Modeling and controlling flow transient in pipeline systems: Applied for reservoir and pump systems combined with simple surge tank

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Abstract

When transient conditions (water hammer) exist, the life expectancy of the system can be adversely impacted, resulting in pump and valve failures and catastrophic pipe rupture. Hence, transient control has become an essential requirement for ensuring safe operation of water pipeline systems. To protect the pipeline systems from transient effects, an accurate analysis and suitable protection devices should be used. This paper presents the problem of modeling and simulation of transient phenomena in hydraulic systems based on the characteristics method. Also, it provides the influence of using the protection devices to control the adverse effects due to excessive and low pressure occuring in the transient. We applied this model for two main pipeline systems: Valve and pump combined with a simple surge tank connected to reservoir. The results obtained by using this model indicate that the model is an efficient tool for water hammer analysis. Moreover, using a simple surge tank reduces the unfavorable effects of transients by reducing pressure fluctuations.

Keywords : Flow Transient, Water hammer, Pipeline System, Surge Tank, Simulation Model, Protection Devices, Characteristics Method.

Notations

A, Ac	pipe and surge tank cross-sectional area (m2)
a	wave speed (m/s)
Av	Area of pipe at inlet to valve (m2)
B	Transient coefficient (Eq. 8)
C+, C-	Compatibility equations (Eqs. 9. 10)
C1-C2	Constants
CM	Eq. 11
CP	Eq. 12
D	diameter
do	Orifice diameter of the surge tank
f	friction factor
g	acceleration of gravity
H	Head
HP	Unknown head
HR1, HR2	Piezometric head of reservoirs
ΔH	Head drop
K	singular loss coefficient
l	Pipe length or characteristic length
Q	Flow rate
QI	Initial flow
QP, QPi	
QPc, QPD	unknown flow rates
R	Friction coefficient (Eq. 8)
t	time
tc	Valve closure time
V	Velocity
x	Linear dimension
XLPc	Unknown head inside surge tank (Fig. 1)
z, Z	Elevation
λ	Constant in method of characteristics

Introduction

In a pipeline system, system flow control is an integrated part of its operation, for instance, the opening and closing of valves, and starting and stopping of pumps. When these operations are performed very quickly, they can cause hydraulic transient phenomena.

Transients are important in hydraulic systems because they can cause rupture of pipe and pump casings, pipe collapse, vibration, excessive pipe displacements, pipe-fitting, and support deformation and/or failure, and vapor cavity formation.

Several methods have been introduced and used to analyze water hammer problem like the energy (Karney, 1990), arithmetic (Zarzycki and Kudzma, 2007), graphical, characteristics, algebraic, implicit and linear analyzing (Chaudhry, 1986; Ghidaoui et al., 2005; Wylie and Streeter, 1983), Euler and Lagrangian based method (Wood et al., 2005), and decoupled hybrid methods (Twyman, 2004).The characteristics method converts the two partial differential equations of motion and continuity into four total differential equations. These equations are then expressed in finite differential form, using the method of specified time intervals, and solutions are carried out with the use of digital computer (Nabi et al., 2011; Streeter and Wylie, 1973; Tezkan et al., 1998; Wylie and Streeter, 1983).

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Karney and al. (1992) used the characteristics method with some modification to obtain more efficient calculations of transient in simple pipe system, while Tezcan et al. (1998) used this method to analyze the transient in complex pipe systems. Kodura and Weinerowska (2005), Karney (1990), Sirale (2007) and Jung et al. (2007) compared between the results obtained for both simple and complex pipe systems by using the method of characteristics, and the results are more accurate in the simple systems. The characteristics method has been used to study the oil pipe systems (Aljanabi, 2010) and cooling networks in nuclear plants (Chaudhry, 1979; 1986). Recently Nabi et al. (2011) used this method to analyze real pipe systems in Pakistan; with a study of the effect of adding a protection device on the system.

To reduce the dangerous effects of water hammer, the surge devices have to be added to the pipeline systems. Most of these protection equipments aim to protect against unfavorable large pressure fluctuations and tend to maintain the pressure at a nearly constant value at some fixed places, or tend to keep the pressure from exceeding a predetermined value (Chaudhry 1986; Larock et al. 2000; Streeter and Wylie 1973). Several criteria can be adopted to determine which surge devices are to be used such as the effectiveness, dependability, evaluation of cost character and frequency of maintenance requirement over an given period (Wylie and Streeter 1983).

Each surge device has its own characteristics: the simple surge tank is placed vertical and has larger diameter than that of pipe to avoid spillage, it is used to minimize the entrance losses (Chaudhry 1986; Streeter and Wylie 1973; Tullis 1989; Wylie and Streeter 1983). When the diameter of the surge tank is smaller than that of the pipe, then it is called a stand pipe. It has lower cost but provides less protection than the simple surge tank, also it is used when the spillage can be allowed (Tullis 1989; Wylie and Streeter 1983). In the case that the size of the surge tank is to be small, then the throttled (orifice) surge tank can be used, but the penalty for that is high pressure in the pipe and the transient continues past the tank (Tullis 1989).

A combination between the simple and stand pipe surge tanks is called the differential surge tank. In this tank, following a change in penstock flow, the accelerating or decelerating head on the pipe develops slower than in an orifice tank and faster than in a simple tank (Chaudhry 1986; Streeter and Wylie 1973; Wylie and Streeter 1983). When the head is very high, then it is not practical to use a surge tank with large height, thus, the air chamber (closed surge tank) can be used (Thorley 2004; Tullis 1989). It may be one chamber or two chambers. In the case of one chamber, the amplitude of pressure oscillation during water hammer is smaller than in the case of the double air chamber (Nabi et al., 2011; Nitescu et al., 2011). Some transient solutions are safest and maintenance-free, like the flow control and pressure reducing device such as relief valves and check valves (Wylie and Streeter, 1983; Zhang et al., 2008).

The use of digital computers for analyze hydraulic transients has been used tenths of years ago (Streeter and Wylie, 1973) and increased considerably in recent years. Sophisticated and numerical methods have been introduced for such analyses (Chaudhry, 1986; Ghidaoui et al., 2005). The computer simulation allow to use a computer in controlling the pipe system devices (Naik et al., 2011).The proper simulation and design for the pipe systems aims to achieve two main goals: the first goal is to reduce the total cost of the system; for example one can compromise between the price and the useful life of the conduit. The other goal is to protect the pipe systems from damage due to pressure in the unsteady state which also reduce the cost of maintenance (Chaudhry, 1986; Tullis, 1989).

In this article a computer software had been developed in order to simulate and design hydraulic transients in pipeline systems.

Materials and Methods

The simplified equations that govern unsteady flow in pipelines are motion and continuity equations which will be solved together (Eq. 1 and Eq. 2), since the two equations provide two unknowns H and V. The method of characteristics is used to transform the partial differential equations into total differential equations.

$$\partial H/\partial x+1/g\ \ \partial V/\partial t+(fV|V|)/2gD=0 \qquad (1)$$

$$\partial H/\partial t+a^{\wedge}2/g\ \ \partial V/\partial x=0 \qquad (2)$$

By multiplying Eq. 2 by unknown constant λ, adding it to Eq. 1, and by rearranging and taking the total derivative, we get the compatibility equations Eq. 3 and Eq. 5.

$$g\, dH/\ a\, dt+dV/dt+\ (fV|V|)/2D=0 \quad C^{+}\text{equation} \qquad (3)$$

$$\text{For}\quad dx/dt=+a \qquad (4)$$

$$g\, dH/\ a\, dt-dV/dt-\ (fV|V|)/2D=0 \quad C^{-}\text{ equation} \qquad (5)$$

$$\text{For}\quad dx/dt=-a \qquad (6)$$

Finite difference solution

Solution of Eqs.3 and 5 is done by using finite differences solution. Figure 2 illustrates a simple reservoir valve system. The pipeline is divided to N equal sections of length Δx. The calculations were made at node *i*.

A transient is generated at time t by instant valve closure, solution of the equations governing the transient phenomena consists of finding the values of head and flow at each node as the transient progresses. Calculations were made at each time interval which calculated by Eq. 7. The nodes are equally spaced at a distance and the wave speed is constant. This means that the time for the pressure wave to travel between any two nodes is the same.

$$\Delta t=L/aN \qquad (7)$$

In general, to calculate the head and flow at a given node i at time $t=t_0+\Delta t$, where H_{i-1}, Q_{i-1}, H_{i+1} and Q_{i+1}, the head and flow respectively at the nodes and at instant time are assumed to be known before any generated transient.

The unknown head and flow at the nodes i at time t+Δt are labeled HP_i, and QP_i can be calculated by integrating Eqs. 3 and 5. The known head and flow at the previous time step are H_i and Q_i. Before integrating, both equations multiplied by, changed from V to Q, and replaced by by dx=adt. For the C^+ equation, integrating from node (i-1) to node (i) gives:

$$\int_{H_{i-1}}^{H_i} dH + B\int_{Q_{i-1}}^{Q_i} dQ + R_1\int_{x_{i-1}}^{x_i} Q|Q|dx = 0 \qquad (8)$$

$$HP_i+BQP_i=CP \qquad C^+ \text{ equation} \qquad (9)$$

The same procedure was made for the compatibility equation, by integrating from node (i+1) to node (i), which gives Eq. 10.

$$HP_i-BQP_i=CM \qquad C^- \text{ equation} \qquad (10)$$

Where:

$$CP=H_{i-1}+BQ_{i-1}-RQ_{i-1}\ |Q_{i-1}\ | \qquad (11)$$

$$CM=H_{i+1}-BQ_{i+1}+RQ_{i+1}\ |Q_{i+1}\ | \qquad (12)$$

In which:

$$B= a/gA \qquad (13)$$

And

$$R= \lambda\Delta x/2gDA^2\ ) \qquad (14)$$

Whose solutions are:

$$HP_i=1/2\ (CP+CM) \qquad (15)$$

$$QP_i=(CP-HP_i\ )/B \qquad (16)$$

Head and flow calculations

In the above section the equations for calculating heads and flows at intermediate nodes were derived, in the following sections the equations needed to calculate heads and flows at the boundaries were derived.

Simple boundary conditions

Reservoir at upstream end

For the system shown in Figure 2, the boundary condition at node 1 is a reservoir, by assuming the size of the reservoirs is large enough; so the fluctuations in water level can be neglected, the head and flow at node 1 determined by using the information available at this end. The first available information is the head at the node 1, is equal to the reduced head drop due to head losses.

$$HP_1=H_{R1}-KQP_1^{\ 2} \qquad (17)$$

Where K is the coefficient of singular head losses that takes into account the local head losses due to sudden narrowing and that caused by the valve.

The head and discharge at node 2 at time t_0 is assumed to be known, Eq. 10 the negative compatibility equation applied between nodes 2 and nodes 1, for the second equation needed to determine the head and discharge at node 1 at instant time, $t=t_0+\Delta t$.

By eliminating the head between these two equations Eqs. 10 and 17, the result is a quadratic equation in QP_1:

$$KQP_1^{\ 2}+BQP_1+CM-H_{R1}=0 \qquad (18)$$

Which the solutions are:

$$QP_1=\sqrt{B\pm B^2-4(CM-H_{R1}\ )/2K} \qquad (19)$$

Valve at downstream end of the pipe

For a valve at downstream boundary condition is governed by the law of head drop across the valve and through the unique character of the reservoir entrance. To simulate the absence of the reservoir two, a zero can assigned to. The head at the valve upstream is given by:

$$HP_N=H_{R2}+KQP_N^{\ 2} \qquad (20)$$

By eliminating from the above two equations Eqs.9 and 20, a quadratic equation obtained in QP_N.

$$QP_N^{\ 2}+C_1\ QP_N+C_2=0 \qquad (21)$$

Where:

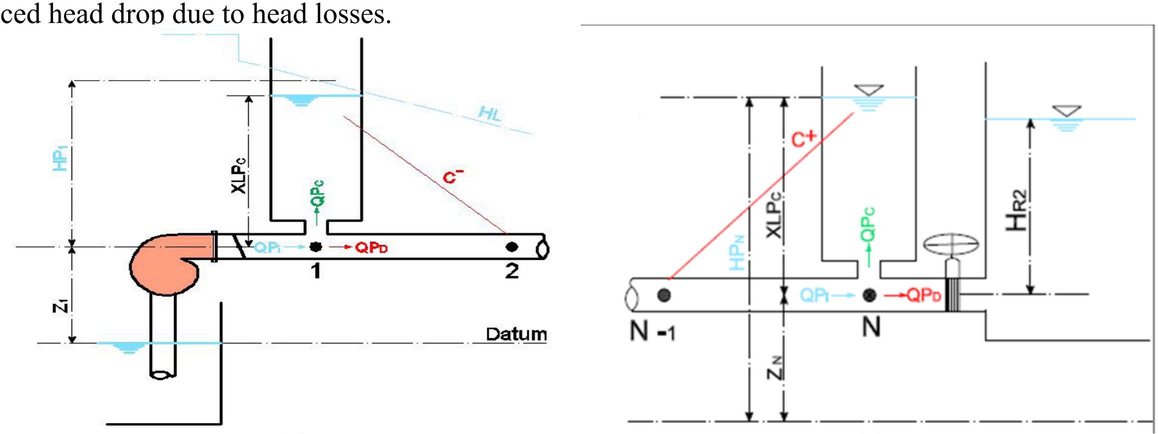
$$C_1=B/K \qquad \text{And} \qquad C_2=1/K\ (H_{R2}-CP)$$

The solutions of this equation are:

$$QP_N=1/\sqrt{2\ (-C_1\pm C_1}{}^2-4C_2) \qquad (22)$$

Controlling water hammer

Ways to control water hammer are classified as either passive or active protections. Protections under the first category do not require any special devices and is limited to protective measures taken during the design of the facility. This is particularly the choice of most suitable



(a) (b)

diameter of the pipe since the average velocity of flow is not excessive, the choice of material and class of pipe pressure to reduce pressure changes with a little risk of bursting or crushing, and finally the choice of valves whose closure durations are relatively slow.

When these passive measures show insufficient protection, then it is necessary to install, on a given pipeline, one or more protective devices against overpressure and\or low pressure.

Open surge tank

A surge tank is a simple vertical tank open to the air connecting to a pipeline. Such a tank can be cylindrical, prismatic, as it can have any shape.

Surge tank at downstream end of the pipe

Instantaneous valve closure

The simplified equation governing the flow at the surge tank location is a single non-linear equation in QP_C.

$$KQP_C|QP_C|+C_1QP_C+C_2=0 \qquad (23)$$

Where:

$$C_1=\Delta t/2A_C+B\ ;\ C_2=XL_C+Q_C\ \Delta t/2A_C+Z_N-CP$$

Slow valve closure

The simplified equations governing the flow at the surge tank location are Eqs.24 and 25, the unknowns in these equations are QP_D and QP_C.

$$BQP_D+K_CQP_C|QP_C|+C_1QP_C+C_2=0 \qquad (24)$$

Where:

$$C_1=\Delta t/2A_C+B\ ;\ C_2=XL_C+Q_C\ \Delta t/2A_C+Z_1-CP\ ;$$

$$K_C=\pm Kdo/2gA_{do}$$

$$KQP_D\ |QP_D\ |+BQP_D-CP+H_{R2}+BQP_C=0 \qquad (25)$$

Surge tank at upstream end of the pipe

Instantaneous pomp stopping

A single non-linear equation in *QPc* is obtained by combining the equations governing the flow at the surge tank location:

$$KQP_C|QP_C|+C_1\ QP_C+C_2=0 \qquad (26)$$

Where:

$$C_1=\Delta t/2A_C+B\ ;\quad C_2=XL_C+Q_C\ \Delta t/2A_C+Z_1-CM$$

A transient analysis program is developed with visual basic. This program can analyze transients caused by suddenly-closing valves, gradually-closing valves, and pump power failures in addition to the studying the effects of adding the protection devices.

Simulation Results

In order to demonstrate the use of characteristics method for transient analysis two problems were solved. 1) A single pipeline considered with a reservoir at upstream end and open valve downstream. In order to simulate transients for this case, two different times of valve closure had been chosen. 2) A pump feeds a reservoir at upstream end.

Case 1: A reservoir connected to a horizontal pipeline and a butterfly valve at downstream end. The pipe characteristics are:L=600, D=0.4m, λ=0.02 and H_{R1}=30m. The pressure wave speed is assumed to be 800 m/s. The valve diameter is equal to the pipe diameter and the initial opening 50%.

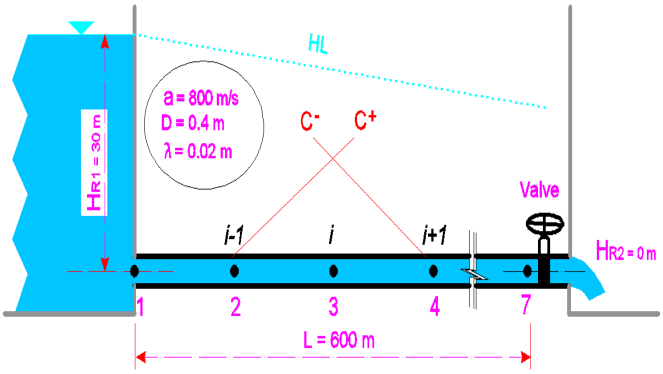


Figure 2: Simple reservoir valve system.

To minimize the effect of overpressure and low pressure, a surge tank installed just immediately upstream of the butterfly valve. The surge tank has 0.75 m^2 cross-sectional area and its entrance diameters 0.2 m.

In this case the behavior of the hydraulic transient for different times of valve closure had been studied, the model was applied for the following times 0 s and 8

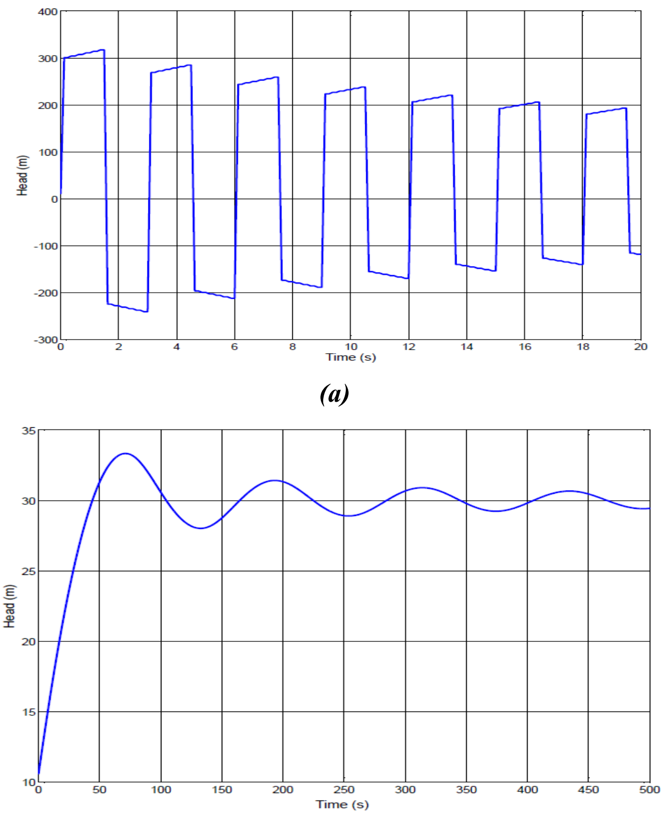
Instant valve closure

Closing the valve instantly causes speed cancellation, an increase in pressure, a radial and longitudinal deformation of the pipe and an increase in liquid density.

By a sudden valve closure, the head on the valve switches instantly from 10 m to 317 m, as it appears in figure 3. The mitigation process can be observed by studying the variation of head as a function of time and space. P(x, t) pressure ranges from an overpressure to low pressure and it becomes weaker from one cycle to another. The pressure along the entire pipe length is much greater than the maximum allowable pressure depending on the pipe materiel. The pipeline system must be fitted with a suitable protective device.

Table 1: Valve flow variation coefficient according to its opening degree

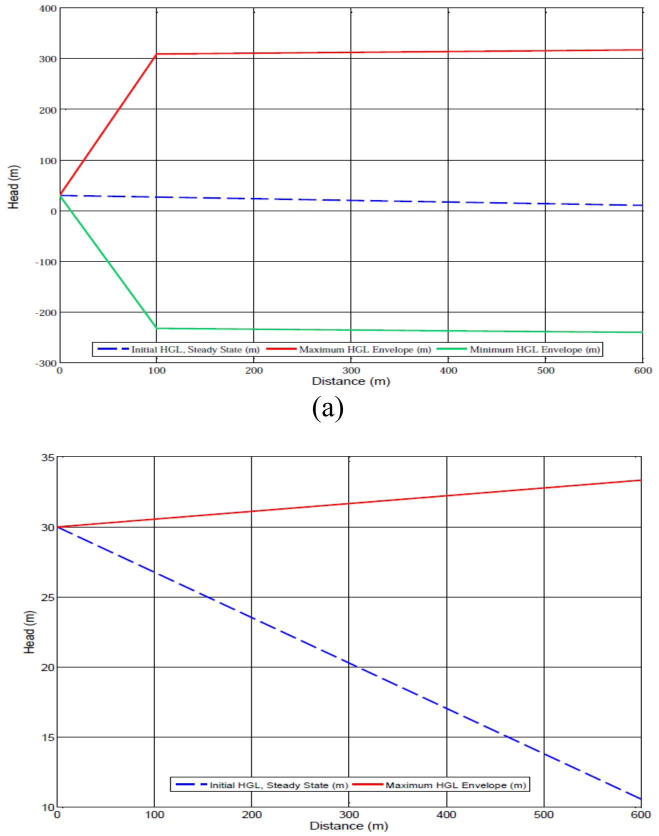
Opening Degree (%)	50	45	40	35	30	25	20	15	10	5	0
flow coefficient Cd	0.24	0.20	0.16	0.13	0.11	0.09	0.07	0.05	0.02	0.01	0.00



(a)

(b)

Figure 3: *Transients in a pipeline system (Instant valve closure) (a) Head change versus time at the valve (Without protection) and (b) Head change versus time at the valve (With protection)*



(a)

(b)

Figure 4: Hydraulic grade lines envelopes ***(a)*** Hydraulic Grade Lines (without Protection) and ***(b)*** Hydraulic Grade Lines (with Protection)

than 317 m. By using the open surge tank, the maximum pressure at the surge tank location is only 33 m. This surge thank ensures adequate protection against both overpressure and depression.

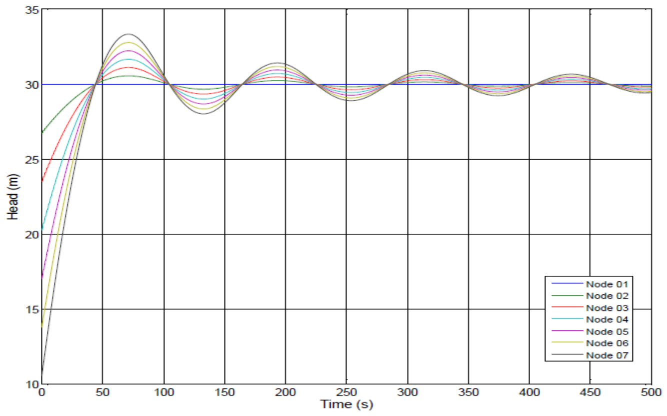
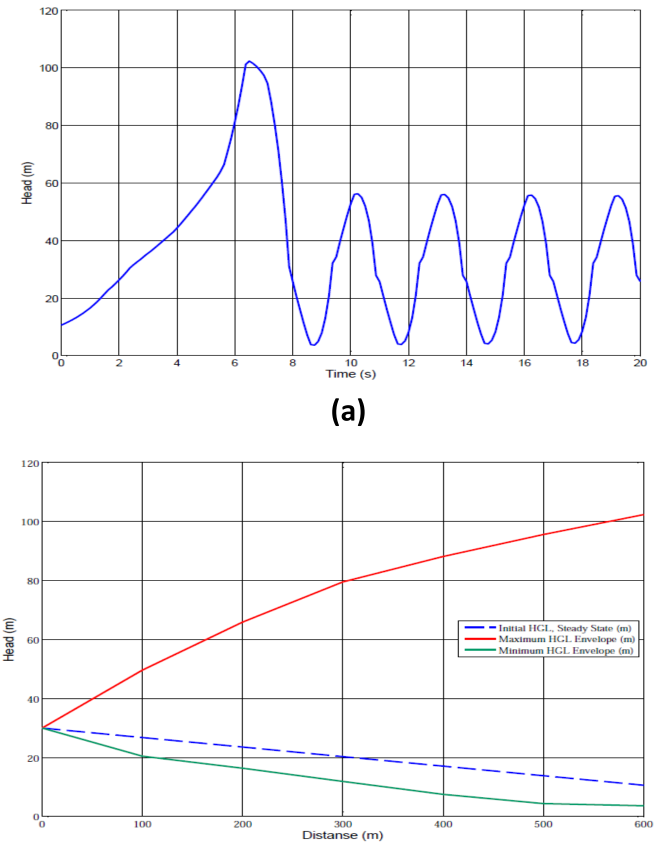


Figure 5: Variation of head at each node versus time

Overpressure generated by closing the valve can be reduced by a simple increase in the valve closure duration. A slow closure results in a small change in speed, and lower pressure. To illustrate the influence of the closure duration on the magnitude of the maximum pressure, the following case is considered.

Slow valve closure time (8 s)



(a)

(b)

Figure 6: Hydraulic grade lines envelopes ***(a)*** Hydraulic Grade Lines (without Protection) and ***(b)*** Hydraulic Grade Lines (with Protection)

The simulation results for the unprotected pipeline in this case shows that the maximum pressure in the pipe is slightly greater than 102 m, while in the previous case it slightly greater than 317 m.

Case2: A pump feeds a reservoir where the water level is at elevation HR = 30 m, through a conduit having the following characteristics, L = 500 m, D = 0.25 m, $\lambda = 0.02$, and a = 800 m/s. Flow delivered by the pump station is Q = 50 l/s. At a given moment the pump is stopped immediately after a power outage. A surge tank installed just immediately downstream of the pumping station. The surge tank has 1.0 m^2 cross-section and it is entrance diameter is 0.2 m.

Figure 8 shows that the maximum and minimum pressure envelops are 110.845m and 52.85 respectively, while after using the surge tank it becomes 32.11m and 29.39m.

Case 2, describes a typical hydraulic transient problems. If special precautions are not taken, the magnitude of the resulting transient pressures can be sufficient to cause severe damage. When the pump is suddenly shutdown, the pressure at the discharge side of the pump rapidly decreases and a negative pressure wave (which reduces pressure) begins to propagate down the pipeline toward the downstream reservoir. When the negative pressure wave reaches the high point (which already has a relatively low pressure due to the higher elevation) in the pipe, the pressure can drop below atmospheric to reach vapor pressure. At this pressure, gas within the liquid is gradually released and the liquid starts to vaporize (column separation). On subsequent cycles of the transient when the pressure recovers, cavity can collapse generating a large pressure surge spike. On the suction side of the pump.

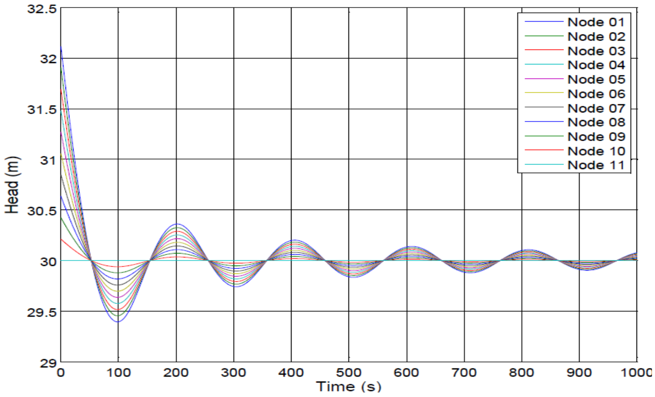
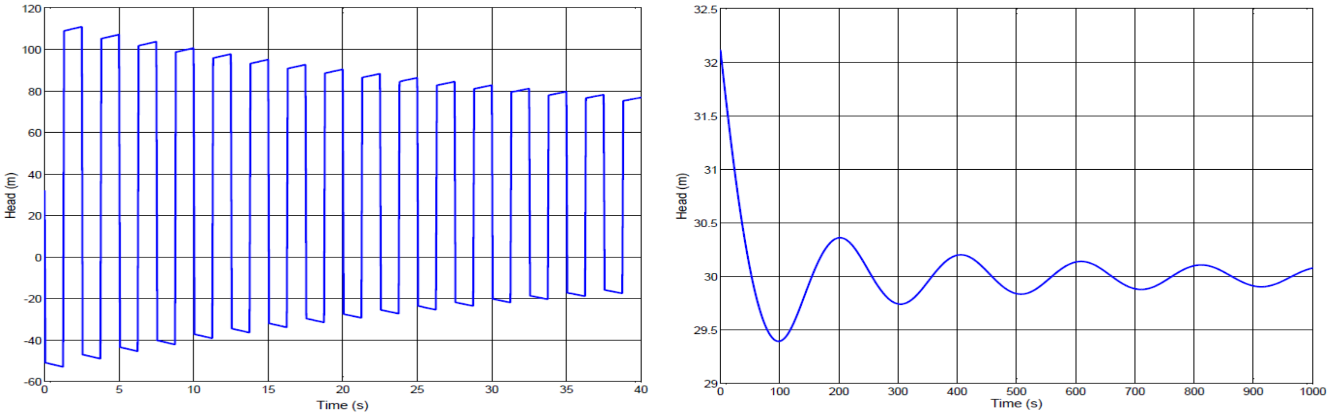
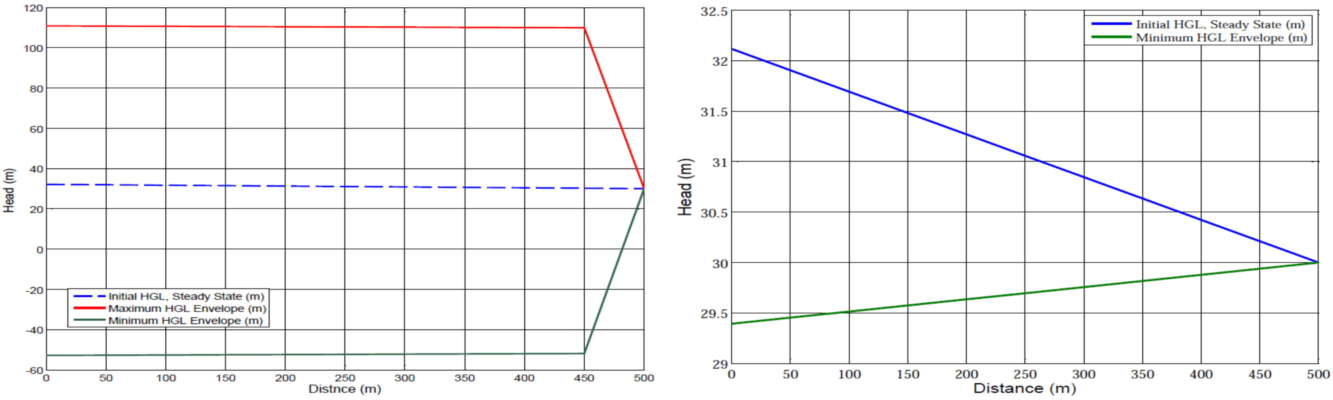


Figure 9: Variation of head at each node versus time



(a) (b)

Figure 7: Transients in a pumping system ***(a)*** Head change versus time at the pomp and ***(b)*** Head change versus time at the pomp



(a) (b)

Figure 8: Hydraulic grade lines envelopes ***(a)*** Hydraulic Grade Lines (without Protection) And ***(b)*** Hydraulic Grade Lines (with Protection)

Conclusions

Transients can introduce large pressure forces and rapid fluid accelerations into a piping system. These disturbances may result in pump and device failures… etc, due to the devastating effects that a hydraulic transient can cause, its analysis is very important in determining the values of transient pressures that can result from flow control operations and to establish the design criteria for system equipment and devices so as to provide an acceptable level of protection against system failure due to pipe collapse or bursting.

Hydraulic transient analysis is an effective and reliable tool to determine the needs for surge protection systems against transient surges. For the conditions presented in this paper, surge tank(s) is recommended for the system as a good engineering practice to minimize the surge impacts, and to prevent water column separations and fatigue failures.

By a simple increase in the valve closure duration, overpressure can be reduced. Using the surge tank ensures adequate protection for the pipeline system against overpressure and low pressure.

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