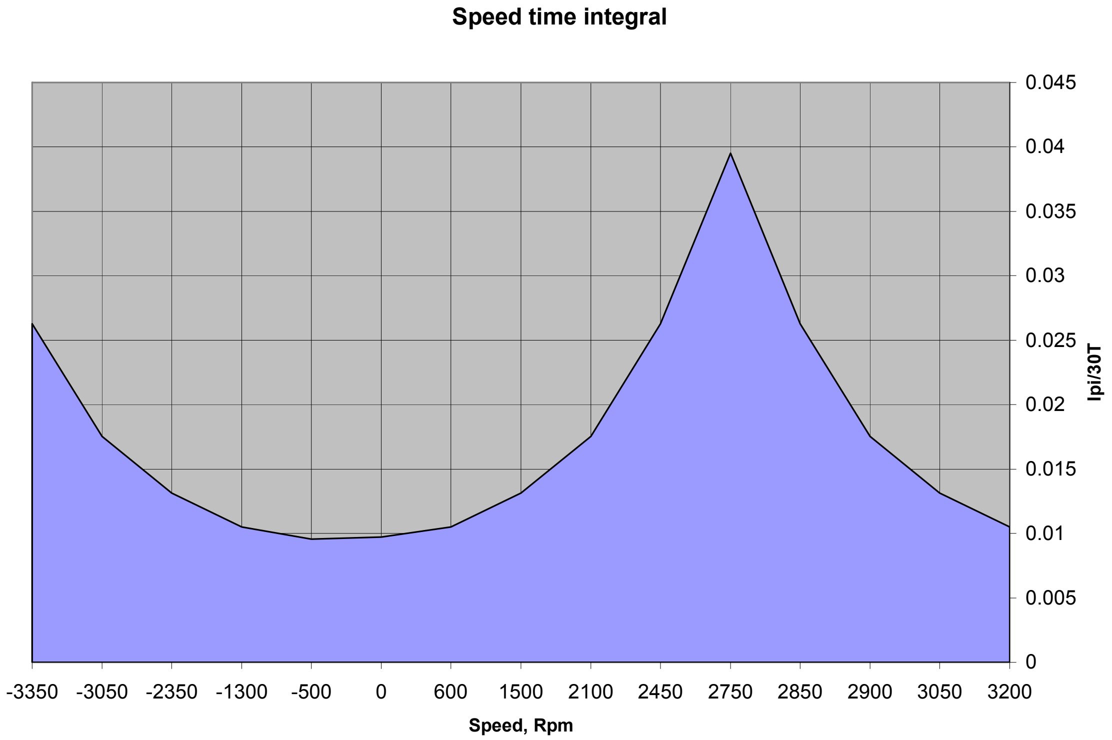


Figure 5.7 Speed Time Integral

The area under the curve was found, using a simple trapezoidal method. The formula for this method is

$$\text{Area} = (I\,\pi)/30)(N2-N1).5(1/T2+1/T1) \qquad (5.8)$$

The cumulative area, or time, is the fourth column in the table. Now the change in angular velocity of the pump with respect to time is known as. A comparison between the calculated time and the experimental time show a very good agreement. Some of the minor disagreement may be due to small error in reading values off the characteristics diagram (Knapp 1937). Figure 5.2 shows the computed and experimental results

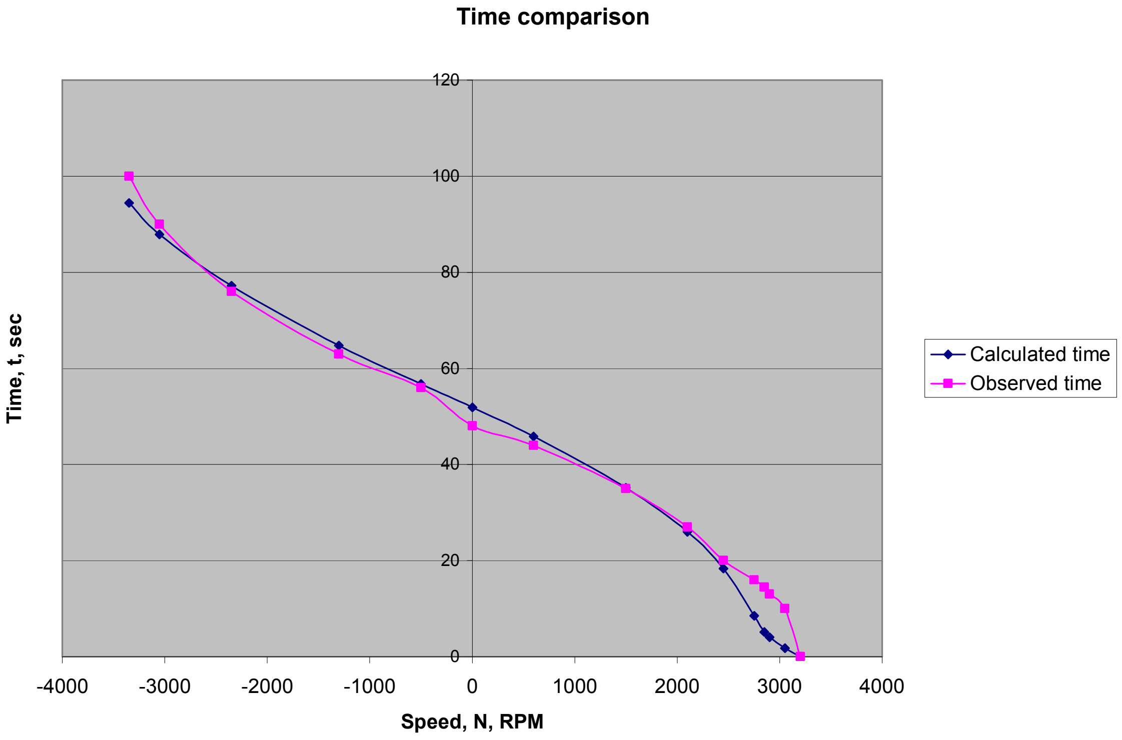


Figure 5.8 Calculated and Experimental Speed Time Relationship

For this example the across the pump was constant so with the head known and the speed known at the next time step, the flow rate and torque could be found from the characteristics of the pump. This constant head case would occur if there was a reservoir directly on the other side of the pump with a constant head. This is the simplest case. In general, the relationship between head across the pump, speed and flow rate is a complex one. It is a function of the head produced by the pump, the flow rate, and the static head. The static head is the head the pump is working against and is changing depending on factors throughout the rest of the system.

It is convenient to use dimensionless parameters for the pump characteristics. The head, flow, speed, and torque at the point of best efficiency are called the rated conditions, indicated with the subscript R. The dimensionless characteristics are the head, flow, speed, and torque divided by their rated quantity.

$h = H/H_R$ Dimensionless head on the pump (5.9)

$v = Q/Q_R$ Dimensionless flow through the pump (5.10)

$\alpha = \omega/\omega_R$ Dimensionless rotational speed of the pump (5.11)

$\beta = T/T_R$ Dimensionless torque applied to the pump (5.12)

Since pump characteristics are usually given in this dimensionless form, it is useful to write eq. (5.1) in dimensionless form as well. Starting with eq. (5.1) multiplying each side by (T_R/T_R) and $(\omega_{R/}\ \omega_R)$ the equation becomes

$$T_R(\beta_M - \beta) = I\ (d\alpha/dt)\ \omega_R \tag{5.9}$$

where, β_M is the dimensionless torque applied to the pump from the motor. Rearranging the equation in terms of $(d\alpha/dt)$ yields

$$(d\alpha/dt) = T_R(\beta_M - \beta)/(\ I\ \omega_R) \tag{5.10}$$

Letting

$$t_m = I\ \omega_R/\ T_R \quad = \eta_R\ I\ \omega_R^2/(\gamma Q_R H_R) \tag{5.11}$$

eq. (15) then becomes

$$(d\alpha/dt) = (\beta_M - \beta)/\ t_m \tag{5.12}$$

The constant t_m is called the pump and motor time constant (Martin 1983).

The rotational motion equation relates the characteristic of torque to speed and time. More relationships are needed to link torque to the three other experimental pump characteristics in order to predict pump behavior during transient events. The complete pump characteristics are offered by the Karman-Knapp diagram are very useful in presenting the physical behavior of the pump, but have computational difficulties arising when the pump passes through zero speed. Marchal et al. (1965) developed a transformation to represent the characteristic data in a way that avoids singularities asymptotes during numerical computation and is the preferred method of arranging the data for computing. Figure 5.9 is Marchal's representation of the data shown in figure 5.5.

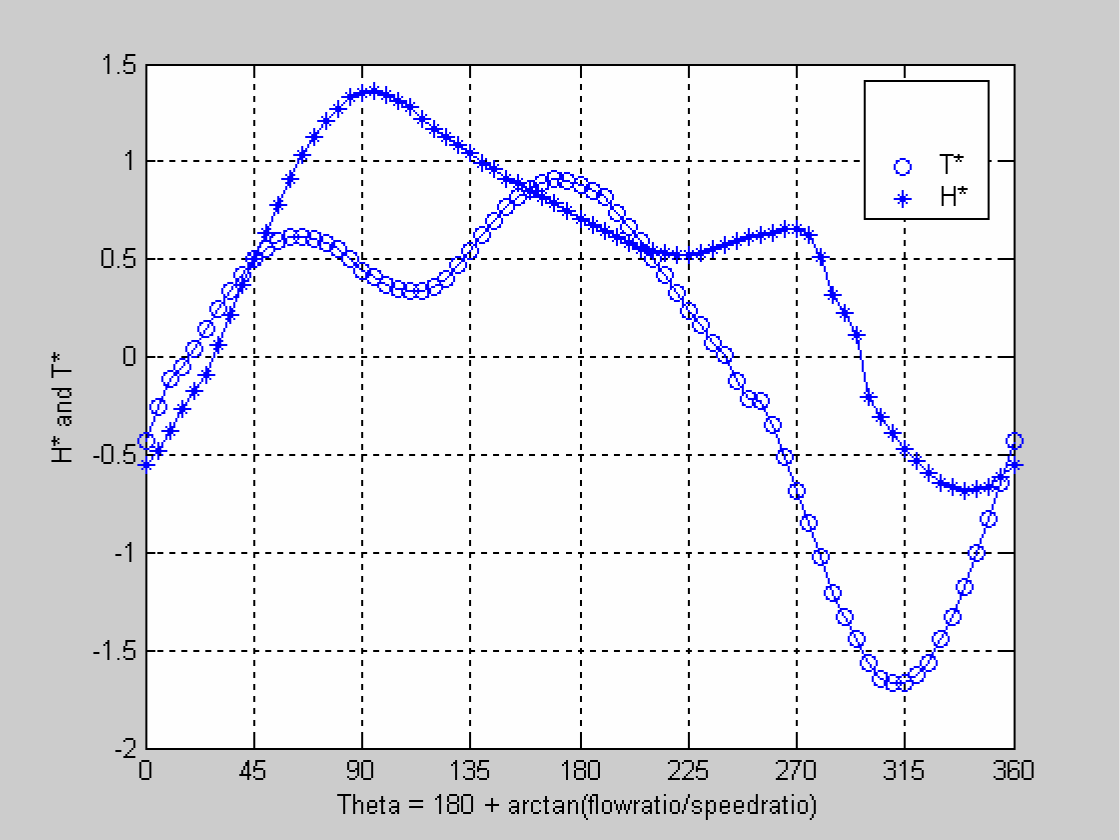


Figure 5.9 Complete Pump Characteristics

The H* curve represents $h/(\alpha^2+v^2)$ and the T* curve represents $\beta/(\alpha^2+v^2)$. They are plotted against theta, $\theta = \arctan(v/\alpha)$. Often, computer programs output the results of $\theta = \arctan(v/\alpha)$ from -180 to 180 degrees. 180 degrees can be added then to theta to shift the coordinate range to 0 to 360. Quadrant III is from 0 to 90 degrees, quadrant IV is from 90-180, quadrant I is from 180-270 and quadrant II is from 270-360.

For the initial rated conditions, $h = 1$, $\beta = 1$, $v = 1$, and $\alpha = 1$. Then, $\arctan(v/\alpha) = 45$ and from the curves, $H^* = .5$ and $T^* = .5$. Therefore, in general we can retrieve h and β as

$$h = [H^*(\alpha^2+v^2)] \tag{5.13}$$

and

$$\beta = [T^*(\alpha^2+v^2)] \tag{5.14}$$

It is clear that T* and H* provide the link between the experimental data and pump transients. In order to solve for the pump characteristics, H* and T* need to represented as a function of θ. The curves are highly irregular and can not be represented by a single equation. However, they can be represented as a simple linear function for short segments. The linear equations for H* and T* are as follows:

$$H^*(\theta) = a_1 + a_2\theta \qquad (5.15)$$

$$T^*(\theta) = a_3 + a_4\theta \qquad (5.16)$$

The constants are found from the known experimental data near θ from the previous solution. For example, if the initial conditions are known that θi = 45, H*i = .5 and T*i = .5, $\theta_{i+1} = 46$ could be used and the H^*_{i+1} and T^*_{i+1} corresponding to their value when θ = 46. These values are then used to create an equation of the line to represent T* and H* as a function of θ. The small difference between θi = 45 and $\theta_{i+1} = 46$ ensure that the linear approximation to the curve is accurate. The constants can be determined in the following way:

$$a_2 = (H^*(\theta_{i+1}) - H^*(\theta_i))/(\theta_{i+1} - \theta_i) \qquad (5.17)$$

$$a_1 = H^*(\theta_i) - a_2\theta_i \qquad (5.18)$$

The constant a_2 is the slope and a_1 is the intercept of the linear equation representing the relationship between H* and θ. The same procedure is done for finding a_3 and a_4, the constants relating T* to θ. These constants are purely from the experimental data, so if the data is known, the constants are always known as well. Now, using eqs. (5.15 and 5.16) in eqs. (5.13 and 5.14) we have the relationships

$$h = [(a_1 + a_2 \arctan(v/\alpha))(\alpha^2+v^2)] \qquad (5.19)$$

$$\beta = [(a_3 + a_4 \arctan(v/\alpha))(\alpha^2+v^2)] \qquad (5.20)$$

in which: $\arctan(v/\alpha) = \theta$

The pump head equation is a follows:

$$Hp = h\,(H_R) = H_j - H_{j-1} \qquad (5.21)$$

Where: H_j is the head on the discharge side of the pump

H_{j-1} is the head on the suction side of the pump

Eq. (5.21) can be rewritten at the time step n

$$[(a_1 + a_2 \arctan(v_n/\alpha_n))(\alpha_n^2+v_n^2)]\, H_R = H_{n,j} - H_{n,j-1} \qquad (5.22)$$

at the next time step

$$[(a_1 + a_2 \arctan (v_{n+1}/\alpha_{n+1}))(\alpha_{n+1}^2+v_{n+1}^2)]\, H_R = H_{n+1,j} - H_{n+1,j-1} \qquad (5.23)$$

This head balance equation, together with the torque speed change equation can be solved, with the appropriate initial and boundary conditions. The torque speed equation needs to be represented in a form suitable for numerical analysis as well. Eq (5.12) can be rewritten

$$t_m(\alpha_{n+1} - \alpha_n)/\Delta t = (\beta_M - .5(\beta_n + \beta_{n+1})) \tag{5.24}$$

in which the torque is represented as the average between time steps. Using the relationship between torque speed and flow, eq. (5.20), eq. (5.24) can be rewritten

$$t_m(\alpha_{n+1} - \alpha_n)/\Delta t = (\beta_M - .5([(a_3 + a_4 \arctan(v_n/\alpha_n))(\alpha_n^2+v_n^2)]+ [(a_3+ a_4 \arctan(v_{n+1}/\alpha_{n+1}))(\alpha_{n+1}^2+v_{n+1}^2)])) \tag{5.25}$$

Now, with an initial condition known, the unknown variables are α_{n+1}, v_{n+1}, $H_{n+1,j}$ and $H_{n+1,j-1}$. There are two equations and four unknowns. The remaining unknowns can be solved using the boundary conditions upstream and downstream of the pump. The equation for water hammer in conduits similarly creates four unknowns with two equations. In a system, when the elements are connected, the interior unknowns become redundant and with equations for the boundaries, there will be as many equations as unknowns and the system can be solve. Chaudhry (1987) and Streeter and Wylie (1978) present methods for solving the pump equations, however, they use an explicit scheme instead of an implicit scheme as shown here.

Chapter 6 – Simulation of the Intrusion Process Using WHAMO

Contaminant intrusion is where outside contaminants are drawn into the drinking water system. For there to be contaminant intrusion in a water distribution system, three things must exist. First, there must be a connection from the water inside the pipe to the external surroundings. Kirmeyer et al. (2001) states that leakage rates in water systems range up to 32 percent which indicates there is a significant connection between the internal system and the external ground. Second, the pressure of the ground water surrounding the pipe must be greater than the water pressure inside the pipe. This is called an adverse gradient. Third, there must be contaminants in the ground water. Normally the pressure of the water distribution system only allows water to exit the system. Water hammer events in water distribution systems can be triggered by the closing of a valve, power failure to a pump, and a sudden release of flow such as a water main break or fire hydrant opening. As has been presented in previous chapters, during water hammer events, low pressure waves develop in the system. If the pressure inside the pipeline drops below the external pressure of the fluid surrounding the pipeline, an adverse pressure gradient is created and this creates a pathway for the fluid from outside of the pipe to be pulled into the water distribution system. Intrusion is especially important if there are harmful contaminants in the surrounding area which could be potentially pulled into the drinking water system. In a study by Karim et al. (2001), it was shown that significant levels of microorganism contaminants exist immediately adjacent to water main drinking lines.

An experimental set up was constructed in the Tulane Hydraulics lab to test for intrusion into the system during transient events (Wang 2002). The Tulane system proved effective in producing a scenario where negative pressure occurred and there was intrusion. A similar system is modeled in this paper and using the computer program WHAMO we test for intrusion in different scenarios.

Figure 6.1 shows the system and the system description in terms of node and pipe data are provided in Tables 6.1 and 6.2. The system starts with a reservoir at elevation zero with zero head at node 100. A vertical conduit joins the reservoir to a pump. Wang

(2002) provides details of the pump used in the Tulane experiment described earlier. At the point of best efficiency, the flow rate and pressure are given. The speed at which the pump was operated was obtained from a correspondence with Ms. Wang. The pump was operated at a speed of 2900 Rpm. The power is known at 10 HP so now the torque can be calculated by the relationship Torque = Power/Speed. The rated quantities for the pump are as follows:

Rated Head = $1.0(10^2)$ feet
Rated Speed = 2900 Rpm
Rated Flow = .20 cfs
Rated Torque = 18.11 ft-lbs

The moment of inertia of the pump is also a necessary piece of information for analyzing a pump during transient events. This quantity is rarely given but estimating techniques are available. Wylie and Streeter (1978) provide an estimating equation

$$I = 3550(HP/N)^{1.435} \tag{6.1}$$

Where, I is in units of lb-ft^2, HP is horse power and N is the speed in Rpm.
The inertia of the pump and motor can also be estimated by a set of empirical functions developed by Thorley (1991).

$$Ipump = 1.5(10^7)(P/N^3)^{.9956} \tag{6.2}$$

$$Imotor = 118(P/N)^{1.48} \tag{6.3}$$

Thorley's expressions are in SI units where inertia is in kgm2, P is the brake horsepower in kilowatts at the best efficiency point and N is in Rpm.

Using eq. (6.1) the inertia estimation for the pump is 1.039 lb-ft^2. The complete pump characteristics are estimate by finding the specify speed of the pump and choosing a set of complete characteristics for a similar specific speed. The equation for specific speed is

$$Ns = \frac{N_R Q_R^{.5}}{H_R^{.75}}. \tag{6.4}$$

Using the pumps rated speed in Rpm, rated flow in gpm, and rated head in feet, yields a specific speed of 271.1 in gpm units. The pump characteristics selected for the experiment are from Knapp (1937) which has a specific speed of 1800 gpm units. Martin

(1983) provides a table of specific speeds with characteristics known, and the Knapp characteristics have a specific speed nearest to 271.1.

After the pump (P1), there is a ball valve (BV1, see figure 6.1), which is used to trigger transient flow. Then the pipes rise to an elevation 8 feet above the pump and starting reservoir. At the high point of the line, the line has a junction (Node 8) that leads to a valve and connects to another reservoir. This valve (BV2) represents a crack or hole in the pipe providing a potential pathway intrusion to occur. The reservoir represents the groundwater table (INTR). Then the pipes branch and continue on and the continuations are represented by two more reservoirs representing the heads downstream in the water main. The system schematic is given in figure 6.1. The elements of the system and their connectivity are given in table 6.1, their properties in tables 6.2 and 6.3, and the node elevations are given in table 6.4

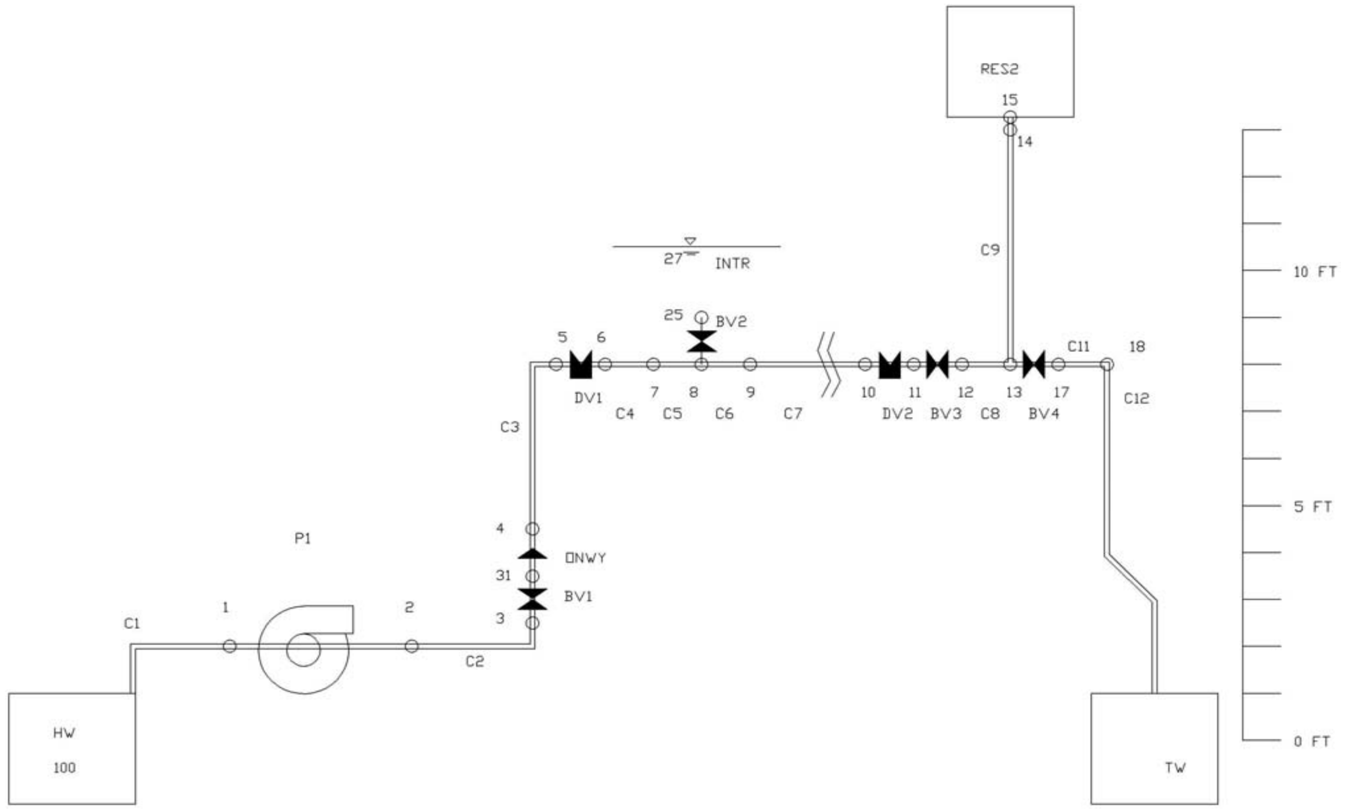


Figure 6.1 System Schematic

Table 6.1 Element List and Connectivity

Element ID	Type	Node Location	Upstream Node	Downstream Node	Comment
HW	Head Boundary	100			Upstream Water Main
C1	Conduit		100	1	
P1	Pump		1	2	
C2	Conduit		2	3	
	Junction	3			
Bv1	Valve		3	31	Closing Valve
Onwy	Oneway		31	4	
C3	Conduit		4	5	
	Junction	5			
Dv1	Valve		5	6	
C4	Conduit		6	7	
C5	Conduit		7	8	
	Junction	8			Node Where Intrusion Could Occur
Dumy	Dummy Conduit		8	25	
Bv4	Valve		25	27	Intrusion Opening
Intr	Head Boundary	27			Groundwater Table
C6	Conduit		8	9	
C7	Conduit		9	10	
Dv2	Valve		10	11	
Bv2	Valve		11	12	
C8	Conduit		12	13	
	Junction	13			
C9	Conduit		13	14	
Dum1	Dummy Conduit		14	15	
Res2	Head Boundary	15			Downstream Main
Bv3	Valve		13	17	
	Junction	17			
C11	Conduit		17	18	
C12	Conduit		18	19	
Tw	Head Boundary	19			Downstream Main

Table 6.2 Conduit Properties

ID	Length (ft)	Diameter (ft)	Celerity (ft/s)	Friction	Minor Loss, k
C1	3	0.1667	4000	0.01	0.5
C2	3	0.20833	4000	0.01	0.5
C3	8	0.1667	4000	0.01	
C4	1	0.1667	4000	0.01	
C5	1	0.1667	4000	0.01	
C6	1	0.1667	4000	0.01	
C7	30	0.1667	4000	0.01	2
C8	1	0.1667	4000	0.01	
C9	1	0.1667	4000	0.01	
C11	1	0.1667	4000	0.01	
C12	10	0.1667	4000	0.01	1
Dum1		0.1667	4000	0.01	
Dumy		0.1667	4000	0.01	

Table 6.3 Valve Properties

ID	Type	Diameter (ft)	Schedule*
Bv1	Gate	0.20833	1
Bv2	Gate	0.1667	2
Bv3	Gate	0.1667	2
Bv4	Gate	0.0416	2
Dv1	Gate	0.1667	2
Dv2	Gate	0.1667	2
Onwy	Oneway	0.1667	-

*Schedule 1 contains the valve closure, Schedule 2 is an open valve

Table 6.4 Node Properties

Node Location	Node ID	Type	Elevation
100	HW	Head Boundary	0
1			0
2			0
3			2
31			2
4			2
5			8
6			8
7			8
8		Junction	8
9			8
10			8
11			8
12			8
13		Junction	8
14			8
15	Res2	Head Boundary	8
17			8
18			8
19			0
25			8
27	INTR	Head Boundary	8

In the Tulane experiment, tanks were used at the supply, to provide backpressure. The system is changed in this set of simulations, replacing the tanks with reservoirs. Tanks are necessary for the physical experiment because of the space required in the laboratory to build the system. However, this system is intended to represent a part of a water distribution system and upstream and downstream parts are modeled as reservoirs to include the vast amount of water contained in the upstream and downstream ends of the water distribution system. The intrusion element was also changed from a small vertical pipe containing the intrusion water to a reservoir which represents the ground water table. As the transient occurs, the external head should not change due to the fluctuations inside the pipe. The WHAMO input code is presented in table 6.6

The valve between nodes 3 and 31 is the closure valve. It has a closure time of 1 second. The OPPUMP command specifies the pump operation schedule and TOFF is the time when the pump loses power.

Simulations

Simulation 1

In the first simulation the upstream reservoir (HW) has a head of zero feet. The pump provides the additional energy to move the water through the system. There is a point of leakage in the pipe at node 8. The opening is a quarter inch in diameter and is represented by a ¼" valve with a loss coefficient of .16. The groundwater table has an elevation of 11 feet, three feet above the opening in the pipe. The orifice coefficient is that of an open gate valve. Additional resistance would be expected as the groundwater flows through pores of the media surrounding the pipe. There are two reservoirs at the end of the system that have heads of 13 feet and 0 feet. The initial conditions for the pipeline pressures before any transients are triggered are very low. Since they are very low, they have a greater chance for the pressure to drop below the external pressure during water hammer events.

The input parameters for the first are summarized in table 6.5.

Table 6.5 Simulation 1 Input Parameters

Rated Head	Inertia	Valve time	Celerity	Orifice	Kvalve	Intrusion Head	T Shutoff
40	1.03	1	4000	1/4"	0.16	3	6

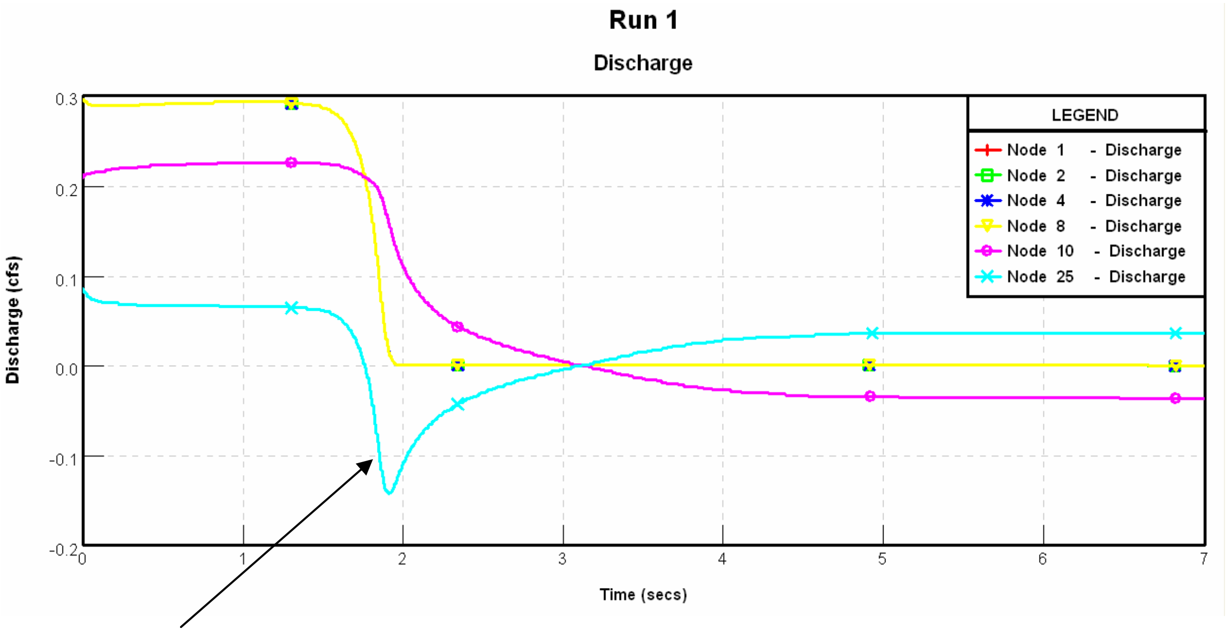
Results:

In this simulation there is a negative suction pressure at the intake for the pump at node 1 before the valve is closed. The dominate factor is the valve closure between node 3 and 31. The steady state head is 23.1 feet at node 31 and then the head rises to 61.8 feet on the upstream side of the valve and drops to -31.4 feet on the downstream side. The negative pressure corresponding to this head is -14.6 psi which is approximately vapor pressure for water at room temperature. In this case the velocity is high at 13.2 feet per second which is the main factor in the large head change. Water distribution systems are typically designed with a maximum velocity of 8 feet per second.

The WHAMO program does not handle phase change so it will output negative pressures that exceed vapor pressure and only give a warning about possible column separation. The negative energy wave produces an adverse gradient and flow intrudes from the outside for about 1.2 seconds. Node 8 experiences a minimum head of -16.3 feet and the energy difference between the intrusion reservoir representing the outside water table and energy inside the pipe cause the water to flow into the pipe, reaching a maximum rate of -.14 cfs. The extreme negative pressure at the intrusion valve is due to the fact that the velocity head is very large as the flow passes through the small diameter of the intrusion opening. The power failure to the pump after the valve is closed has little impact on the simulation. Table 6.6 provides a summary of the maximum and minimum heads and their respective times as well as the maximum and minimum flows and their time of occurrence. Figure 6.2 is important because it shows the flow rate of node 25. A negative flow at node 25 indicates that the outside groundwater is being drawn into the system.

Table 6.6 Simulation 1 Summary

Node	Max Head (FEET)	Time (SEC)	Min Head (FEET)	Time (SEC)	Max Q (CFS)	Time (SEC)	Min Q (CFS)	Time (SEC)
100	0	0	0	0	0.3	0	0	7.4
1	7.2	1.9	-2.1	0	0.3	0	0	7.4
2	58.1	1.9	5.2	10	0.3	0	0	7.4
	58.1	1.9	5.2	10	0.3	0	0	7.4
3	61.8	1.9	5.2	10	0.3	0	0	7.4
	61.8	1.9	5.2	10	0.3	0	0	7.4
31	25.8	0	-31.3	1.9	0.3	0	0	7.4
4	22.9	0	-31.4	1.9	0.3	0	0	7.4
5	21.2	0	-18.4	1.9	0.3	0	0	7.4
	21.2	0	-18.4	1.9	0.3	0	0	7.4
6	20.8	0	-18.4	1.9	0.3	0	0	7.4
7	21.1	0	-17.3	1.9	0.3	0	0	7.4
8	20.8	0	-16.3	1.9	0.3	0	0	7.4
	20.8	0	-16.3	1.9	0.1	0	-0.1	1.9
	20.8	0	-16.3	1.9	0.2	1.3	0	10
25	20.8	0	-16.3	1.9	0.1	0	-0.1	1.9
27	11	0	11	0	0.1	0	-0.1	1.9
9	21.7	0	-15.3	1.9	0.2	1.2	0	10
10	15.4	0	11.4	1.9	0.2	1.3	0	10
11	15.2	0	11.3	1.9	0.2	1.3	0	10
12	15	0	11.2	1.9	0.2	1.3	0	10
13	14.1	0	12.1	1.9	0.2	1.3	0	10
	14.1	0	12.1	1.9	-0.2	1.3	-0.5	10
	14.1	0	12.1	1.9	0.5	0.2	0.5	2.1
14	13	0	13	0	-0.2	1.3	-0.5	10
15	13	0	13	0	-0.2	1.3	-0.5	10
17	12.9	0	10.9	1.9	0.5	0.2	0.5	2.1
	12.9	0	10.9	1.9	0.5	0.2	0.5	2.1
18	13	0	10.9	0	0.5	0.2	0.5	2.1
19	0	0	0	0	0.5	0.2	0.5	2.1



Intrusion Event

Figure 6.2 Run 1 Flow Results

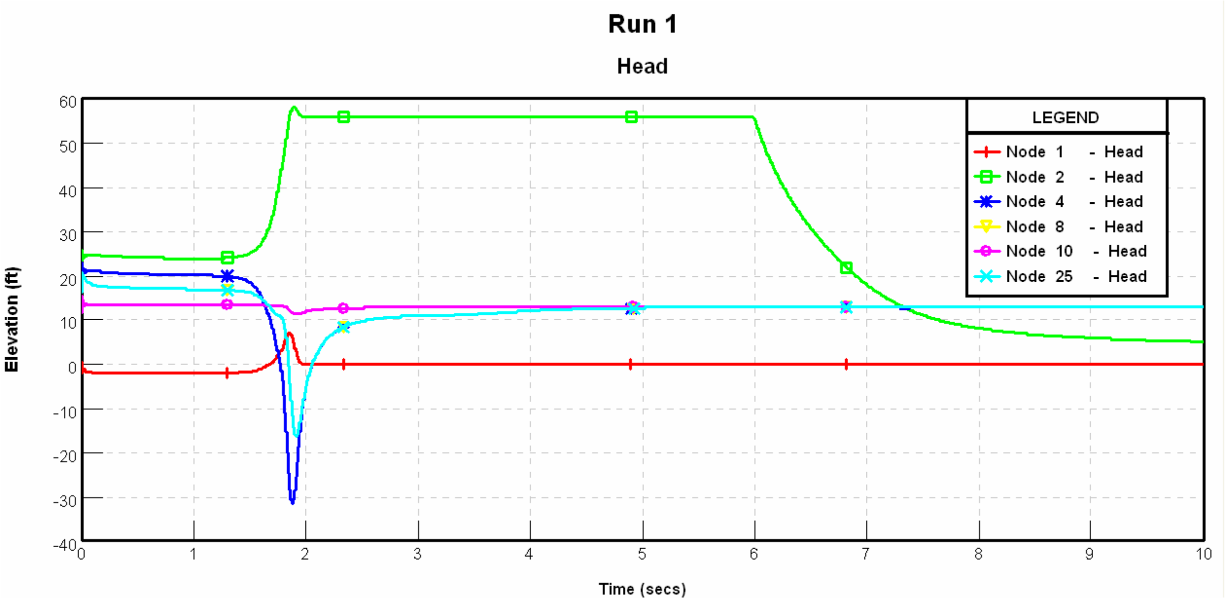


Figure 6.3 Run 1 Head Results

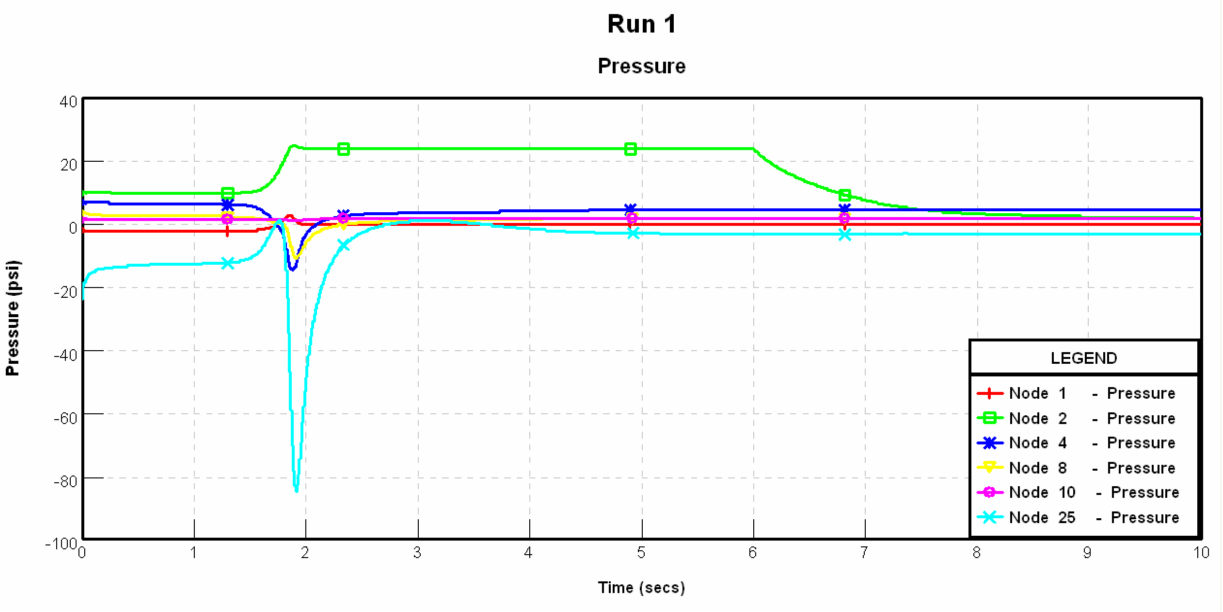


Figure 6.4 Run 1 Pressure Results

In this trial intrusion occurs. The intrusion flow rate is relatively large due to the large difference between the internal and external head and the small entrance loss coefficient. The head difference between nodes 8 and ground water elevation reaches a maximum of 27.3 feet. The difference is found by taking the subtracting the minimum energy elevation for node 8 as shown in table 6.8 from the constant elevation of the ground water table. We know from the energy equation that flow is driven by the energy gradient so the initial head boundaries can be changed to a constant value and the flow would be the same. In this case, adding 27.3 feet of head to each of the head boundaries would bring the system to the point where no intrusion would occur.

Simulation Run 2

In the first simulation the intrusion flow rate was very large into the system, and the pressure dropped below vapor pressure where cavitation would occur and the system would not behave as WHAMO predicts it to. Simulation 2 attempts to model the problem more accurately by increasing the entrance loss coefficient (Kvalve) from 0.16 in simulation 1 to 1.25 this simulation. All the other parameters are the same as in simulation 1 and are given in figure 6.1 and tables 6.1-6.4. Table 6.7 summarizes the input parameters.

Table 6.7 Input Parameters for Simulation 2

Rated Head	Inertia	Valve time	Celerity	Orifice	**Kvalve**	Intrusion Head	T Shutoff
40	1.03	1	4000	1/4"	**1.25**	3	6

Results:

The increase in the intrusion flow resistance decreases the effects of the reservoir acting as the water table above the intrusion point in the system in two ways. The increase in the loss coefficient on the intrusion opening decreases the intrusion flow rate, with a maximum intrusion flow rate of .09 cfs as opposed to .14 in simulation 1, and the dampening effects on the transient are less as well. The negative head drops all the way to -83.1 feet at node 4 (See figure 6.6) right after the valve during closure. The lowest head observed at node 8 is -59.9 creating quite a large a head difference of 70.9 feet from the ground water elevation. The maximum head rises to 62.9, which was not affected by the loss of the ground water reservoir’s wave dampening ability. Compared to simulation 1, the adverse gradient is more severe but the increased flow resistance results in a smaller intrusion flow rate.

The pressure at certain locations drops below vapor pressure. When the pressure in the pipe reaches vapor pressure, vapor cavities form and the system would act differently than the WHAMO model predicts. Nevertheless, the simulation is useful in fact predicting where cavitation may occur. The formation and subsequent collapse of the vapor cavities can be extremely destructive. The results are summarized in table 6.8 and figures 6.5-6.7.

Table 6.8 Simulation 2 Summary

Node	Max Head (FEET)	Time (SEC)	Min Head (FEET)	Time (SEC)	Max Q (CFS)	Time (SEC)	Min Q (CFS)	Time (SEC)
100	0	0	0	0	0.3	0	0	7.4
1	7.7	1.9	-1.9	0	0.3	0	0	7.4
2	58.7	1.9	5.2	10	0.3	0	0	7.4
	58.7	1.9	5.2	10	0.3	0	0	7.4
3	62.9	1.9	5.2	10	0.3	0	0	7.4
	62.9	1.9	5.2	10	0.3	0	0	7.4
31	26.8	0	-83	1.9	0.3	0	0	7.4
4	24.1	0	-83.1	1.9	0.3	0	0	7.4
5	22.3	0	-64.4	1.9	0.3	0	0	7.4
	22.3	0	-64.4	1.9	0.3	0	0	7.4
6	21.9	0	-64.4	1.9	0.3	0	0	7.4
7	22.2	0	-62.2	1.9	0.3	0	0	7.4
8	22.1	0	-59.9	1.9	0.3	0	0	7.4
	22.1	0	-59.9	1.9	0	0	-0.1	1.9
	22.1	0	-59.9	1.9	0.3	1.1	0	9.9
25	22.1	0	-59.9	1.9	0	0	-0.1	1.9
27	11	0	11	0	0	0	-0.1	1.9
9	22.7	0	-57.7	1.9	0.3	1.1	0	9.9
10	15.3	0	8.8	1.9	0.3	1.1	0	9.9
11	15	0	8.7	1.9	0.3	1.1	0	9.9
12	14.6	0	8.6	1.9	0.3	1.1	0	9.9
13	14	0	10.9	1.9	0.3	1.1	0	9.9
	14	0	10.9	1.9	-0.2	1.1	-0.5	9.8
	14	0	10.9	1.9	0.5	0	0.5	2
14	13	0	13	0	-0.2	1.1	-0.5	9.8
15	13	0	13	0	-0.2	1.1	-0.5	9.8
17	12.8	0	9.7	1.9	0.5	0	0.5	2
	12.8	0	9.7	1.9	0.5	0	0.5	2
18	12.8	0	9.9	1.9	0.5	0.2	0.5	2
19	0	0	0	0	0.5	0	0.5	2

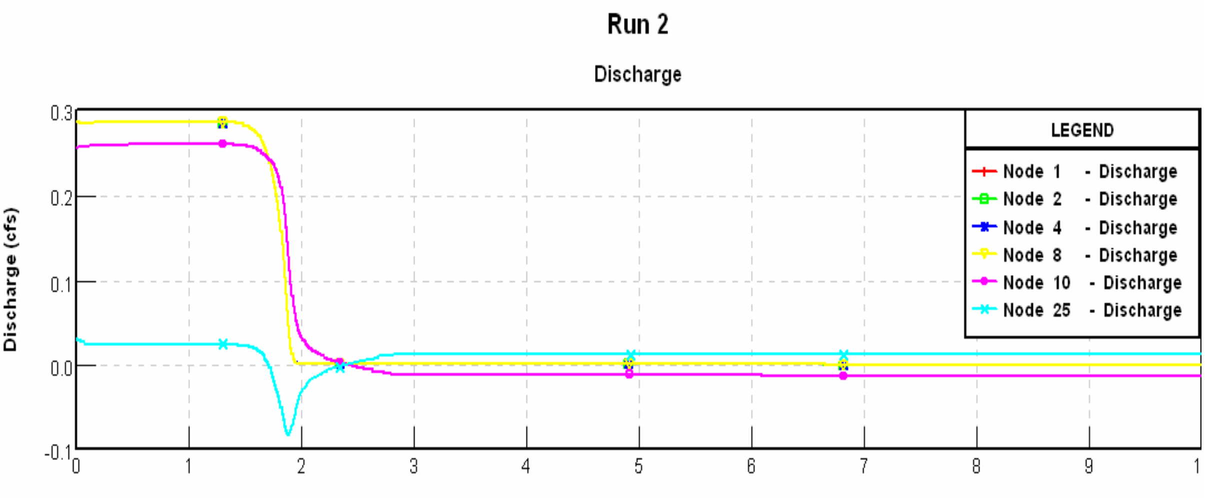


Figure 6.5 Run 2 Flow Results

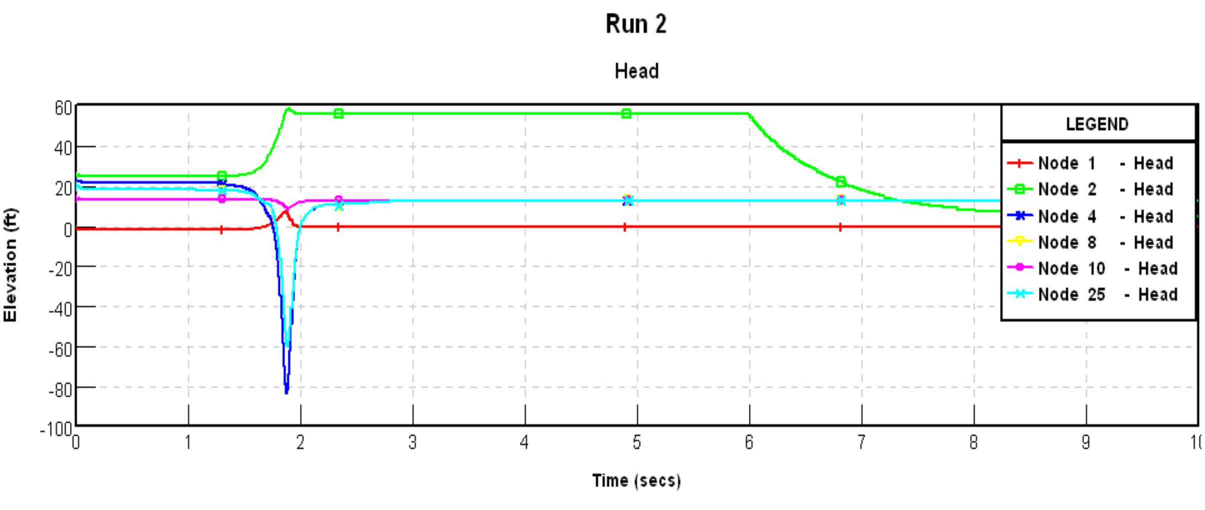


Figure 6.6 Run 2 Head Results

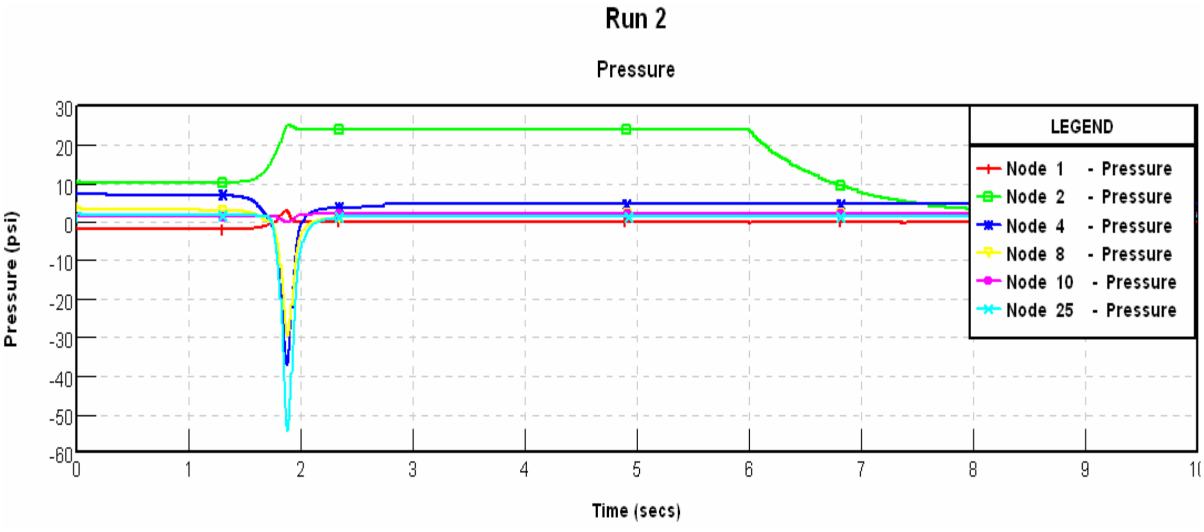


Figure 6.7 Run 2 Pressure Results

Simulation 3

In simulation 3, the upstream reservoir has a head of 80 feet and the two downstream reservoirs have a head of 76 feet. This is different from the first two simulations in the fact that the pump is off for this simulation, and the flow is driven by the difference in head between the upstream and downstream reservoirs. There is an entrance loss of 1.25 for the intrusion element. The valve between nodes 3 and 31 closes from time equals 1 second to time equals 2 seconds. The conduit and node properties are given in tables 6.1-6.4

Results:

This simulation is set up to recreate part of a water distribution system where the flow is driven by a head gradient. The difference in head of 4 feet between the upstream reservoir and the downstream reservoirs creates a flow rate of .19 cubic feet per second. For a two-inch diameter pipe, the velocity is 8.7 feet per second. Water distribution systems are typically designed for the velocity not to exceed 8 feet per second. The change in the velocity is the key factor in the magnitude of the water hammer event. With the valve closing fully, the initial velocity in the pipe is the velocity change. So, pipelines with large velocities are subject to water hammer problems. In this case there is a difference in head of 4 feet. Extreme events such as a fire flow situation or a water main break could cause the head gradient to increase dramatically, increasing the velocity further. The simulation results summary is given in table 6.9

Table 6.9 Simulation 3 Summary Table

Node	Max Head	Time	Min Head	Time	Max Q	Time	Min Q	Time
	(FEET)	(SEC)	(FEET)	(SEC)	(CFS)	(SEC)	(CFS)	(SEC)
100	80	0	80	0	0.2	0	0	5
1	102.9	0	78.9	0	0.2	0	0	5
2	102.9	0	78.9	0	0.2	0	0	5
	102.9	0	78.9	0	0.2	0	0	5
3	110.4	0	78.6	0	0.2	0	0	5
	110.4	0	78.6	0	0.2	0	0	5
31	110.4	0	9.1	1.9	0.2	0	0	5
4	109.3	0	9	1.9	0.2	0	0	5
5	122.4	0	22.8	1.9	0.2	0	0	5
	122.4	0	22.8	1.9	0.2	0	0	5
6	122.2	0	22.8	1.9	0.2	0	0	5
7	124.7	0	24.4	1.9	0.2	0	0	5
8	126.1	0	25.9	1.9	0.2	0	0	5
	126.1	0	25.9	1.9	0.1	0	0	1.9
	126.1	0	25.9	1.9	0.1	1.4	-0.1	4.9
25	126.1	0	25.9	1.9	0.1	0	0	1.9
27	11	0	11	0	0.1	0	0	1.9
9	129.5	0	27.4	1.9	0.1	1.4	-0.1	4.9
10	92	0	60.7	0	0.1	1.4	-0.1	4.9
11	92	0	60.7	0	0.1	1.4	-0.1	4.9
12	92	0	60.6	0	0.1	1.4	-0.1	4.9
13	85.5	0	69.2	0	0.1	1.4	-0.1	4.9
	85.5	0	69.2	0	0.1	1.4	-0.1	5
	85.5	0	69.2	0	0	0	0	2.1
14	76	0	76	0	0.1	1.4	-0.1	5
15	76	0	76	0	0.1	1.4	-0.1	5
17	85.5	0	69.2	0	0	0	0	2.1
	85.5	0	69.2	0	0	0	0	2.1
18	86.1	0	68.7	0	0	0	0	2.1
19	76	0	76	0	0	0	0	2.1

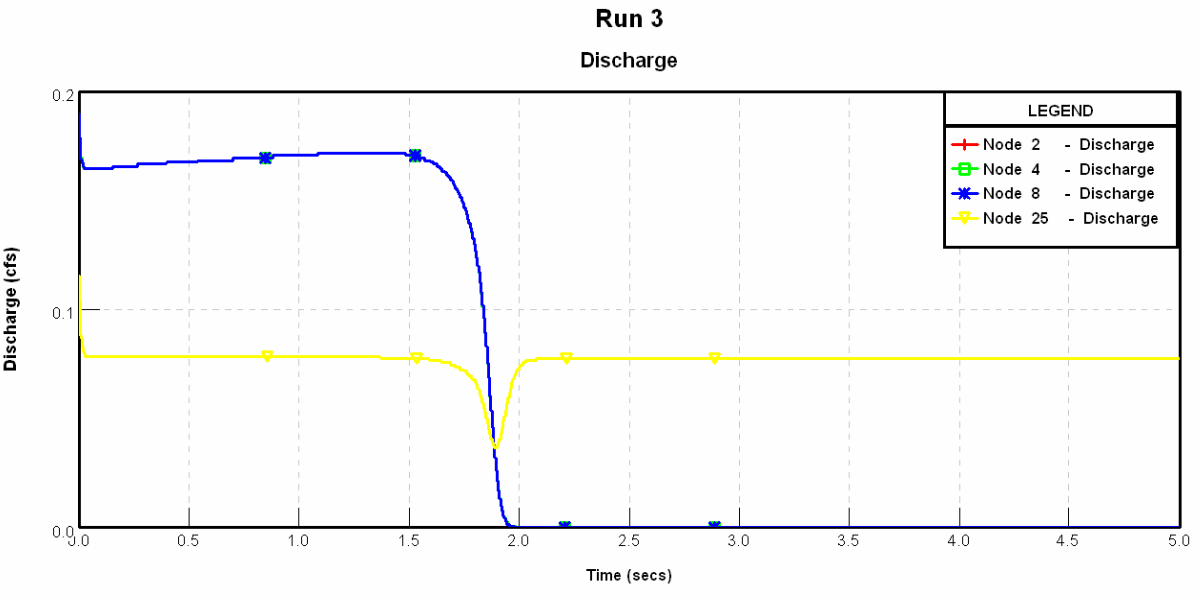


Figure 6.8 Run 2 Discharge Results

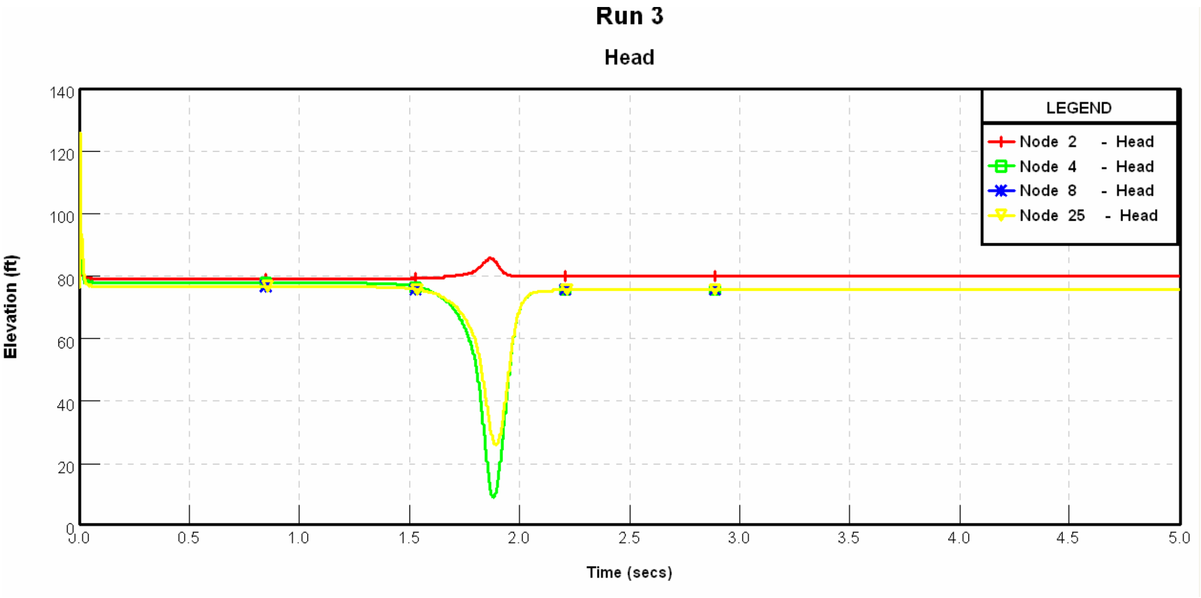


Figure 6.9 Run 3 Head Results

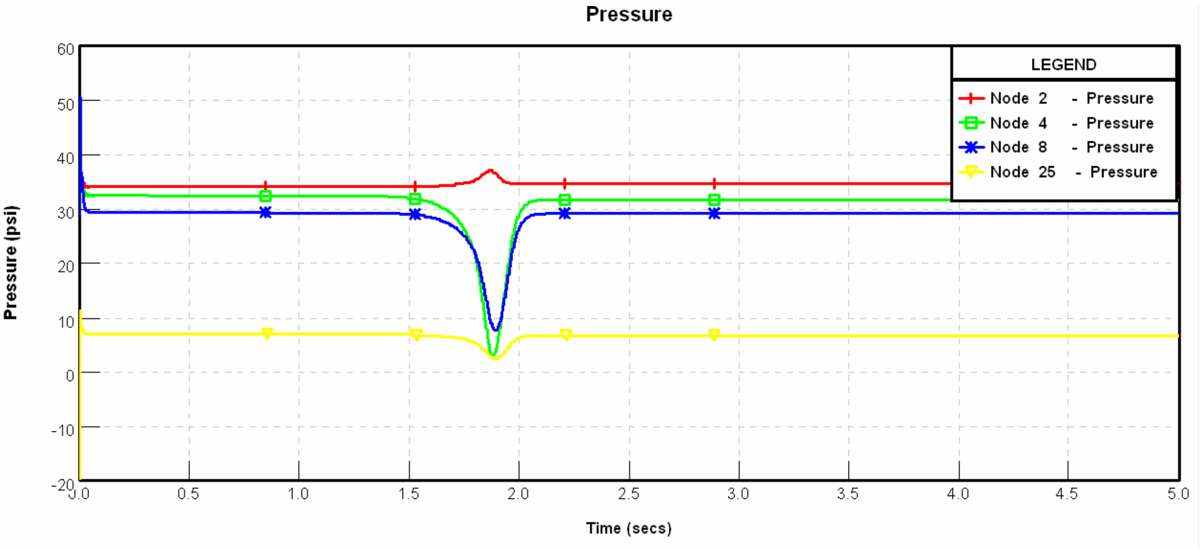


Figure 6.10 Run 3 Pressure Results

Graphs show that the numerical solver takes a few time steps to arrive at the steady state conditions. The summary table includes these initial data points in the maximum head column which should be ignored. The minimum head values correspond to figure 6.9 and the lowest head experienced is 9 feet, a drop of 69.8 feet. In this scenario the head at node 8 never drops below the external head. The starting head of 80 feet corresponds to a pressure of 34.7 psi which is in the normal pressure design range. The velocity is slightly above the design range, but this simulation could easily represent actual conditions. A slightly lower steady state pressure could create a possible intrusion situation. Likewise, a faster steady state velocity would create a larger change in head, which in turn could create the conditions for intrusion as well.

Simulation 4

Sudden power loss to a pump can cause significant transient events. In simulation 4, the pump loses power at the time of 3 seconds. There is a check valve to prevent the flow from reversing direction. There is no other valve closure to trigger water hammer. The system connectivity and properties are given by the Figure 6.1 and the Tables 6.1, 6.2, 6.3, Table 6.4.

Results

Pump failure has been known to cause significant pressure waves. Walski and Lutes (1994) observed significant short lived low pressure problems in Austin where pump operation was the source of the transient. In this simulation the lowest head occurs during steady state operation at the intake node of the pump. The head rises to 22 feet at node 8. Again there is a little bit of instability in the solution at the beginning of the simulation which is making the maximum head results in the summary table slightly high. The head in this situation never drops below zero in the discharge line of the pipe. At node 8 it drops below the 11 feet of external head on the pipe for an extended period of time where intrusion to the system occurs. The solution is summarized in table 6.10 and figures 6.11-13.

Table 6.10 Simulation 4 Summary Table

Node	Max Head	Time	Min Head	Time	Max Q	Time	Min Q	Time
	(FEET)	(SEC)	(FEET)	(SEC)	(CFS)	(SEC)	(CFS)	(SEC)
100	0	0	0	0	0.4	0	0	3.1
1	0.5	3.1	-2.8	0.1	0.4	0	0	3.1
2	34	0	2.2	1.4	0.4	0	0	3.1
	34	0	2.2	1.4	0.4	0	0	3.1
3	33.7	0	2.6	1.4	0.4	0	0	3.1
	33.7	0	2.6	1.4	0.4	0	0	3.1
31	33.4	0	2.5	1.4	0.4	0	0	3.1
4	29.3	0	1.1	1.4	0.4	0	0	3.1
5	26.3	0	3	1.4	0.4	0	0	3.1
	26.3	0	3	1.4	0.4	0	0	3.1
6	25.7	0	2.8	1.4	0.4	0	0	3.1
7	26	0	3.2	1.4	0.4	0	0	3.1
8	26	0	3.6	1.4	0.4	0	0	3.1
	26	0	3.6	1.4	0	0	0	1.4
	26	0	3.6	1.4	0.3	1	0	5
25	26	0	3.6	1.4	0	0	0	1.4
27	11.5	0	11.5	0	0	0	0	1.4
9	26.7	0	4.1	1.4	0.3	1	0	5
10	16.1	0	12.2	0	0.3	1	0	5
11	15.6	0	11.7	0	0.3	1	0	5
12	15.1	0	11.1	0	0.3	1	0	5
13	14.2	0	12.2	0	0.3	1	0	5
	14.2	0	12.2	0	-0.2	1	-0.5	5
	14.2	0	12.2	0	0.5	0.2	0.5	1.6
14	13	0	13	0	-0.2	1	-0.5	5
15	13	0	13	0	-0.2	1	-0.5	5
17	13	0	11	0	0.5	0.2	0.5	1.6
	13	0	11	0	0.5	0.2	0.5	1.6
18	13.1	0	10.9	0	0.5	0.2	0.5	1.6
19	0	0	0	0	0.5	0	0.5	1.6

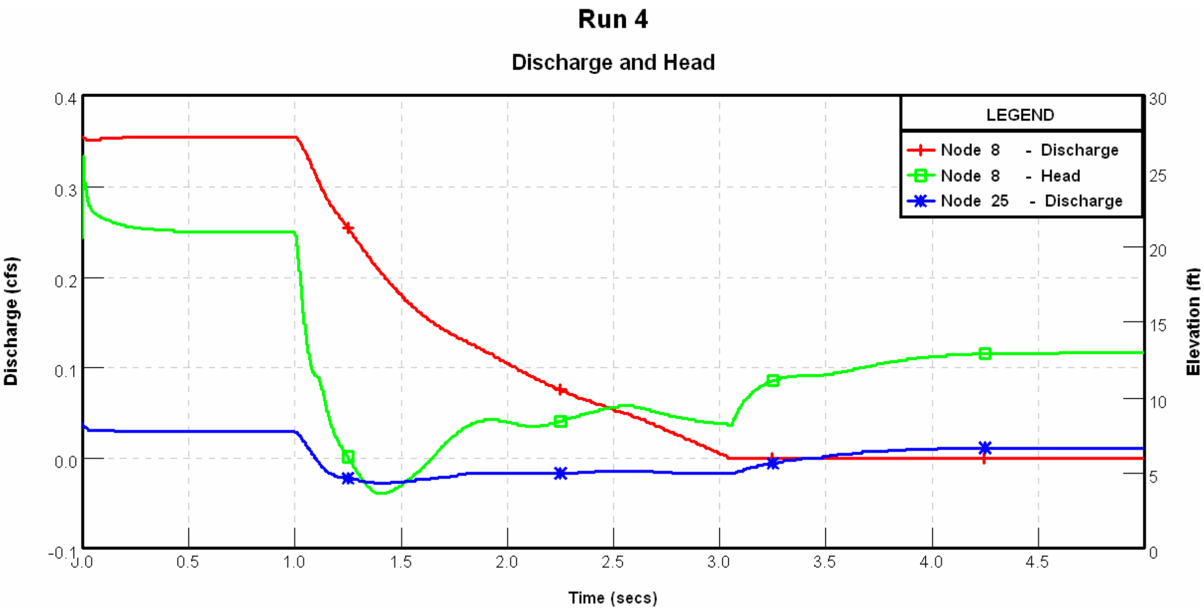


Figure 6.11 Run 4 Discharge and Head Results

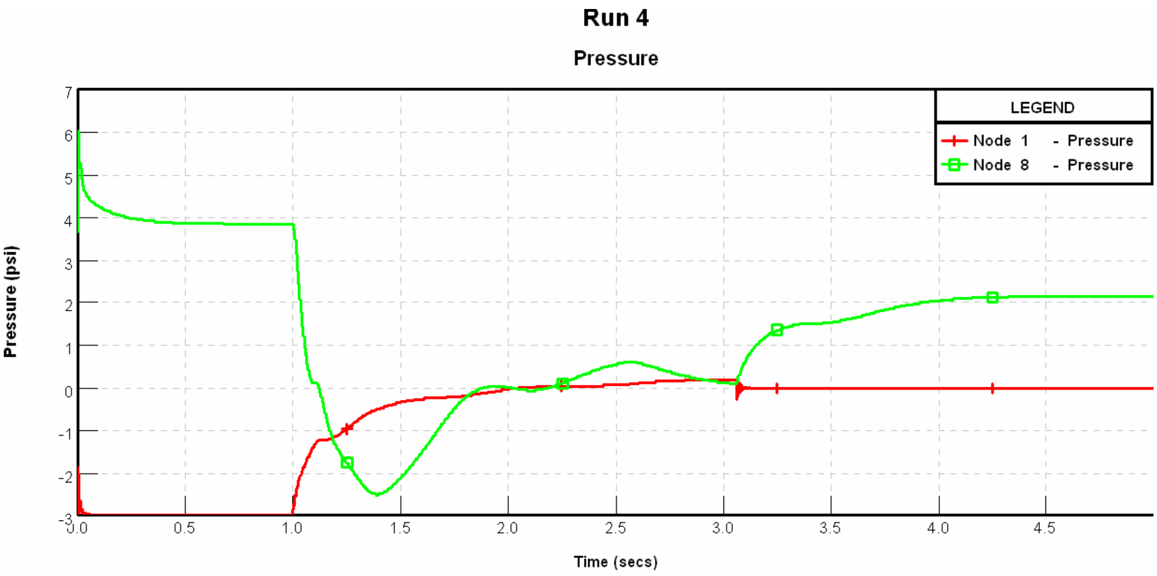


Figure 6.12 Run 4 Pressure Results

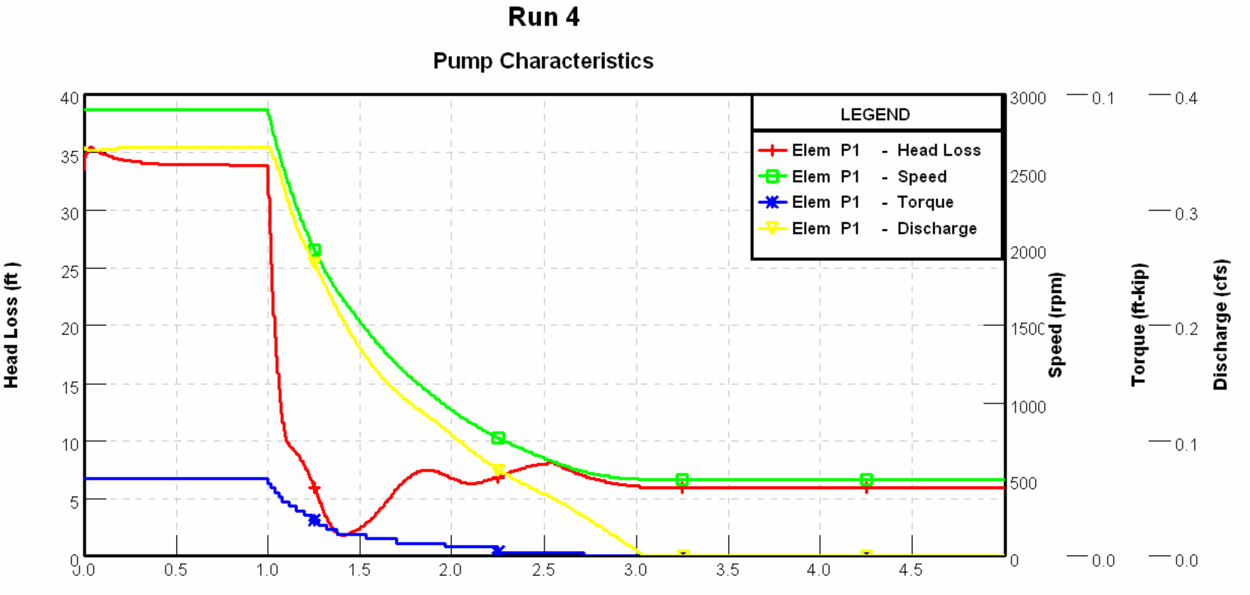


Figure 6.13 Run 4 Pump Characteristics

Simulation 5

At the time of 3 seconds, the pump experiences a power failure. There is no check valve to prevent the reversal of flow. There pump trip is the only factor in creating the transient flow. The intrusion loss coefficient is 1.25. All of the other system components and properties are given by the figure 6.1 and the tables 6.1, 6.2, 6.3, table 6.4.

Results

Without the check valve to prevent the reversal of flow, the head drops slightly lower than if there were a check valve in place. The head at node 8 drops below the external head and there is a period of intrusion of about 3.5 seconds. The pump reaches a speed of -600 Rpm at the end of the simulation. The pump behavior after the power failure is interesting to observe. It is clear that the complete characteristics play a part in the prediction of the transient behavior. A long period of intrusion is observed in the two pump trip simulations. The initial case is a critical one though. The starting reservoir is 11 feet below the ground water table at node 8. The downstream reservoir is only 2 feet above the ground water table as well. In this case the pump is critical in adding energy to the system to create a positive gradient. The negative wave caused by the power failure increases the intrusion into the system but if there were no pump at all there would be a small amount of intrusion as well. The scenarios presented in simulations 4 and 5 are possible and could occur. Situations where water is forced uphill by a pump could create a similar scenario. Other factors in pump transients are the pump characteristics and specific speed, the moment of inertia, and the head gradient. Pumps with smaller specific speeds are subject to large transients than larger specific speed pumps (Donsky 1969). Similarly, pumps with greater moments of inertia are slower in their changes in behavior, and produce smaller water hammer waves. A large head gradient forces the pump to change its mode of operation faster, creating greater transients.

Table 6.11 Simulation 5 Summary Table

Node	Max Head	Time	Min Head	Time	Max Q	Time	Min Q	Time
	(FEET)	(SEC)	(FEET)	(SEC)	(CFS)	(SEC)	(CFS)	(SEC)
100	0	0	0	0	0.4	0	-0.1	4.2
1	0.7	3.5	-2.9	0.1	0.4	0	-0.1	4.2
2	30.4	0	0.9	1.4	0.4	0	-0.1	4.2
	30.4	0	0.9	1.4	0.4	0	-0.1	4.2
3	30.1	0	1.3	1.4	0.4	0	-0.1	4.2
	30.1	0	1.3	1.4	0.4	0	-0.1	4.2
4	29.8	0	1.2	1.4	0.4	0	-0.1	4.2
5	26.7	0	3.1	1.4	0.4	0	-0.1	4.2
	26.7	0	3.1	1.4	0.4	0	-0.1	4.2
6	26	0	2.9	1.4	0.4	0	-0.1	4.2
7	26.4	0	3.3	1.4	0.4	0	-0.1	4.2
8	26.4	0	3.7	1.4	0.4	0	-0.1	4.2
	26.4	0	3.7	1.4	0	0	0	1.4
	26.4	0	3.7	1.4	0.3	1	-0.1	4.8
25	26.4	0	3.7	1.4	0	0	0	1.4
27	11.5	0	11.5	0	0	0	0	1.4
9	27.1	0	4.1	1.4	0.3	1	-0.1	4.8
10	16.2	0	12.2	0	0.3	1	-0.1	4.8
11	15.6	0	11.6	0	0.3	1	-0.1	4.8
12	15.1	0	11.1	0	0.3	1	-0.1	4.8
13	14.2	0	12.2	0	0.3	1	-0.1	4.8
	14.2	0	12.2	0	-0.1	1	-0.6	4.8
	14.2	0	12.2	0	0.5	0.2	0.5	1.6
14	13	0	13	0	-0.1	1	-0.6	4.8
15	13	0	13	0	-0.1	1	-0.6	4.8
17	13	0	11	0	0.5	0.2	0.5	1.6
	13	0	11	0	0.5	0.2	0.5	1.6
18	13.1	0	10.9	0	0.5	0.2	0.5	1.6
19	0	0	0	0	0.5	0	0.5	1.6

Figure 6.14 Run 5 Discharge and Head Results

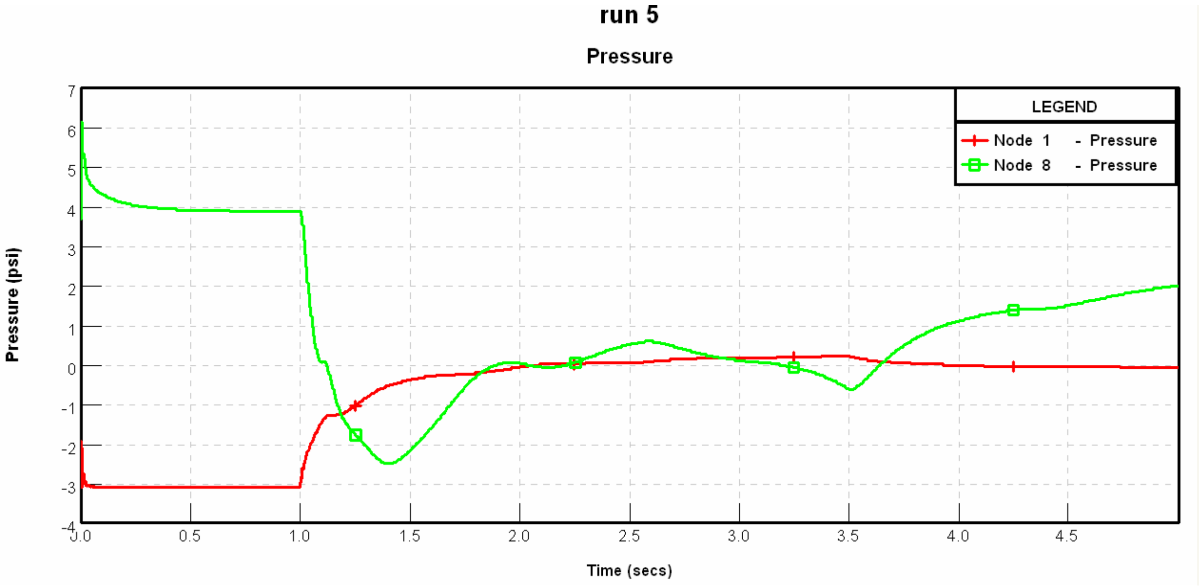


Figure 6.15 Run 5 Pressure Results

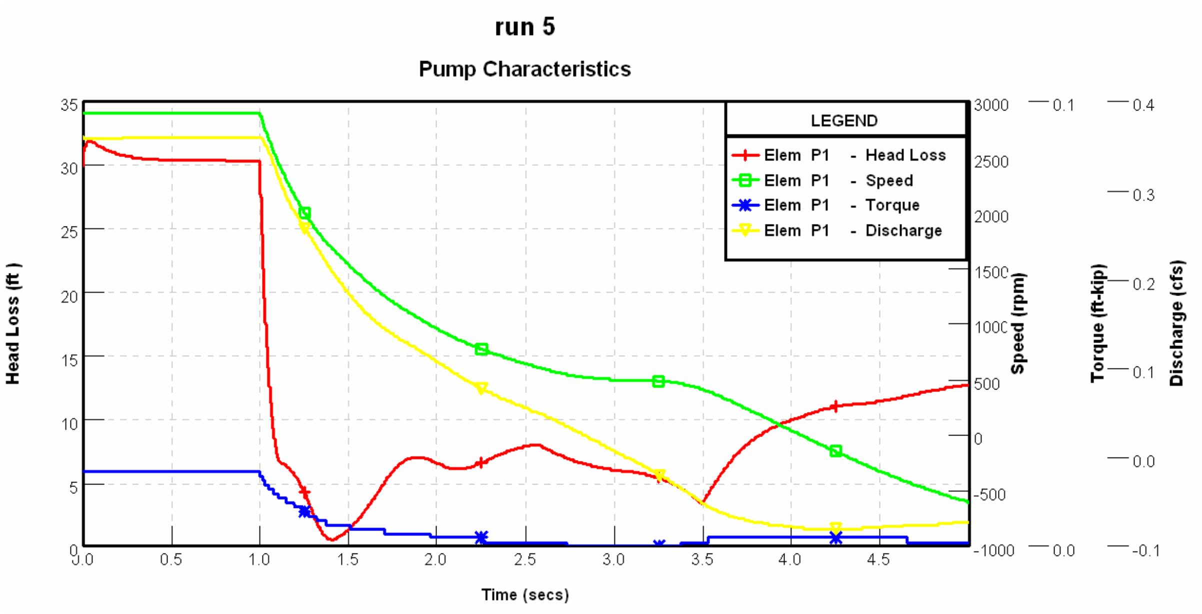


Figure 6.16 Run 5 Pump Characteristics

Conclusions:

In the scenarios presented in this chapter, the valve closure creates larger water waves than the power failure to the pump. For valve closure, the most sensitive nodes are the ones closest to the valve that is closing. The downstream nodes see a much greater impact from the transient than the upstream nodes. The upstream nodes are very close to the starting reservoir which dampens the effect. The downstream side has a much longer run of pipe so the dampening effects of the reservoir take a longer time to make their impact. Important parameters affecting the magnitude of the water hammer wave include the initial velocity in the pipe, the closure time of the valve and the celerity of the pipe. We also see that the initial pressure plays a critical role in determining the potential for intrusion as well as the water table or external head on the pipe. There are an infinite number of scenarios possible to model but these show that intrusion is possible, and some of the design features influence the possibilities of an intrusion occurrence.

Table 6.12 Intrusion Summary Table

Simulation	HW	TW	Res2	INTR	Kvalve	Pump	Tclose	Check	Intrusion

									Results
1	0	0	13	11	0.16	on	1 sec	Yes	Yes
2	0	0	13	11	1.25	on	1 sec	Yes	Yes
3	80	76	76	11	1.25	off	1 sec	Yes	No
4	0	0	13	11	1.25	Toff at 3 sec	N/A	Yes	Yes
5	0	0	13	11	1.25	Toff at 3 sec	N/A	No	Yes

Table 6.13 WHAMO Input file for Intrusion Simulations

```
Experimental Setup
C CASE 1 3.5 FEET OF HEAD ON THE INTRUSION ELEMENT
c 1/2" INTRUSION ORIFICE

SYSTEM
 EL HW AT 100
 EL c1 LINK 100 1
 el p1 link 1 2
 junc at 2
 el c2 link 2 3
 junc at 3
 el bv1 link 3 31
 el onwy link 31 4
 el c3 link 4 5
 junc at 5
 el dv1 link 5 6
 el c4 link 6 7
 el c5 link 7 8
junc at 8
 el dumy link 8 25
 el bv4 link 25 27
 el INTR at 27
 el c6 link 8 9
 el c7 link 9 10
 el dv2 link 10 11
 el bv2 link 11 12
 el c8 link 12 13
 junc at 13
 el c9 link 13 14
 el dum1 link 14 15
 el res2 at 15
 el bv3 link 13 17
 junc at 17
 el c11 link 17 18
 el c12 link 18 19
 el tw at 19
 node 100 elev 0
 node 1 elev 0
 node 2 elev 0
 node 3 elev 2
 node 4 elev 2
```

```
 node 5 elev 8
 node 6 elev 8
 node 7 elev 8
 node 8 elev 8
 node 9 elev 8
 node 10 elev 8
 node 11 elev 8
 node 12 elev 8
 node 13 elev 8
 node 14 elev 8
 node 15 elev 8
 node 17 elev 8
 node 18 elev 8
 node 19 elev 0
NODE 25 ELEV 8
NODE 27 ELEV 8
NODE 31 ELEV 2
FINI

RESE ID HW ELEV 0 FINI
RESE ID TW ELEV 0 FINI
rese id res2 elev 13 fini
Pump id p1 type 1 RQ .2027 Rhead 40 Rspeed 2900 rtorque 18.11
 wr2 1.03 fini
COND ID c1 LENGTH 3 NUMSEG 3 DIAM .1667 FRICT 0.01 CELER 4000.
ADDEDLOSS AT 1.5 CPLUS .5 CMINUS .5 FINI
COND ID c2 LENGTH 3 NUMSEG 3 DIAM .20833 FRICT 0.01 CELER 4000.
ADDEDLOSS AT 1.5 CPLUS .5 CMINUS .5 FINI
COND ID c3 LENGTH 8 NUMSEG 3 DIAM .1667 FRICT 0.01 CELER 4000.
ADDEDLOSS AT 6 CPLUS .5 CMINUS .5 FINI
COND ID C4 LENGTH 1 DIAM .1667 CELE 4000 FINI
COND ID C5 LENGTH 1 DIAM .1667 CELE 4000 FINI
COND ID C6 LENGTH 1 DIAM .1667 CELE 4000 FINI
COND ID C7 LENGTH 30 DIAM .1667 CELE 4000
ADDEDLOSS AT 8 CPLUS .5 CMINUS .5
ADDEDLOSS AT 12 CPLUS .5 CMINUS .5
ADDEDLOSS AT 18 CPLUS .5 CMINUS .5
ADDEDLOSS AT 22 CPLUS .5 CMINUS .5 FINI
COND ID C8 LENGTH 1 DIAM .1667 CELE 4000 FINI
COND ID C9 LENGTH 1 DIAM .1667 CELE 4000 FINI
COND ID DUM1 DUMMY fini
COND ID DUMY DUMMY fini
COND ID C11 LENGTH 1 DIAM .1667 CELE 4000 FINI
COND ID c12 LENGTH 10 NUMSEG 3 DIAM .1667 FRICT 0.01 CELER 4000.
ADDEDLOSS AT 3 CPLUS .5 CMINUS .5
ADDEDLOSS AT 6 CPLUS .5 CMINUS .5 FINI
VALvE ID BV1 GATE DIAM .2083 VSCHED 1 FINI
VALvE ID BV2 GATE DIAM .1667 VSCHED 2 FINI
VALvE ID BV3 GATE DIAM .1667 VSCHED 2 FINI
VALvE ID BV4 type 1 DIAM .0416 VSCHED 2 FINI
VALvE ID DV1 GATE DIAM .1667 VSCHED 2 FINI
VALvE ID DV2 GATE DIAM .1667 VSCHED 2 FINI
RESE ID INTR ELEV 11 FINI
oneway id onwy diam .1667 closs 1 fini

PcharACTERISTICS type 1
```

```
Sratio
-10 -6 -3 -1.5 -1.25 -1 -0.75 -0.5 -0.25 0 0.25 0.5 0.75 1 1.25 1.5 3 6 10
Qratio
-10 -6 -3 -1.5 -1.25 -1 -0.75 -0.5 -0.25 0 0.25 0.5 0.75 1 1.25 1.5 3 6 10
Hratio
104.0 73.2 65.4 67.4  67.8 68.2 68.8 69.5 70.2
 71.0 72.2 73.5 74.9 76.3 77.9 79.6 90.5 125.1 208.0
77.0 37.4 24.6 23.6   23.9 24.2 24.4 24.7 25.1 25.6
 26.3 27.1 28.0 29.1 30.1 31.1 40.3 74.9 158.1
67.9 26.3 9.4 6.2 6.0 5.9 5.9 6.0 6.2 6.4 6.8 7.3
 7.8 8.4 9.2 10.1 18.7 54.2 141.7
66.0 24.2 6.6 2.3 2.0 1.7 1.5 1.5 1.5 1.6 1.8 2.1 2.5
 3.1 3.8 4.7 13.5 50.3 137.6
66.2 23.9 6.3 2.0 1.6 1.3 1.1 1.0 1.0 1.1 1.3 1.6 2.0
2.5 3.3 4.2 13.2 49.9 137.3
66.4 23.8 6.2 1.8 1.4 1.0 0.8 0.7 0.7 0.7 0.9 1.1 1.5
2.1 2.8 3.7 12.9 49.7 137.1
66.4 23.8 6.0 1.6 1.2 0.8 0.6 0.4 0.4 0.4 0.5 0.8 1.2
1.7 2.5 3.4 12.6 49.4 136.6
66.2 23.9 5.9 1.5 1.1 0.7 0.5 0.3 0.2 0.2 0.3 0.5 0.9
1.5 2.3 3.2 12.4 49.3 135.9
66.0 23.8 6.0 1.5 1.0 0.7 0.4 0.2 0.1 0.0 0.1 0.4 0.8
1.4 2.2 3.1 12.3 48.9 135.4
66.0 23.8 5.9 1.5 1.0 0.7 0.4 0.2 0.0 0.0 0.1 0.3 0.8
1.4 2.1 3.0 12.2 48.6 135.0
64.9 23.1 5.6 1.2 0.7 0.4 0.2 0.0 -0.1 0.0 0.1 0.3 0.7
 1.3 2.0 3.0 12.1 48.3 134.5
63.9 22.5 4.8 0.6 0.3 0.0 -0.2 -0.2 -0.2 -0.1 0.0 0.3
0.7 1.2 2.0 2.9 11.8 48.2 134.2
62.9 21.0 3.4 0.0 -0.5 -0.5 -0.5 -0.5 -0.4 -0.3 -0.1
0.1 0.6 1.1 1.9 2.8 11.7 47.7 134.0
61.0 19.3 2.6 -0.9 -0.9 -0.9 -0.9 -0.8 -0.7 -0.6 -0.3
 -0.1 0.4 1.0 1.7 2.6 11.6 47.2 133.5
58.2 16.6 1.8 -1.5 -1.5 -1.4 -1.3 -1.2 -1.1 -0.9 -0.6
 -0.3 0.2 0.8 1.6 2.5 11.4 46.9 132.5
55.5 13.6 0.1 -2.1 -2.0 -2.0 -1.8 -1.7 -1.5 -1.2 -0.9
-0.5 -0.1 0.6 1.4 2.3 11.2 46.7 131.7
31.5 0.6 -8.5 -7.4 -7.1 -6.8 -6.4 -6.1 -5.5 -5.0 -4.4
 -3.6 -2.8 -2.0 -1.4 -0.5 9.0 44.7 128.9
30.1 -33.8 -29.4 -25.6 -24.9 -24.2 -23.1 -22.0 -20.9
-19.8 -18.6 -17.5 -16.0 -14.5 -12.8 -11.1 -1.9 36.0 120.4
-94.0 -85.7 -73.4 -66.0 -64.1 -62.3 -60.5 -58.6 -56.8
-55.0 -53.0 -51.1 -49.3 -47.0 -44.4 -41.9 -25.7 12.4 100.0

Tratio
48.0  65.9    78.1  84.7  85.0  85.4  85.9  86.5  87.2
88.0   88.6  89.4  90.2  91.0   91.8  92.7  95.9 102.9 108.0
2.9   17.3    25.3  28.9  29.7  30.5  30.6  30.9  31.2
31.7   32.1  32.6  33.1  33.6   33.9  34.2  36.2 38.9 50.0
-23.6 -3.6    4.3   6.3   6.6   6.9   7.2   7.6   7.7
 7.9    8.1   8.4   8.5   8.7    8.9   9.0   9.7 15.6 37.8
-40.6 -9.4    -0.9  1.1   1.3   1.4   1.6   1.7   1.9
2.0    2.1   2.2   2.3   2.3    2.4   2.4   3.9 13.5 39.0
-44.9 -11.4   -1.7  0.6   0.8   0.9   1.0   1.2   1.3
 1.4    1.5   1.5   1.6   1.6    1.7   1.8   3.6 13.6 39.9
-49.2 -13.6   -2.1  0.2   0.3   0.5   0.6   0.7   0.8
```

```
0.9    0.9   1.0   1.0   1.1    1.2   1.3   3.4 13.8 40.8
-53.7 -16.2   -2.3  -0.2  0.0   0.2   0.3   0.4   0.4
0.5    0.5   0.6   0.6   0.7    0.8   1.0   3.4 14.4 41.7
-58.4 -18.8   -3.4  -0.5  -0.3  -0.1  0.0   0.1   0.2
0.2    0.3   0.3   0.3   0.4    0.6   0.9   3.5 14.9 42.4
-63.2 -21.6   -4.7  -0.8  -0.5  -0.3  -0.1  0.0   0.0
0.1    0.1   0.1   0.2   0.4    0.6   0.9   3.7 15.4 43.2
-68.0 -24.5   -6.1  -1.5  -1.1  -0.7  -0.4  -0.2  0.0
0.0    0.0   0.1   0.2   0.4    0.7   1.0   4.0 15.8 44.0
-72.9 -27.4   -7.6  -2.3  -1.7  -1.2  -0.8  -0.5  -0.2
0.0    0.1   0.2   0.4   0.6    0.9   1.3   4.5 16.9 45.7
-77.9 -30.5   -9.3  -3.2  -2.5  -1.8  -1.3  -0.8  -0.4
-0.1   0.1   0.3   0.5   0.8    1.1   1.5   5.0 18.0 47.6
-83.0 -33.7   -11.2 -4.2  -3.4  -2.6  -1.9  -1.2  -0.7
-0.2   0.0   0.3   0.6   0.9    1.3   1.7   5.5 19.1 49.4
-88.3 -37.1   -12.9 -5.3  -4.3  -3.3  -2.5  -1.7  -1.0
 -0.4   -0.1  0.2   0.6   1.0    1.4   1.9   5.9 20.2 51.2
-93.7 -40.8   -14.7 -6.4  -5.2  -4.1  -3.1  -2.2  -1.4
-0.7   -0.2  0.1   0.6   1.0    1.6   2.1   6.4 21.1 52.9
-99.2 -44.9   -16.6 -7.5  -6.2  -5.0  -3.8  -2.8  -1.9
-1.0   -0.3  0.0   0.5   1.0    1.6   2.3   6.9 22.0 54.7
-136.3 -66.5  -30.1 -15.4 -13.3 -11.2 -9.2  -7.5  -5.7
 -3.9   -2.4  -1.2  -0.6  0.1    1.0   2.0   9.0 27.5 64.0
-214.5 -120.2 -61.4 -37.0 -33.4 -30.0 -26.4 -22.8 -19.1
-15.5  -12.6 -9.7  -7.2  -4.7   -3.3  -2.4  7.8 36.0 82.4
-334.0 -199.0 -115.7 -79.2 -73.2 -67.4 -61.4 -55.2 -49.0
-43.0 -38.2 -33.4 -28.6 -24.1  -19.9 -15.8 -2.1 36.4 100.0
fini

VCHar type 1 g 100 hc 1.25 g 50 hc 2.5 g 0 hc 100000000
fini

OPPUMP
ID P1 shutoff toff 6
FINI

SCHEDULE
VSCHED 1 T 0.0 G 100 t 1.0 g 100 t 2.0 g 0.0
Vsched 2 t 0.0 g 100
VSCHED 3 T 0.0 G 100 T 0.5 G 100 T .6 G 0
FINI


HIST
 node 1 q head psi
 node 2 head q psi
 NODE 4 Q psi head
 node 8 q psi HEAD
 node 10 q psi HEAD
 node 25 q psi HEAD
 element p1 head speed torque q
 ELEMENT BV1 POSITION
 decimal 3
 LINES 51

 FINI
```

```
PLOT
 node 1 q head psi
 node 2 head q psi
 NODE 4 Q psi head
 node 8 q psi HEAD
 node 10 q psi HEAD
 node 25 q psi HEAD
 element p1 head speed torque q
 ELEMENT BV1 POSITION
FINI

DISPLAY ALL FINI
Snapshot time 1.88 fini

CONTROL
 DTCOMP 0.001 DTOUT .5 TMAX 1
 DTCOMP 0.001 DTOUT .1 TMAX 3
 DTCOMP 0.005 DTOUT .5 TMAX 6
 DTCOMP 0.001 DTOUT .2 TMAX 7
 DTCOMP 0.005 DTOUT .5 TMAX 10
 FINI

C CHECK
GO
```

Summary

This thesis provides a comprehensive look at water hammer with an emphasis on home plumbing systems. The mathematics of water hammer is explained, including the momentum and continuity equations for conduits, system construction, and the four-point implicit finite difference scheme to numerically solve the associated differential equations.

Residential plumbing systems have been analyzed by modeling household fixtures for their hydraulic functions, and several water hammer simulations are run using the Water Hammer and Mass Oscillation program (WHAMO). The WHAMO program, originally intended for water hammer analysis on large scale hydraulic systems, such as dams and pumping plants, has been used for simulating residential plumbing systems. It is determined from the WHAMO simulations that the amount of air volume in the system is a key factor in controlling water hammer. Back flow preventors are important in two ways; they lessen negative pressure drop during water hammer events and they prevent contamination from leaving the home system into the distribution network.

This work also shows how the unsteady momentum and continuity equations can be used to solve water distribution problems instead of the steady-steady state energy and continuity equations, along with the examples problems which show that an unsteady approach is more suitable than the standard Hardy-Cross method as varying demands create a unsteady flow conditions. A comparison was done between EPANET and WHAMO. An unsteady model captures the true dynamic behavior of distribution systems, however the added complexity of the problem limits the accuracy of computing the friction factor, and the scale of the problem.

Abnormal pump operation is clearly explained including a description of the four quadrants and eight zones of operation as well as the mathematics and a numerical scheme for computation. Typically an explicit scheme, including the method of characteristics, is used, but an implicit scheme is presented which is consistent with the scheme used to solve the water hammer equations for conduits.

Low pressures caused by transients can lead to intrusion and contamination of the drinking water supply. Several scenarios are simulated using the WHAMO program and cases are provided in which intrusion occurs. From the intrusion scenarios, key factors for intrusion to occur during transients include the starting energy in the system, the magnitude of the transient, the hydraulics of the intrusion opening, and the external energy on the pipe (the level of the groundwater table). A primer for using WHAMO is provided as an appendix as well.

Appendix I: Pipe Expansion due to Water Hammer

(Based on Parmakian, 1963)

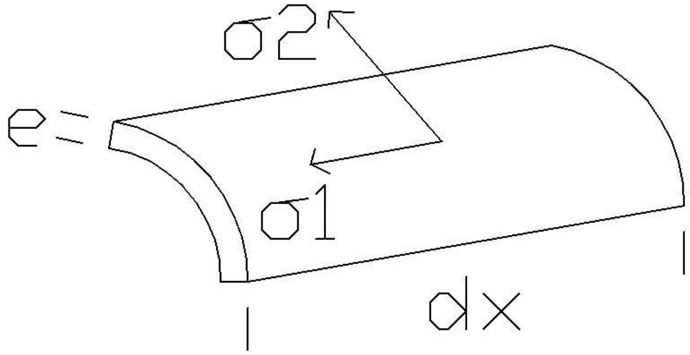


Figure A-1 Stresses on a Pipe Element

According to Timoshenko (1943) the deformation of a circular element due to stresses is

$$\Delta R = \{(R + \frac{e}{2})\,(\Delta\sigma_2 - \nu\Delta\sigma_1)\}/\,E \qquad \text{(A-1)}$$

When the thickness, e, is small the expression can be simplified

$$\Delta R = \{R(\Delta\sigma_2 - \nu\Delta\sigma_1)\}/\,E \qquad \text{(A-2)}$$

The change in the axial length is

$$\Delta x = \frac{dx}{E}(\Delta\sigma_1 - \nu\Delta\sigma_2) \qquad \text{(A-3)}$$

in which: R = pipe radius

E = Young's Modulus of Elasticity

ν = Poisson's ratio

$\Delta\sigma_1$ and $\Delta\sigma_2$ = the changes in longitudinal and circumferential stresses

The approximation of pipe being thin walled versus the pipe being thick walled results in a different wave speed equation. Other conditions, such as the how the pipe is anchored and if there are expansion joints factor into the wave speed equation as well. The varying conditions can all be captured by using the term ψ in the wave speed equation, where ψ varies to represent the different pipe conditions.

After a time dt the new fluid element has a new length, radius and volume.

Length = $dx + \Delta x$

Radius = $R + \Delta R$

Volume = $\pi(R + \Delta R)^2(dx + \Delta x)$

Therefore, the change in volume would be

$$\delta\forall = \pi(R + \Delta R)^2(dx + \Delta x) - \pi R^2 dx \qquad \text{(A-4)}$$

Dividing the change in volume by the original area produces the change in length of the element.

$$\delta L = \frac{\pi(R + \Delta R)^2(dx + \Delta x) - \pi R^2 dx}{\pi R^2} \qquad \text{(A-5)}$$

After simplifying and neglecting the very small terms the above expression results in

$$\delta L = \Delta x + \frac{2\Delta R dx}{R} \qquad \text{(A-6)}$$

Substituting the equations for Δx and ΔR eq. (A-6) becomes

$$\delta L = \frac{dx}{E}(\Delta\sigma_1 - \nu\Delta\sigma_2) + \frac{2\mathrm{dx}}{\mathrm{R}}\ (\mathrm{R}(\Delta\sigma_2 - \nu\Delta\sigma_1))/\mathrm{E} \qquad \text{(A-7)}$$

As stated earlier, the pipe anchoring conditions influence the change in pipe stress due to a change in head. The first case is one where pipe is anchored throughout its length against longitudinal movement. For this case, the changes in stresses on the pipe wall are

$$\Delta\sigma_1 = \frac{\nu\,\gamma\,\mathrm{DdH}}{2\mathrm{e}} \qquad \Delta\sigma_2 = \frac{\gamma\,\mathrm{D\,dH}}{2\mathrm{e}} \qquad \text{(A-8)}$$

in which we have used $\sigma_1 = \frac{pD}{4e}$ and $\sigma_2 = \frac{pD}{2e}$; p = γH and Δp = γΔH; e = pipe wall; and γ = specific weight of water.

Substituting into eq.(A-7) yields

$$\frac{dx}{E}\left(\frac{\nu\,\gamma\,\mathrm{DdH}}{2\mathrm{e}} - \nu\frac{\gamma\,\mathrm{D\,dH}}{2\mathrm{e}}\right) + \frac{2\mathrm{dx}}{\mathrm{E}}\left(\frac{\gamma\,\mathrm{DdH}}{2\mathrm{e}} - \nu^2\frac{\gamma\,\mathrm{D\,dH}}{2\mathrm{e}}\right) \qquad \text{(A-8)}$$

The equation can be further simplified to

$$\frac{\gamma\,\mathrm{DdH}}{\mathrm{Ee}}\ (1-\nu^2)\mathrm{dx} \qquad \text{(A-9)}$$

For the case where the pipe is anchored at the upper end but free to move throughout its length the equation for the change in length of the pipe due to a pressure change is

$$\frac{\gamma\,\mathrm{DdH}}{\mathrm{Ee}}\,(1.25-\nu)\mathrm{dx} \qquad \text{(A-10)}$$

The two are similar in the fact that the $\frac{\gamma DdH}{Ee}$ term is constant is both. Many texts (Streeter and Wylie, 1978; Parmakian, 1963) use the variable c to represent the varying terms of the equation. For the first case where the pipe is anchored against longitudinal movement throughout its length, $c_1 = 1-\nu^2$. For the second case where the pipe is anchored at the upper end but free to move throughout its length, $c_2 = 1.25-\nu$. The variable c is useful for assumption of the pipe being thin walled. For a more general expression the variable ψ can be used. For thin walled pipes $\psi = \frac{D}{e}c$. The variable ψ can be used for thick walled conduits, rigid conduits, tunnels, etc. The two previous equations can be represented by

$$\frac{\gamma\, dHdx\, \Psi}{E} \tag{A-11}$$

Using the derivation of the continuity equation based on pipe expansion due to water hammer presented here in appendix I produce same final expression as is shown in chapter 2.

Appendix II: Chapter 4 input data

```
******************************************************
*                    E P A N E T                     *
*            Hydraulic and Water Quality             *
*            Analysis for Pipe Networks              *
*                    Version 2.0                     *
******************************************************
```

Table 4.4. Input Data

Link - Node Table:

Link ID	Start Node	End Node	Length feet	Diameter in
1	1	2	1000	8
2	2	3	1000	8
3	3	4	1000	8
4	3	5	1000	8
5	8	7	1000	8
6	7	5	1000	8
7	5	4	1000	8
8	5	6	1000	8
9	6	4	1000	8
10	2	9	1000	8
11	5	10	1000	8
12	7	11	1000	8
13	11	5	1000	8

Table 4.5 WHAMO Input File

```
SYSTEM
 EL RES1 AT 1
 EL C1 LINK 1 2
 JUNC AT 2
 EL C10 LINK 2 9
 EL FBC1 AT 9
 EL C2 LINK 2 3
 JUNC AT 3
 EL C3 LINK 3 4
 JUNC AT 4
 EL C4 LINK 3 6
 JUNC AT 6
 EL DUM1 LINK 6 13
 EL FBC3 AT 13
 EL C9 LINK 4 6
 EL C7 LINK 4 5
 EL C8 LINK 6 5
 JUNC AT 5
 EL DUM2 LINK 5 14
 EL FBC4 AT 14
 EL C11 LINK 5 10
 EL FBC2 AT 10
 EL C13 LINK 5 11
 JUNC AT 11
 EL DUM3 LINK 11 15
 EL FBC5 AT 15
 EL C12 LINK 11 7
 JUNC AT 7
 EL C6 LINK 5 7
 EL C5 LINK 7 12
 EL RES2 AT 12
 NODE 9 ELEV 0
 NODE 10 ELEV 0

 FINI

RESE ID RES1 ELEV 150. FINI
RESE ID RES2 ELEV 140. FINI
CONDUIT ID DUM1 DUMMY FINI
CONDUIT ID DUM2 DUMMY FINI
CONDUIT ID DUM3 DUMMY FINI
CONDUIT ID C1 LENGTH 1000 DIAM .666667 FRICT 0.021 CELE 4000 FINI
CONDUIT ID C2 LENGTH 1000 DIAM .666667 FRICT 0.021 CELE 4000 FINI
CONDUIT ID C3 LENGTH 1000 DIAM .666667 FRICT 0.022 CELE 4000 FINI
CONDUIT ID C4 LENGTH 1000 DIAM .666667 FRICT 0.022 CELE 4000 FINI
CONDUIT ID C5 LENGTH 1000 DIAM .666667 FRICT 0.021 CELE 4000 FINI
CONDUIT ID C6 LENGTH 1000 DIAM .666667 FRICT 0.022 CELE 4000 FINI
CONDUIT ID C7 LENGTH 1000 DIAM .666667 FRICT 0.022 CELE 4000 FINI
CONDUIT ID C8 LENGTH 1000 DIAM .666667 FRICT 0.022 CELE 4000 FINI
CONDUIT ID C9 LENGTH 1000 DIAM .666667 FRICT 0.024 CELE 4000 FINI
CONDUIT ID C10 LENGTH 1000 DIAM .666667 FRICT 0.017 CELE 4000 FINI
CONDUIT ID C11 LENGTH 1000 DIAM .666667 FRICT 0.017 CELE 4000 FINI
CONDUIT ID C12 LENGTH 1000 DIAM .666667 FRICT 0.017 CELE 4000 FINI
CONDUIT ID C13 LENGTH 1000 DIAM .666667 FRICT 0.017 CELE 4000 FINI
```

```
FLOWBC ID FBC1 Q 0 FINI
FLOWBC ID FBC2 Q 0 FINI
FLOWBC ID FBC3 Q 1 FINI
FLOWBC ID FBC4 Q 5 FINI
FLOWBC ID FBC5 Q 1 FINI

HIST
 NODE 9 PSI DECIMAL 3
 NODE 10 PSI
 FINI
PLOT
 NODE 9 PSI
 FINI
DISPLAY ALL FINI
SNAPSHOT TIME 30.3 FINI

CONTROL
 DTCOMP 0.1 DTOUT 5.0 TMAX 10.
 DTCOMP 1.0 DTOUT 5.0 TMAX 25.
 DTCOMP 1.0 DTOUT 1.0 TMAX 35.0
 FINI

C CHECK
GO
```

Appendix III: Characteristics Conversion Program

The preferred method of representing characteristics for computation is the method Marchal proposed. The program WHAMO accepts pump characteristics in a way that corresponds to the Karman-Knapp diagram. The following matlab script file converts pump characteristics from the Marchal form to the form that can be used for WHAMO, and produces the Karman-Knapp diagram.

```
% The goal of this program is to provide the table of pump characteristics
% needed for the WHAMO program

%Characteristics are assumed to be the same for pumps with the same
%specific speed

N = .46
u = [-100:10:100];
% specific speed

theta = [0:5:360];
%input of characteristics for a certain specific speed pump
%values of h/(alpha^2+v^2)
col1 = [-0.55,-0.48,-0.38,-0.27,-0.17,-
0.09,0.06,0.22,0.37,0.5,0.64,0.78,0.91,1.03,1.13,1.21,1.27,1.33,1.35,1.36,1.34,1.31,1.28,1.22,1.17,1.13,1
.09,1.04,0.99,0.96,0.91,0.89,0.85,0.82,0.79,0.75,0.71,0.68,0.65,0.61,0.58,0.55,0.54,0.53,0.52,0.52,0.53,0
.55,0.57,0.59,0.61,0.63,0.64,0.66,0.66,0.62,0.51,0.32,0.23,0.11,-0.2,-0.31,-0.39,-0.47,-0.53,-0.59,-0.64,-
0.66,-0.68,-0.67,-0.66,-0.61,-0.55;];
%values of beta/(alpha^2+v^2)
col2 = [-0.43,-0.26,-0.11,-
0.05,0.04,0.14,0.25,0.34,0.42,0.5,0.55,0.59,0.61,0.61,0.6,0.58,0.55,0.5,0.44,0.41,0.37,0.35,0.34,0.34,0.3
6,0.4,0.47,0.54,0.62,0.7,0.77,0.82,0.86,0.89,0.91,0.9,0.88,0.85,0.82,0.74,0.67,0.59,0.5,0.42,0.33,0.24,0.1
6,0.07,0.01,-0.12,-0.21,-0.22,-0.35,-0.51,-0.68,-0.85,-1.02,-1.21,-1.33,-1.44,-1.56,-1.65,-1.67,-1.67,-1.63,-
1.56,-1.44,-1.33,-1.18,-1,-0.83,-0.64,-0.43;];

% Enter the range of speed and head ratios desired
Speedratios = [-10 -6 -3 -1.5, -1.25:.25:1.25 1.5 3 6 10];
Flowratios = [-10 -6 -3 -1.5, -1.25:.25:1.25 1.5 3 6 10];

% speed ratio/flow ratio
n = size(Speedratios);
m = size(Flowratios);

for i = 1:n(2)
  for j = 1:m(2)
    Matrix1(j,i) = atan2(Speedratios(1,i),Flowratios(1,j));
    if Matrix1(j,i) < 0
      Matrix1(j,i) = Matrix1(j,i) + 2*pi;
    end
    Matrix1(j,i) = Matrix1(j,i)*(180/pi);
    % at this point matrix1 is the angle theta on degrees
    Matrix2(j,i) = interp1(theta,col1,Matrix1(j,i));
    %matrix2 is the value h/(alpha^2+v^2)
    Matrix3(j,i) = interp1(theta,col2,Matrix1(j,i));
     %matrix2 is the value beta/(alpha^2+v^2)
```

```matlab
   end
end
% calculation head ratios
for i = 1:n(2);
   for j = 1:m(2);
      h(j,i) = Matrix2(j,i).*(Speedratios(1,i).^2+Flowratios(1,j).^2);
   end
end
% calculation torque ratios
for i = 1:n(2);
   for j = 1:m(2);
      B(j,i) = Matrix3(j,i).*(Speedratios(1,i).^2+Flowratios(1,j).^2);
   end
end

%plotting commands
[a,v] = meshgrid(Speedratios,Flowratios);
contour(a,v,h,u,'-');
hold on
[C,l] = contour(a,v,h,u,'-');
clabel(C,l,'LabelSpacing',372);
contour(a,v,B,u,'-.');
hold on
[C2,l2] = contour(a,v,B,u,'-.');
clabel(C2,l2,'LabelSpacing',372);
```

Appendix IV: WHAMO Simulation Program & WHAMGR Graphical Interface Primer

The U.S. Army Corps of Engineer's Water Hammer and Mass Oscillation (WHAMO) package includes two main programs. The first is the WHAMO simulation program, which is a DOS-based solution algorithm for water hammer analysis. As stated in the above "Water Hammer" section, WHAMO utilizes a four-point implicit finite-difference solution technique to simulate transient flow conditions. This program is included in the WHAMO package as an executable file. WHAMGR is the second program included in the WHAMO package. It is a graphical interface program designed to work seamlessly with the simulation program to produce time history plots of hydraulic transient analyses. WHAMGR is included in the WHAMO package as an MFC application file. These two programs provide robust means for studying water hammer events occurring in piping systems.

Running a WHAMO simulation requires the user to be familiar with four different files types used/outputted by the program. The input file (extension of *.INP) provides all the information WHAMO uses to run a simulation. This includes, but is not limited to, the system connectivity, system elements and attributes, computational options, and execution statements. Input files may be generated in a text editor (i.e. Microsoft Notepad ®), or in other word-processing programs, although they must be formatted as ASCII files. These files will be discussed in detail later in this text. Output files (extension of *.OUT) report the tabular input data of the system, as well as the results for the simulation. Outputs are formatted as ASCII files, and can be easily viewed in a text editing program. Plot files (extension of *.PLT) are unformatted files used by WHAMGR to create graphical output. Spreadsheet files (extension of *.TAB) may be used in compatible spreadsheet programs for data manipulation and analysis. These are formatted as ASCII files. The WHAMO simulation program will ask for the names of all the four aforementioned files before any analysis is completed. The WHAMO user's manual, for organizational purposes, recommends using identical names for each file.

Running a WHAMO simulation is a complex procedure which can be made easier by introducing a framework for problem formulation. The following framework provides a sequential path for simulating hydraulic transient situations in a system. (1) Generate a schematic representing the interconnection of all system components. It is vital to represent the system’s interconnection in terms of the WHAMO model input in which individual elements must be joined with uniquely numbered node points. This is intuitive because all elements are represented by mathematical equations, and hence necessitate individual consideration. Unfortunately, WHAMO does not provide a graphical interface to build the system, and this step must be completed outside of the WHAMO software package. As a corollary, boundary elements cannot be joined directly to another boundary element or junction. A dummy link must be utilized for connection. Elements are defined using commands specific to themselves. The user’s manual should be consulted for a full listing of all element commands. (2) Define the characteristic tables for any machines or valves located in the piping system. Characteristic tables refer to how an element operates. For example, a pump characteristic includes the speed ratios, discharge ratios, head ratios, and torque ratios. Characteristic tables can be input under PCHAR, VCHAR, and others. (3) Define the operational characteristics of the system. This step involves defining how the equipment within the system works with respect to time. These characteristics, which are often represented as schedules, will determine how the hydraulic travel through the system. For example, a valve must be assigned a open/close schedule. Operational characteristics are defined by OPPUMP, OPTURB, OPPT, or SCHEDULE commands. (4) Specify output elements. Each element in the system has the capability of producing output values during the transient event. Since not all of the elements are relevant to the final analysis, therefore it is necessary to determine what components should be analyzed. For example, a surge tank may be modeled for its capability to alleviate hydraulic shock on a power plant’s penstock. All pipe links comprising the penstock may not need to be included in the analysis because the main component in question is the surge tank. Output elements are cited by using the HISTORY, PLOT, or SPREADSHEET commands. (5) Specify the computational parameter of the WHAMO simulation. These refer to the time step for the finite-difference solution, the total time of simulation, and the output interval for the chosen output elements. They are defined by the CONTROL command.

Creating a WHAMO input file is the heart of running a water hammer simulation. The input file defines points highlighted in the above framework, and serves as the interface between the user and WHAMO. WHAMO uses a Problem Orientated Language (POL) for its input code, which means that each data value in the input file is identified by an alphanumeric tag. This tag allows the data value to be assigned to its desired location. WHAMO also reads input files in a “free format”. “Using such a format, each command tag and/or data value will have no fixed location in an input line, but will be simply separated from the other data by one or more blanks acting as delimiters of the data string” (Fitzgerald and Van Blaricum, 1998). Input files are comprised of Primary and Secondary commands. Primary commands “are used to specify the type of data which follow” (Fitzgerald and Van Blaricum, 1998). Secondary commands include the data values that define the primary commands. For example, pipe links are defined by the primary command “CONDUIT”. The secondary commands associated with CONDUIT define the pipe length, diameter, roughness, etc. Computational parameters fall under the primary command “CONTROL”. Secondary commands include the computational time step, the output time step, and the time interval. An abbreviated list of common primary commands is located below (see the user’s manual for all commands and explanations).

1. <u>System Commands</u>: used to define the interconnection of the system elements
    a. SYSTEM: defines interconnection by identifying node values bounding each element (this is where the system schematic from step 1 of the framework is critical)
2. <u>Element Commands</u>: identifies each element of the system.
    a. CONDUIT: defines a pipe link
    b. FLOWBC: defines a discharge condition at a system boundary
    c. PUMP: defines a pump
    d. RESERVOIR: defines any water body with a static level of head
    e. SURGETANK: defines a surge tank (there are multiple types)
    f. VALVE: defines a valve used a throttling device
    g. PCHAR: defines the operational characteristics of a pump
    h. VCHAR: defines the operational characteristics of a valve
3. <u>Output Commands</u>: allows the user to define the output of the simulation
    a. DISPLAY: defines what input data will be presented in the output
    b. HISTORY: defines what elements will be presented as a time history in the output file
    c. PLOTFILE: defines the elements that will be output in the *.PLT file for plotting within WHAMGR
4. <u>Simulation Commands</u>:

    a. CONTROL: controls the computational parameters of the simulation
    b. SCHEDULE: defines the operating schedule for valves, and other boundary elements
5. Execution Commands:
    a. CHECK: checks the network data, but does not allow for WHAMO simulation (can be used for interconnection diagnostics)
        i. NOTE: this must be erased for the WHAMO simulation to run
    b. GO: indicates that simulation should begin
    c. GOODBYE: ends the program

Secondary commands are specific to their respective primary command. The user's manual should be referenced for all necessary secondary commands. WHAMO requires that any primary command must terminate with a FINISH command. Below are examples of two typical command sequences found in a WHAMO input files.

Table A-1: CONDUIT Command Sequence

Primary Command	Secondary Command Block		Secondary Command Block		Secondary Command Block		Secondary Command Block		Termination Command
	Tag	Data	Tag	Data	Tag	Data	Tag	Data	
CONDUIT	ID	Pipe	LENGTH	3000	DIAM	10	CELER	6000	FINISH

Table A-2: CONTROL Command Sequence

Primary Command	Secondary Command Block		Secondary Command Block		Secondary Command Block		Termination Command
	Tag	Data	Tag	Data	Tag	Data	
CONTROL	DTCOMP	0.1	DTOUT	5.0	TMAX	10.0	FINI

Table 1 shows a pipe link defined using the CONDUIT primary command. The secondary command blocks, which are comprised of a "tag" block and a "data" block, define the attributes of the pipe link. The tag refers to the alphanumeric value that defines the data value. Here, a pipe is identified as "Pipe" and has a length of 3000 feet, a diameter of 10 feet, and a wave celerity (speed) of 6000 ft/s. The CONDUIT command terminates with the FINI command (short for FINISH). Table 2 displays the command sequence for a CONTROL primary command. The secondary command DTCOMP refers to the time step of the simulation computation, DTOUT is output time step, and TMAX is the maximum duration for which the simulation will run. Again, the primary CONTROL command is terminated with FINI. WHAMO input files allows the use of comments within the code. Comments can be denotes one of two way. First, comments can be made with secondary commands using closed parentheses. Second, comments can be made between primary blocks if a "C" is located on left hand side of a line. If "C" is used within a primary block, the WHAMO simulation will not run. The first line of an input file is reserved for the title of the project. The string within the first line will show up in the title block of the ASCII formatted output file. Furthermore, WHAMO allows all primary and secondary commands to be abbreviated to four characters in length. For example, a CONDUIT primary command can be input as COND and a DIAMETER secondary command may be expressed as DIAM.

Running a WHAMO simulation is very simple. First, it is best to place a main WHAMO folder directly under the C: drive of the computer's hard drive. Place all contents of the original zip file into this directory. All input files and associated output files should also reside within this folder (the folder can get very cramped after multiples simulations!). After the input file has been created, the WHAMO executable program should be pulled up (do not run WHAMO from DOS, jus simply double-click on the executable file). The program will prompt the user to identify the name of the input file. It will then ask you to choose the names of the output file, the plot file, and the spreadsheet file. Simulation will begin immediately after the spreadsheet file has been named. WHAMO automatically places the three generated files into the same directory where the executable file has been placed. The output file can be viewed by simply double-clicking on the *.OUT file. WHAMGR must be activated to view the graphical output from the *.PLT file. If the spreadsheet command is executed, a *.TAB file is created and produces an excel file of the report history. The *.TAB files can be viewed using the WHAMO graph utility but the WHAMGR program produces much nicer quality graphs.

To fully explain the inner-workings of WHAMO, a text-based input file named "Valve Closure in a Simple Pipeline" has been attached to this report. The code was taken directly from the WHAMO user's manual, although the U.S. Army Corps does not supply this text file within the WHAMO Zip Folder package. The system is comprised of 3 pipe links, 2 head boundaries, and a valve. As the name implies, the downstream valve is closed suddenly thereby creating a transient event. Figure 1 below displays the system.

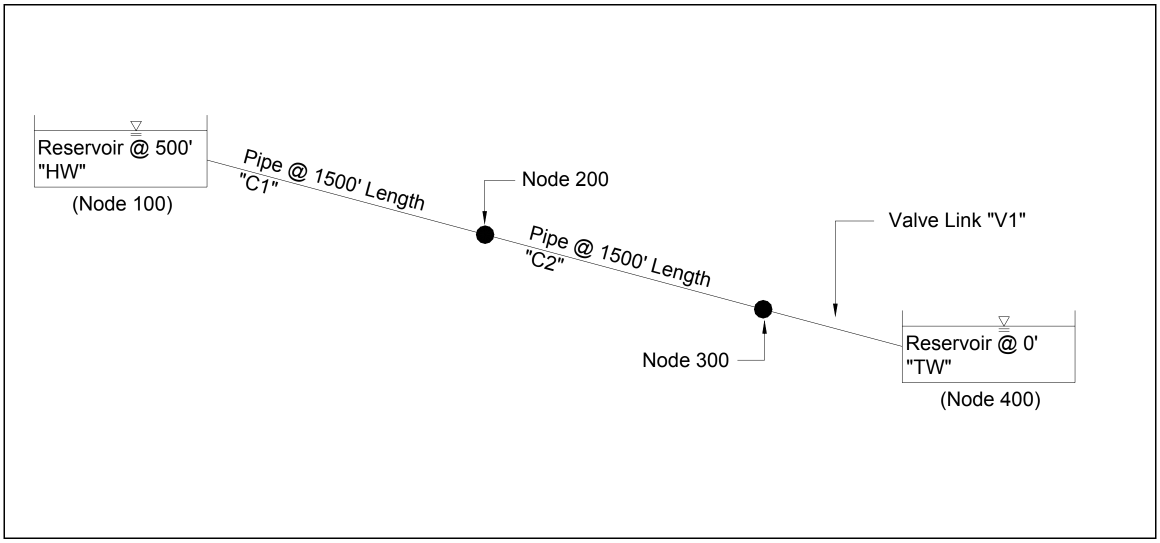


Figure A-2: Valve Closure in a Simple Pipeline – System Interconnection

The following explanations refer to the attached input file. Comment bullets are indexed with respect to the line number of the input file (shown in the left-most column). Note that this file MAY NOT be used as direct input into the WHAMO simulation program (it is not in the correct format). A second attachment has been provided without markup for this purpose.

1. Specifies the header of the input file. It is not processed by the program, and will be printed in the title block of the output file.
2. Blank between the header and the first primary command.
3. "SYSTEM" refers to the primary command that defines the interconnection of the system. This is input sequentially with respect to the system connections, as shown in Figure 1.
4. This is a string of secondary command blocks. "EL" refers to an element named "HW". "AT" is a numerical identifier that states at what node the element is located. In this case there is only one node defined because element "HW" is a boundary element of the system (it's the upstream reservoir).
5. Another string of secondary command blocks. "C1"is analogous to the first pipe link shown in Figure 1. "LINK" identifies the upstream and downstream nodes, respectively.
6. See Line 5.
7. See Line 5. Here, the element is identifying the valve "V1".

8. Identical to Line 4 except "TW" identifies the downstream boundary element.
9. "FINISH" terminates the SYSTEM primary command.
10. A blank line between primary commands.
11. "RESERVOIR" is a primary element command defining a boundary water surface elevation. The "ID" designates element "HW", from the SYSTEM primary command, as a reservoir (until this point the program did not know that HW was a reservoir). "ELEV" defines the water surface elevation as 500 feet. The RESERVOIR command is terminated with a FINISH command

*NOTE: all numerical values must have a decimal place for proper definition!

12. "CONDUIT" is the primary element command defining a pipe link. Here, the conduit is identified as "C1" from the SYSTEM command. "DIAM" is given as 10'. "CELERITY" is the wave speed within the pipe as 6000 ft/second. "FRICTION" is the Darcy-Weisbach friction factor defined as 0.00001 (*this value is considered constant). "LENGTH" is given as 1500'. "NUMSEG" refers to the number of computational segments along the pipe length. This value is used in the finite-difference scheme, and is defined as 5 segments over 1500'.
13. Defines the pipe link "C2". Here the "AS" command is used to define "C2" exactly as "C1". The "AS" command can be used for any element which is defined more than twice.
14. "VALVE" identifies valve "V1" as having a diameter of 10'. "TYPE" specifies the valve as a special type. "1" refers to i^{th} valve type with characteristics as defined under the following "VCHAR" command(s). The characteristics are defined in Lines 17 – 20. "VSCHED" refers to the operating schedule, with respect to time, of the valve "V1". The schedule is defined in lines 22 – 24.
15. Defines the downstream reservoir.
16. A blank line between primary commands.
17. "VCHAR" is a primary element command defining the operational characteristics of a valve. "TYPE" refers to a special valve type, and is identified as being type "1" as defined under line 14 (this is a logistical secondary block used to allocate the characteristics to the correct VALVE element).

18. “GATE” specifies a disk type gate valve. The string of following numbers refers to the percent openness of the valve (where 0 is fully closed and 100 is fully open).
19. “DISCOEF” is the secondary command referring to the discharge coefficients respective to the openness of the valve (Line 18).
20. “FINISH” terminates the VCHAR primary command. This is the end of all primary element commands.
21. A blank line between primary commands
22. “HISTORY” designates the beginning of the primary output commands. This command identifies which elements should have associated time histories printed as output (in the *.OUT file).
23. “NODE” requests from the program that output is desired from a node, namely the node identified as “100”. “HEAD” identifies that a time history of the total head in terms of the energy gradient elevation (ft) is wanted at Node 100.
24. See Line 23
25. See Line 23
26. “ELEM” is the secondary command referring to the element “V1”. The desired output is the time history of the head values at the valve.
27. See Line 26, but the desired output is the time history of the flow values at the valve “V1”.
28. “FINISH” terminates the “HISTORY” primary output command.
29. A blank line between primary commands
30. “PLOT” identifies which elements should have associated time histories output to the WHAMGR files (the *.PLT file). The time histories of these elements can be graphically displayed in WHAMGR. The format of the secondary commands are identical to those used under the “HISTORY” command.
31. See Line 23
32. See Line 23
33. See Line 23
34. See Line 26
35. See Line 27
36. “FINISH” terminates the “PLOT” primary command.

37. A blank line between primary commands
38. “DISPLAY” primary command controls what input data will be printed in the output file (*.OUT). Simply, the output file will contain the specified input parameters. “ALL” is a secondary command identifying that input data should be printed in the output file. “FINISH” terminates the “DISPLAY” primary output command. This is the end of all primary output commands.
39. Blank line between primary commands
40. “SCHEDULE” designates the beginning of primary simulation commands. This primary command defines an operating schedule. “VSCHED” is the secondary command that tells WHAMO the associated schedule is for a valve, and is identified as being valve schedule number “1”. Note that in Line 14 this exact schedule has been called by the “VALVE” primary command.
41. “DELT” is a secondary command identifying the constant time step for the valve’s operation. Here, the time step is 0.1 seconds. “GATE” is the secondary command identifying that the valve is of the gate type. The following numerical string defines the percentage of valve openness with respect to the indicated time step. For example, at t = 0 seconds, the gate valve is 100% open. At t = 0.1 seconds, the valve is 80 % open, and so on.
42. “FINISH” terminates the “SCHEDULE” primary command.
43. A blank line between primary commands.
44. “CONTROL” is a primary simulation command that defines the computational and output time steps of the WHAMO simulation.
45. “DTCOMP” is the secondary command that identifies 0.1 seconds as the computational time step used by WHAMO within its four-point finite difference solution algorithm. “DTOUT” defines the time step at which output will be the specified output parameters are stored (for both the output file and the plot file). Furthermore, the elements identified under the “HISTORY” and “PLOT” primary commands will have a time step of 0.5 seconds (see Lines 22 – 37). “TMAX” refers the length of simulation time, or in other words, when the WHAMO simulation terminates.
46. “FINISH” ends the “CONTROL” primary command. This is the end of all primary simulation commands.

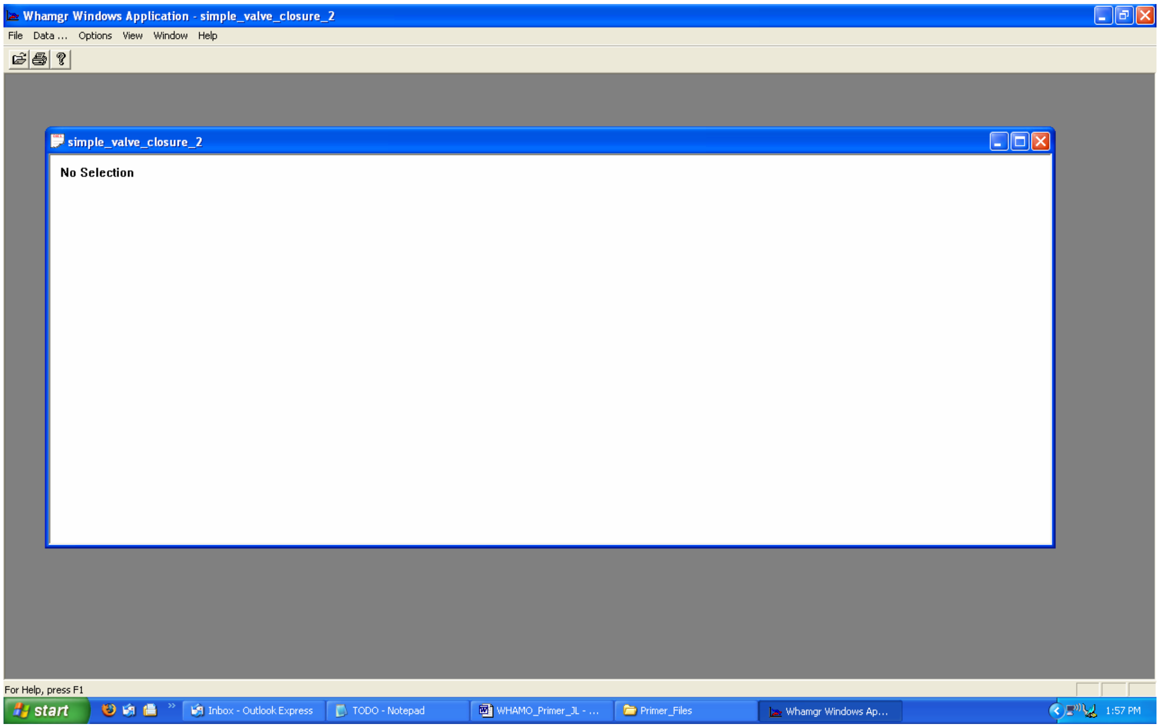
47. A blank line between primary commands.
48. "CHECK" designates the beginning of the primary execution commands. The "CHECK" command is ONLY input when running a check run to ensure the accuracy of the input network data. "CHECK" should be used before any simulations are run, and helps with diagnostics and debugging. After the check has been completed, a "C" should be placed in front of it. This will designate the command as a comment, and hence WHAMO will process an entire transient analysis. This approach makes it easy for re-checking systems when changes have been made (just erase the "C").
49. "GO" is a primary execution command that indicates that data definition is complete. "GO" induces the program's execution.
50. "GOODBYE" terminates WHAMO program execution.

For another sample input file, please see the file titled "Whamtest" which has been supplied by the U.S. Army Corps of Engineers. The "Whamtest" file includes a surgetank simulation. It is important to note that this "Valve Closure in a Simple Pipeline" input file was created to coincide with the files shown in the user's manual (page 160). Some changes have obviously been made to create more structured input file. Because WHAMO allows free format input files, the structure of the primary commands is arbitrary. Also note that all input files must be saved with a "*.INP" extension (this must be manually types in when saving the input file from a text editor).

WHAMGR has the capability of graphically presenting the time histories of the designated elements from the WHAMO simulation. More specifically, WHAMGR can plot the time histories of those elements indicated under the "PLOT" primary output command. It can also display any characteristics of machine components within the input file. Using WHAMGR begins by opening the program, which needs to be separately installed from the original zip file. Follow the steps below to generated graphical output.

1. Open the WHAMGR program by double-clicking on its icon.
2. A WHAMGR interface screen will appear. In the top left-hand corner select the open folder button. A dialogue box will pull up entitled "Open". Select the *.PLT file that corresponds to the simulation made in WHAMO.

3. A new dialogue screen will appear named after the title of the *.PLT file just opened. The dialogue will read “No Selection”, which means that no elements have been chosen for plotting. See Figure 2 below.

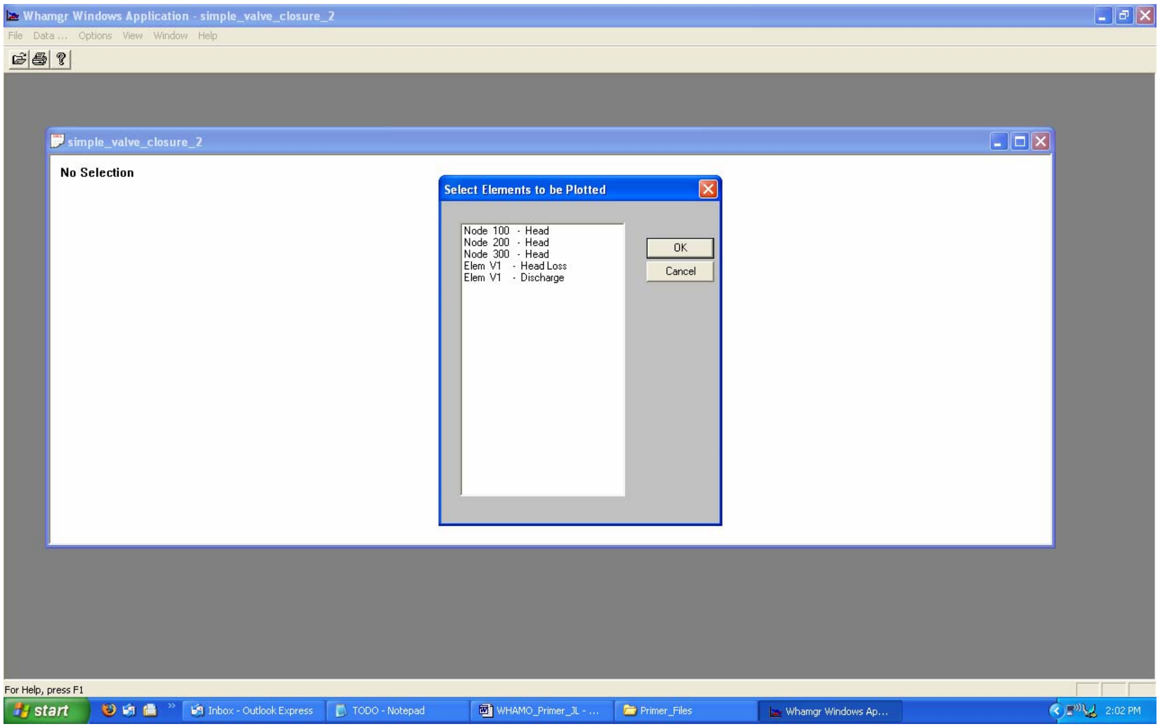


No Selection

For Help, press F1

Figure A-3: WHAMGR Dialogue Screen – “No Selection”

4. Choose elements for plotting by clicking on the “Data…” pull down menu on the main menu tool bar (at the top of the page). A dialogue box will pull up titled “Select Elements to be Plotted”. These elements should directly correspond to the elements indicated under the “PLOT” primary output command in the original input file. See Figure 3 below.



No Selection

Node 100 - Head
Node 200 - Head
Node 300 - Head
Elem V1 - Head Loss
Elem V1 - Discharge

Figure A-4: WHAMGR Dialogue Screen – "Select Elements to be Plotted"

5. At this point, select the desired element or elements for graphical time history output. It is possible to select multiple elements by simply single-clicking on each element (this will produce a graph will multiple elements simultaneously plotted). Click "OK".
6. The resulting plot shows the selected elements superimposed on each other. Figure 4 shows the time history plots of Head vs. Time for nodes 100, 200, and 300.
7. Plots of the other elements are conducted in the same manner.

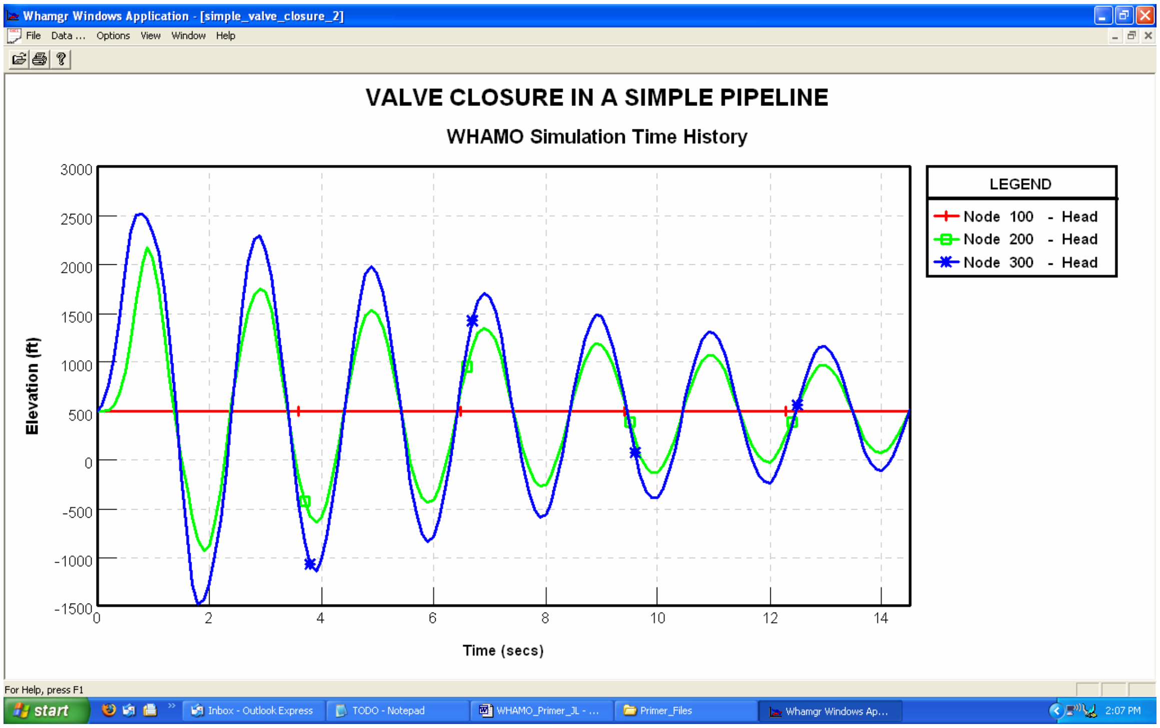


Figure A-5: WHAMGR Results

WHAMGR also includes tools to manipulate the graphical output. These options are under the "Options" pull down on the main tool bar menu. The user can create custom graphical output files to best represent the simulation data.

The purpose of this document is to provide the reader with a technical introduction to WHAMO, how to the run hydraulic simulations with it, as well as providing a simple example. Although the example in this paper is a generic water hammer problem, much more complex systems can be modeled. Real life case studies that have used the WHAMO simulation can be found in the user's manual. The lack of a graphical interface for the input is a drawback, but the text file input is fairly easy to use with a little familiarity to the program. The WHAMGR feature provides excellent graphing tools. Overall the WHAMO simulation program provides a useful tool to model and study hydraulic transients.

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