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Effect of Hydraulic Characteristics on Fluid Transients Analysis under Different Types of Control Valves

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ABSTRACT
In this study, several types of valves were used to study the impact of the valves types and closure characteristics on fluid transients. The valve closure curves, which are the variation of the effective valve opening as a function of percentage opening area, were derived for different selected valves. Six different types of valves were selected to study the effect of the valves types on fluid transient conditions. For simplification, a very simple pipeline system was assumed and presented in this study. The system is about two pipes connected in a series junction and they take the water from a constant-level reservoir at upstream and a valve at downstream. The duration of valve closure was taken as six seconds which plays an important role in the pressure development in the system. A method of characteristics is applied to compute the transient conditions under gradual closure of the valves. Valve data of various forms were compiled and reported as discharge and headloss coefficients as a function of valve opening. The effect of valve geometry and operation on the relative valve opening were compared. Discharge and headloss coefficients were also compared between valve types. The study concluded that transient conditions depend on the valve type. The comparison between the results of all valve types indicated that the changes in pressure and discharges depend on valve type where there is a difference in effective valve opening. It can be concluded that the valve with the highest value of valve effective opening has less effect on transient conditions, i.e., the faster changes of effective valve opening the larger the effect on transient conditions (discharge and the greater the magnitude of the pressure wave). This study would help to select the property valve in pipeline design.

Keywords: hydraulic characteristics, fluid transients, valves.

INTRODUCTION

The use of pipes to transmit fluid from a source is quite common. The flow in a pressurized pipeline can be classified into two types of flow which are steady and transient flow. The transient flow happens due to rapid changes in flow velocity. This rapid change in velocity can generate a pressure wave in the pipeline system. The best description of this pressure wave is called the water hammer phenomenon [Tullis, 1989]. Transients (also called water hammer or hydraulic shock) is one of the most important issues that should be well considered in designing piping systems. The flow in pipelines is often regulated or controlled using some devices. One of these devices is the valve, which is an important part of pipeline design. Besides regulating the flow, valves can be used for several functions, such as regulating the flow and pressure, preventing reversing the flow through the pump, removing air, protecting the pipe and the system from over pressurization, as well as helping to prevent transients [Tullis, 1989]. Valve closure is the source of transients in pipes and pressure development or what is called water hammer, and the magnitude of pressure rise in the pipe depends on several factors, such as; the speed at which the valve is closed, pipe length, and elasticity of pipe materials [Tullis, 1989; Nerella et al., 2015], and these must be taken in consideration in pipe design. If the valves are not selected and operated properly, they can cause several problems. Different types of valves have been used for a variety of purposes [Tullis, 1989]. The values of flow coefficients vary with the type of valves that are used in the system, so it is necessary to provide valve characteristics, and then these will help in constraining the factors of the pipeline design. In this field, there are numerous studies presented by many researchers around the world. For instance, Nerella et al. (2015) explained the Method of Characteristics (MOC) model, a technique used to solve the equations governing the unsteady flows in closed conduits, through a single case of closing the valves that were placed at the end of the pipeline. It was observed from the results, after the appearance of the first pressure wave led to an increase in the pressure head, due to the immediate closure of the valve at the end of the pipeline. Ali et al. (2013) studied the effect of a group of factors on water hammer in a network of water supply pipes to provide an acceptable level of protection against system failure as a result of a pipe burst or collapse. It was studied by a program called Water Hammer and Mass Oscillation (WHAMO) to solve the equations of both continuity and momentum for the unsteady state. The factors that have been studied are; the closure of some pipelines in the network, the sudden change in water demand, and the event of a failure in some pipelines as a result of leakage. It was found through the results that the sudden change in water demand causes fluctuations in flow rates and an increase in the pressure head, but in the event of closure in some pipelines, it also leads to an increase in the pressure head in a region and a decrease in other regions; in turn, if there is a failure in some pipelines, leakage and intrusion from outside the network may occur. At the end of this study, it was concluded that the use of a non-return valve protects the pipeline network from water hammer very effectively. Kodura (2016) analyzed and described the results of physical experiments using water hammer in polyethylene and steel pipes. The characteristics of the valve closure and pressure change were recorded and the results obtained from the measurements were compared with the results of the calculations used by (Michaud's equation and Wood and Jones's method). A comparison of the results showed statistically significant differences, and it was also found that closing the butterfly valve has a very significant effect on the water hammer. Han et al. (2022) studied the change in pressure resulting from the water hammer caused by the ball valve through different closing laws, and to perform this, the computational fluid dynamics method was used to conduct a transient numerical simulation by changing the closing times and closing laws. The results showed that the pressure of the water hammer increases as the closing speed of the valve increases and that the pressure vibrations are affected by the closing laws. Pires et al. (2004) analyzed the transient pressure behavior in short pipes for loading tankers at a marine station by using a commercial program (TELNET). Many dynamic components, such as check, block valves, flow control, and elasticity of pipes and pumps were simulated. The purpose was to increase the flow rate to the maximum limits and thus reduce the time the tanks are docked without exceeding the permissible pressure limits.

The effect of valves on transient is rarely considered. In this paper, an attempt was made to study the effect of valve types on fluid transients. Factors such as head loss usually dominate valve choice, and this can be achieved by considering the effect of valve type in transient analysis to provide additional useful information when choosing valve type. The objective herein was to apply the fluid transient principle to predict the rise of pressure due to the gradual closure of the valve downstream by using several kinds of valves to predict what will be the effect of the types of the valves on the transient conditions.

VALVE TYPES

Valves are a very important part of pipeline design. Valves control the transients by reducing the net change in the pipeline flow velocity, reducing high pressure, and preventing vacuum pressure [Tullis, 1989; Chaudhry, 2014]. There are many different types of valves, and they are classified based on the purpose of their use. Mainly, they are classified into four categories [Tullis, 1989; Chaudhry, 2014]:

- Control valves.
- Pressure regulating valves.
- Nonreturn flow valves (check valves).
- Air control valves.

The term control valve refers more to the function of the valve than the type of the valve. Each type of valve may have several different designs. In the current research, all the mentioned types of valves were considered in the analysis. There are several kinds of control valves such as Butterfly, Cone, Globe, Diaphragm weir, Ball full bore, Disc gate valve, ring-follower gate, and Plug. Etc. In this study, six different kinds of valves were used to study the effect of valve types on transient conditions, namely Butterfly, Cone, Globe, Diaphragm weir, Ball full bore, and Plug. These five types of valves were selected as the input to a computer model computing transient conditions for a piping system with an upstream constant-level reservoir and a downstream valve, transient conditions were computed and compared.

HYDRAULIC CHARACTERISTICS

To develop the boundary condition of the valve, some terminologies should be known before, and these are:

a) Effective valve opening (relative valve opening) τ – effective valve opening τ is the relative valve opening, and valve closure curve is the τ vs time curve which is the variation of effective valve opening τ with the time or what is called closure scheduling which means the relationship between the effective valve opening and time. The τ values at the intermediate time are determined by the interpolation method. The effective valve opening is defined as:

$$\tau = \frac{\mathrm{C_d\,A_v}}{(\mathrm{C_d A_v})_\mathrm{o}} \qquad (1)$$

where: C_d – the discharge coefficient;
A_V – the area of the valve opening, the subscript o indicates the steady state condition.

Parmakian (1963) presented the valve closure curve for some typical valves which are the Butterfly valve, Disc gate valve, Ring-follower gate, and Plug valve [Parmakian, 1963]. Parmakian (1963) stated that in the water hammer problem, it is necessary to determine the variation in the effective area of the valve as a function with the time from other considerations. These considerations are related to flow characteristics which are flow or discharge coefficients C_d or C_V, and the variation of these coefficients with the opening area of the valve which is the area that normal to flow. The effective area of the valve is determined first by multiplying the opening area by a coefficient of discharge [Parmakian, 1963; Liou, 1991]. In the calculations, the closure schedule of the valve is determined by the former.

b) Flow coefficient and discharge coefficient – the flow through the orifice can be applied to the valve [Tullis, 1989].

$$Q = C_d A_v \sqrt{2g\Delta h} \qquad (2)$$

where: C_d – the discharge coefficient;
$\mathrm{A_V}$ – the area of valve opening, g is the acceleration of gravity;
Δh – the head loss across the valve [Wylie and Streeter, 1993].

The flow coefficient C_V is defined as the amount of water in (gpm in BG) (max flow required), at 60°F that will pass through a given orifice with a one-pound pressure drop (psi), and thus flow coefficient C_V represents the relation between the flow and pressure drop [Tullis, 1989; Rahmeyer et al., 1985]:

$$C_v = \frac{Q}{\sqrt{\Delta \mathrm{P}/sg}} \qquad (3)$$

where: sg – the specific gravity of the fluid. This means the pressure drop across the valve is proportional to flow discharge [Tullis, 1989].

There are several coefficients in use by different engineering groups, and they can be transferred from one to another using some relations.

$$C_d = \frac{1}{\sqrt{\frac{890d^4}{{C_v}^2} + 1}} \qquad (4)$$

where: C_d the discharge coefficient, and d is the pipe diameter in inches. Some references give the tables of valve opening (%) and C_V, so the last relation can be used to compute the discharge coefficient C_d and then the relation between the valve opening and C_d. The values of C_d are used for determining the relative valve opening τ. For example, discharge coefficients C_d for several in-line valves were provided by Tullis (1989) and were used in this study.

METHODOLOGY

A very simple situation in which the pipes series are connected to the reservoir at upstream and to the valve at downstream was presented. Here, the objective is to determine the effect of valve kind

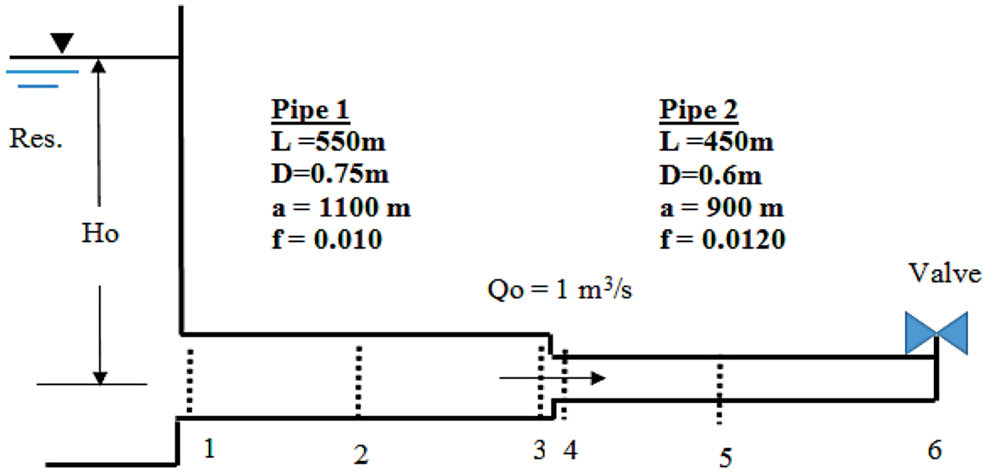

Figure 1. Schematic of piping system with a downstream valve and an upstream constant water level reservoir

on pressure due to the gradual closure of the valve at the outlet of the system as shown in Figure 1. The data in the pipeline system shown in Figure 1 and the procedure of calculations and materials for this study are provided [Chaudhry, 2014].

Several assumptions are used for simplification:

1. The pipe material is rigid regardless of the change in pressure inside the pipe, and all the pipes have the same material.
2. Neglect the entrance losses at the reservoir;
3. The liquid in the pipe system is slightly compressible (water);
4. The reservoir level is constant (large reservoir), i.e., the water level in the reservoir remains constant during the operation time of the system;
5. The pressure is uniform over the entire cross-section of the pipe and it is equal at the center-line of the cross-sectional area; and
6. The flow in the pipe is run full.

It is important to mention here that the valve closure is said to be gradual if the time (t) is greater than (2L/a), and it is said to be sudden if the time (t) is less than (2L/a). Where (t) is the time required to close the valve, i.e., initial velocity v is brought to be zero in time t seconds, and L is the length of the pipe, and a is wave velocity (velocity of pressure wave).

The wave velocity is computed from the following:

$$a = \sqrt{K/\rho} \tag{5}$$

where: K – the bulk modulus of water;
ρ – the water density. Wave velocity is a given data.

In this study, the case of water hammer analysis for gradual closure of the valve at downstream was considered. This means, that when the valve is fully open at steady state condition there is no obstructed flow taking place in the system, and when the valve is partially closed some reduction in flow would take place in the pipe until it reaches the case of no flow past the valve. In the latter, the wave will be generated and proceed in the opposite direction toward the reservoir. This wave will again be reflected when it reaches the reservoir, and so on until it will be dampened with time due to the frictional losses, and thus the original situation will hold again in the system [Chaudhry, 2014]. Therefore, the duration of the valve closure is important in pressure development inside the pipe, and when the valve is instantaneously closed, this will be more critical as the wave produced will increase the pressure on the pipe, i.e., such pressure change would occur or what is called water hammer because of the hammering sound resulted in from the pressure changes [Pires et al., 2004; Ramos et al., 2002].

The time interval Δt is computed from the following Equation (6), and it must satisfy the Courant stability condition. To satisfy the Courant number (C_N = 1) stability, i.e., the reach length of any conduit in the system $\Delta x \geq a\Delta t$ [Chaudhry, 2014].

$$\Delta t = \frac{L_i}{a_i n_i} \tag{6}$$

where: n_i – the number of reaches into which the ith conduit is divided, and i is from 1 to N, which is the number of pipes in the system. It is assumed that the total closure time t_c is 6 sec, and all the valves are closed with a constant closing rate.

There are many kinds of valves that have been used in the pipeline system. In this study, six different types of valves were selected to assess the effect of the valve type on the transient conditions. The valve closure curves were used as the input to a computer model computing transient conditions for a piping system with an upstream constant level reservoir and a downstream valve, transient conditions were computed and compared between the selected valves. As previously mentioned, some references give valve characteristics as tables of valve opening (%) and C_V, so the last relation can be used to compute the discharge coefficient C_d and then the relation between the valve opening and C_d. To determine the valve closure curve, i.e., the relation between the effective valve opening and time (t or t/tc), the closure time (% close) from the opening percent can be assessed [Chaudhry, 2014].

$$\text{time(t)} = \frac{\text{close}}{100} \times \text{t}_\text{c} \tag{7}$$

where: t_c – the total closure time of the valve (6 sec). Then, the valve closure curves are used as the input to a computer model computing transient conditions for a piping system. The values between the interval, are computed iteratively.

First, the steady-state condition, i.e., the discharge and pressure head at the sections where the pipes are divided into subreaches, is computed. Then, the time is incremented by the interval of Δt. A method of characteristics is applied to compute the transient conditions [Chaudhry, 2014].

The upstream boundary condition is assumed to neglect the entrance losses, so the pressure head at the upstream end would be set equal to the height of the reservoir water surface above the datum ($H_p = H_{res}$). The equation of negative characteristics was applied to compute the unknown flowrate at the upstream end, and positive characteristics at the downstream end [Chaudhry, 2014]:

$$Q_{P_{i,1}} = C_{ni} + C_{ai}H_p \tag{8}$$

$$Q_{P_{i,1}} = C_{pi} - C_{ai}H_p \tag{9}$$

At the downstream valve the negative characteristics may be combined with the orifice discharge to compute the discharge at the unknown step [Chaudhry, 2014]:

$$Q_{p_{i,n+1}} = 0.5(-C_v + \\ + \sqrt{C_v^2 + C_{pi}C_v} \tag{10}$$

And C_V is computed from:

$$C_v = \frac{\left(\tau Q_{oi,n+1}\right)^2}{\left(C_a H_{oi,n+1}\right)} \tag{11}$$

where: τ – the effective valve opening;
$H_{oi,n+1}$ – the head upstream of the valve. The subscript i indicates the conduit number, and the second subscript refers to the sections.

The transition condition at the interior points is computed using the Equations 8 and 9. The constants C_{ni} and C_{pi} are computed based on the method of characteristics, and the constant C_{ai} is computed by:

$$\text{C}_\text{a} = \frac{\text{gA}}{\text{a}} \tag{12}$$

where: g – the acceleration of gravity;
A – is the area of the conduit.
The steps for increasing the time by the interval Δt and calculating the transient condition are repeated until the transients for the desired duration are computed.

RESULTS

In this study, six different kinds of valves were used to study the effect of valve types on transient conditions, namely Butterfly, Cone, Globe, Diaphragm weir, Ball full bore, and Plug. The closure curve, i.e., the effective valve opening τ of each valve with the closing time has been proposed. These curves are necessary as input data to the model. The method of interpolation is used to predict the values between the time intervals. Figure 2 shows the valve closure curves for the in-line valves that are derived from data of the discharge coefficients presented by Tullis (1989). After extracting the C_d values from the curves, the effective valve opening is computed from Equation 1, where (C_d and $A_V)_O$ are the values at 100% opening.

The closure curves of the valves shown in Figure (2) are presented in Figure (3), where t_c is the closure time (valve operation time) (6 sec),

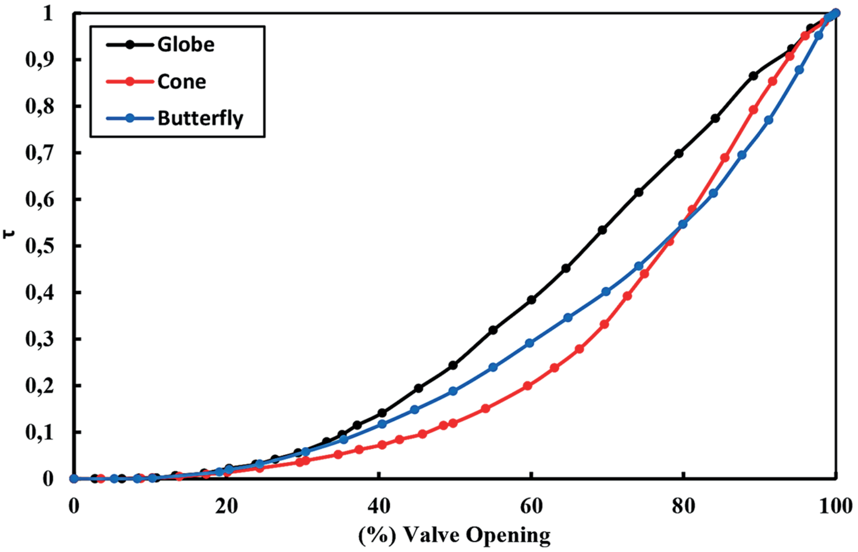

Figure 2. Closure curves for some valves globe, cone, and butterfly

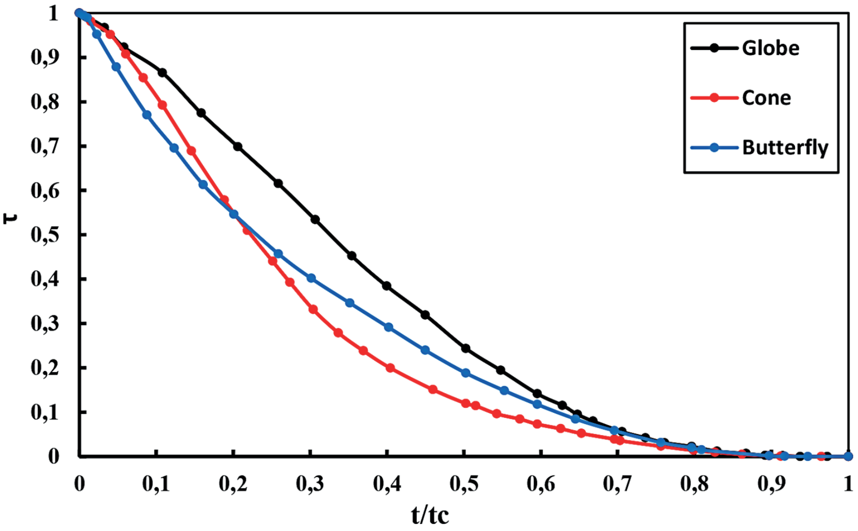

Figure 3. Closure curves of valves butterfly, cone or ball, and globe

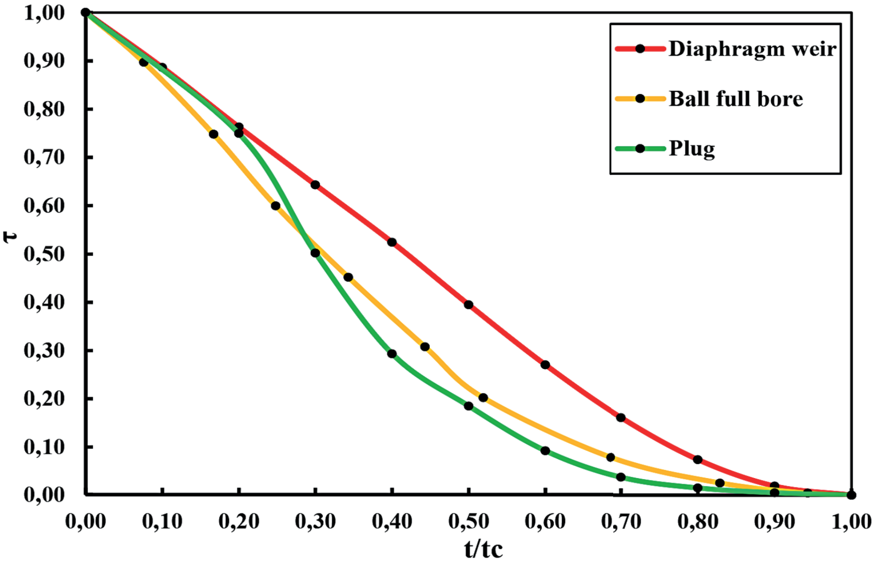

Figure 4. Closure curves of valves diaphragm weir, ball full bore, and plug

and the values of t/t_c are then multiplied by t_c to determine the time coordinate.

The remaining three valves are shown in Figures (4 and 5), where the closure curves are presented. Figure 6 collects the closure curves of the whole valves (6 valves) selected in the study.

It can be noticed from Figure (6) that the slope of the closure curve is lowest all the time in the case of the Diaphragm, and it is steepest at the initial stages of the time in the case of the Butterfly valve and at the end of the time in the case of Cone valve. Moreover, it can be noticed that even for different types of valves, the effective valve opening charts may be similar (or close to) for different designs such as the valves of Globe and Ball full bore. From the model results, it can be concluded that the mechanical performance of each valve type has a different impact on water hammer analyses. The Diaphragm, plug, and Globe valves have different characteristics than the Butterfly, Cone, and Ball full bore valves. The Diaphragm and Plug valves produce less drastic changes in flow at the beginning and end of a linear closure schedule. However, the Butterfly valve creates the greatest change of flow at the initial stages of closure. Moreover, the Globe and Ball full bore valves produce the most linear change in flow throughout the time of closure. Thus, these differences should be considered in the planning of valve systems and closure schedules.

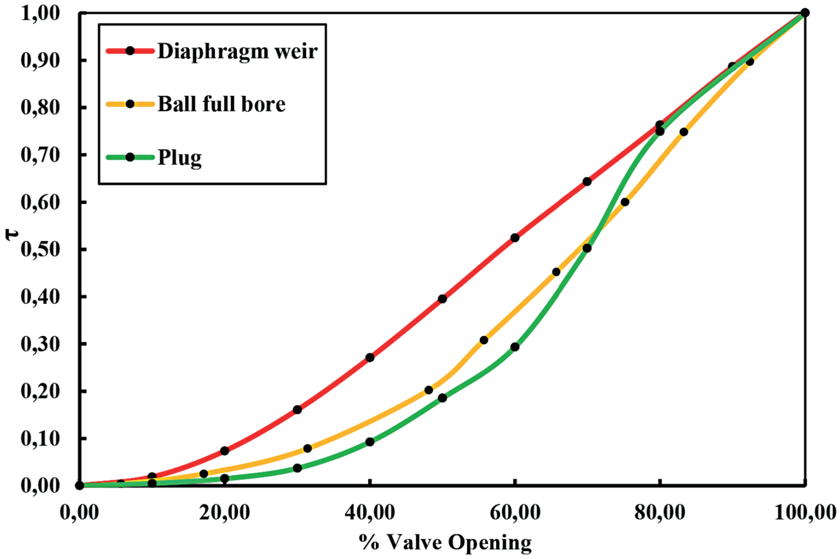

Figure 5. Closure curves of valves diaphragm weir, ball full bore, and plug

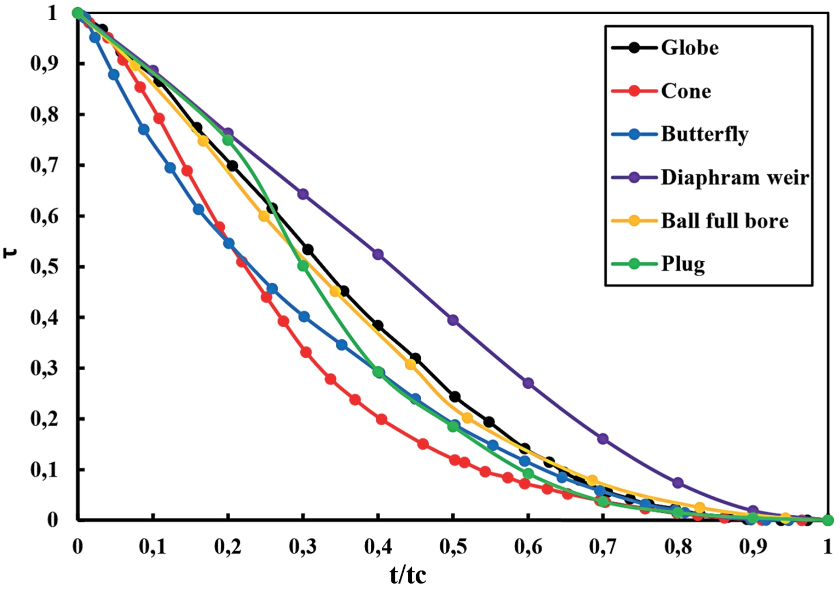

Figure 6. Closure curves for the selected valves

The model is run for time calculations (15 min), and the input data for the code are shown in Table 1.

Here, the authors were interested to show the variation in discharge and pressure at distinct locations in the system, namely at the entrance of the system and at the downstream end at the valve, and even at the junction point between the two pipes. The results of the discharge variation at the entrance of the system vs. time and the pressure head variation at the valve vs. time for the selected valves are shown in Figures (7) through (11). Moreover, it is necessary to determine the max

Table 1. Input parameters to the model

Symbol	Description	Value (s)	Unit
L1	Length of the pipe 1	550	m
L2	Length of the pipe 2	450	m
D1	Diameter of pipe 1	0.75	m
D2	Diameter of pipe 2	0.65	m
a1	Wave velocity in pipe 1	1100	--
a2	Wave velocity in pipe 2	900	--
f1	Friction coefficient of pipe 1	0.01	--
f2	Friction coefficient of pipe 2	0.012	--
Q_s	Steady-state discharge	1	m^3/s
H_{res}	Reservoir elevation	60	m

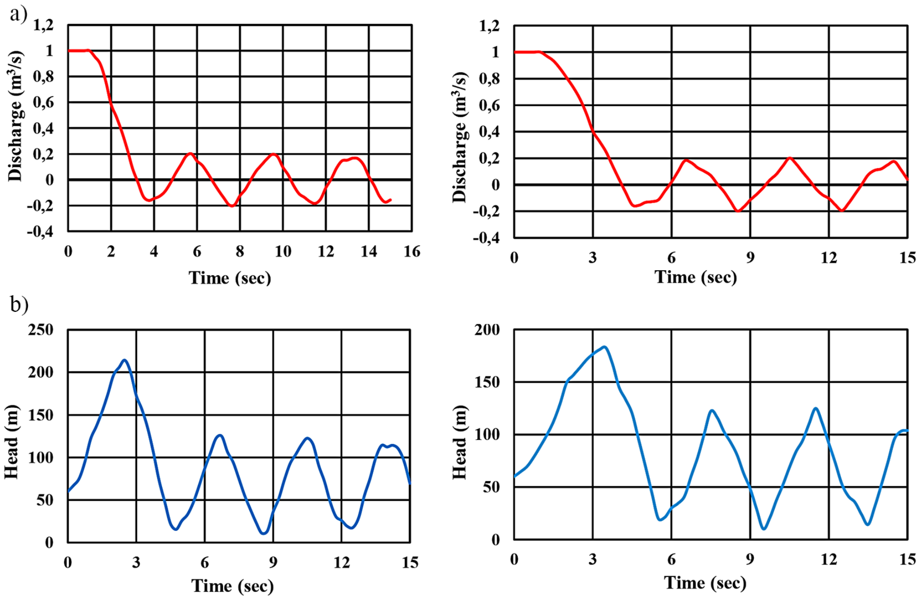

Figure 7. Model results for (a) discharge and (b) pressure head of cone and globe valves

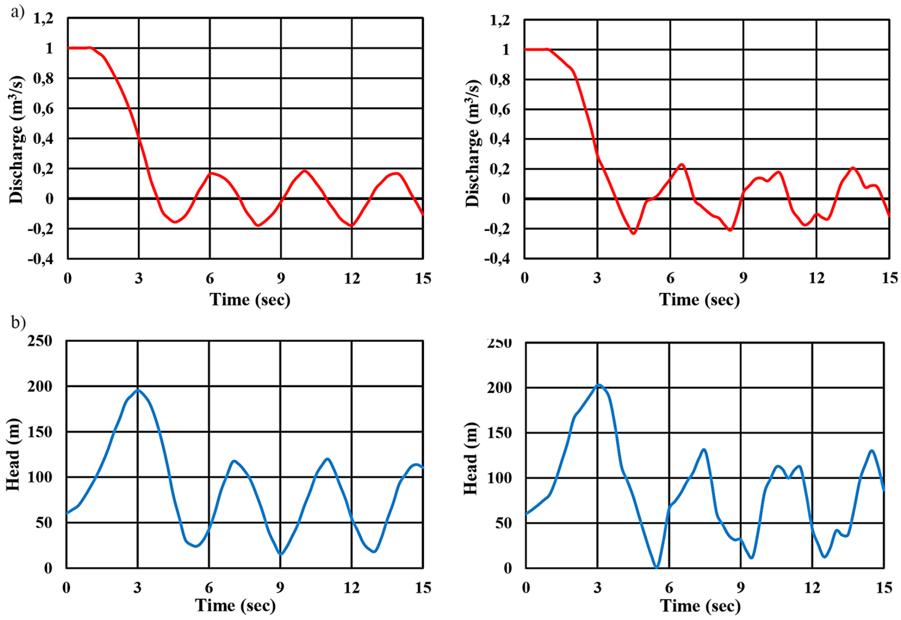

Figure 8. Model results for (a) discharge and (b) pressure head of ball full bore and plug valves

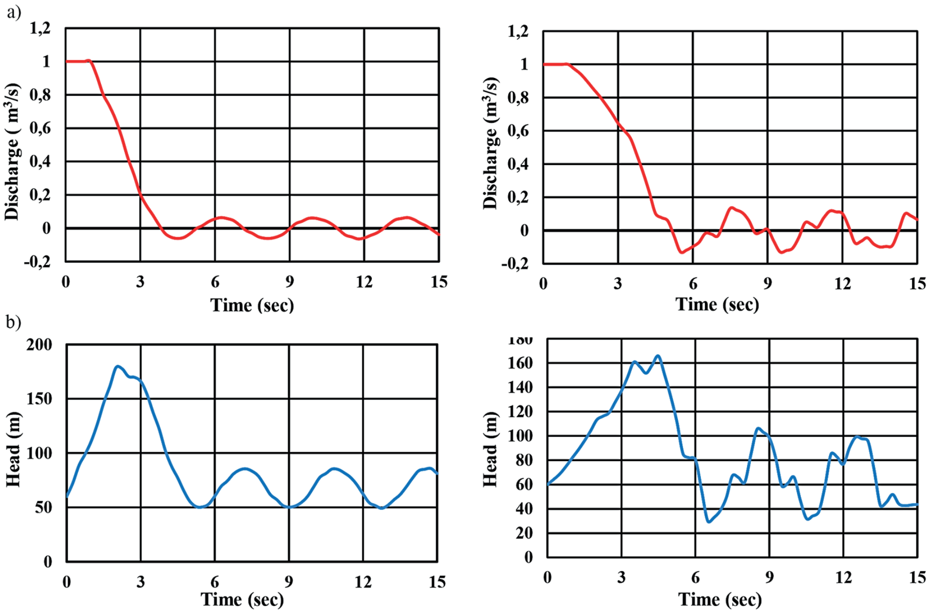

Figure 9. Model results for (a) discharge and (b) pressure head of butterfly and diaphragm weir valves

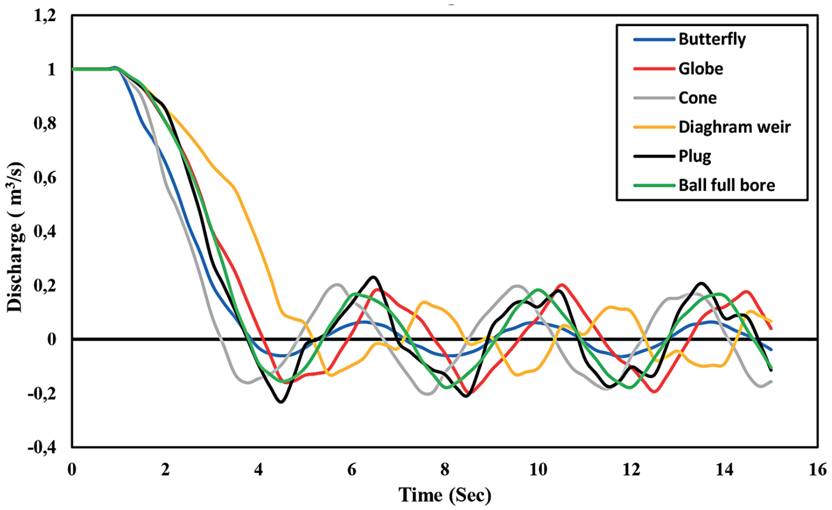

Figure 10. Discharge at the entrance for all the valves

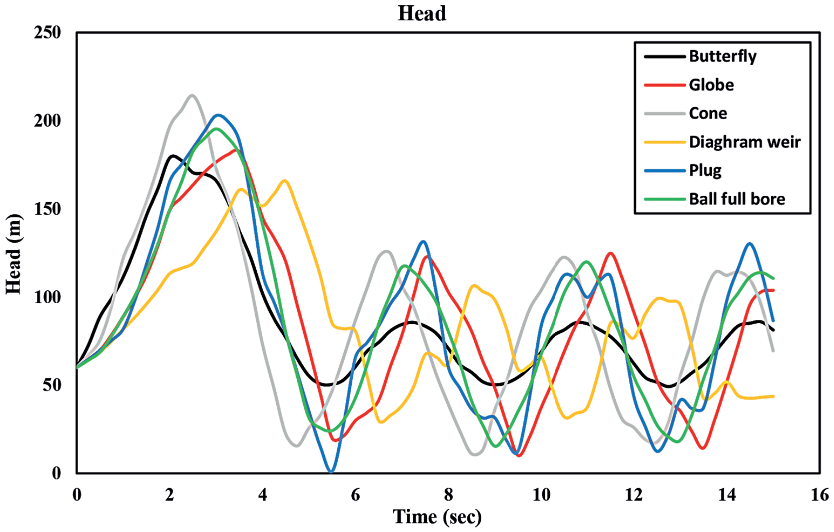

Figure 11. Head at the valve for all the valves

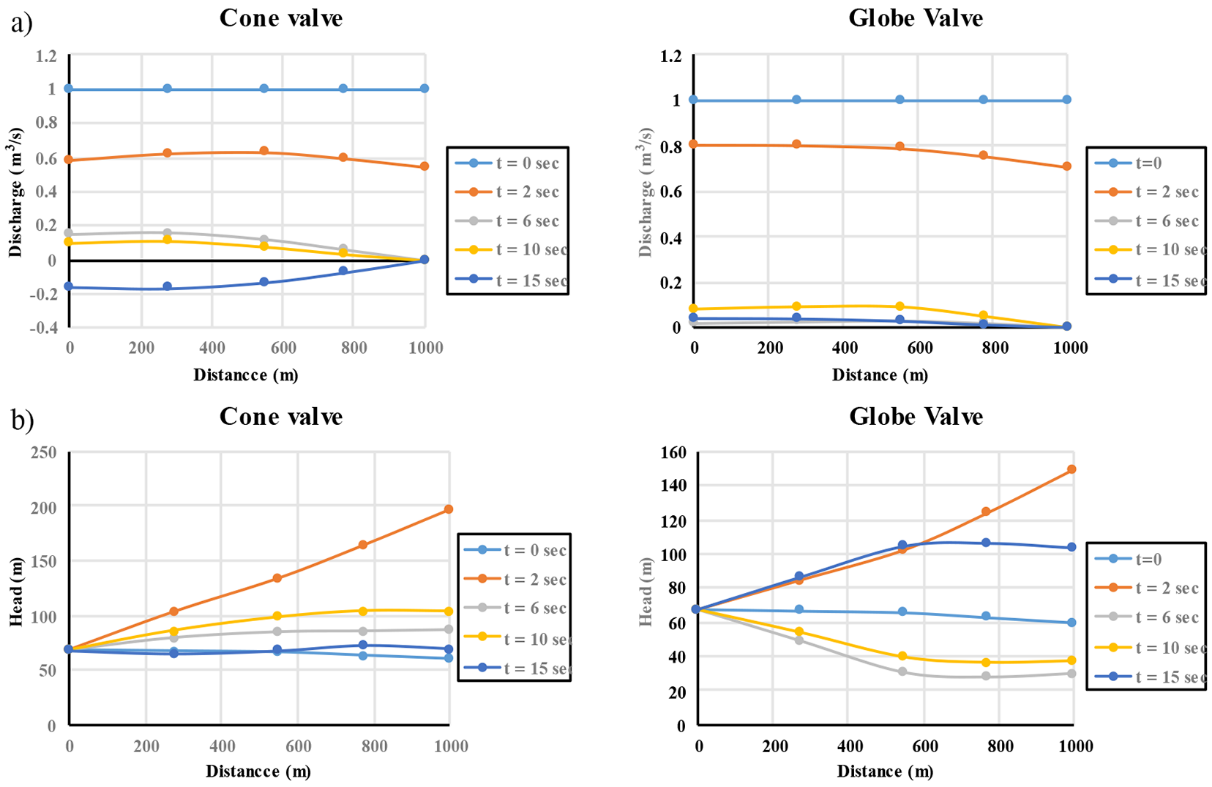

Figure 12. (a) Discharge and (b) head variation with the distance for selected time intervals of cone and globe valves

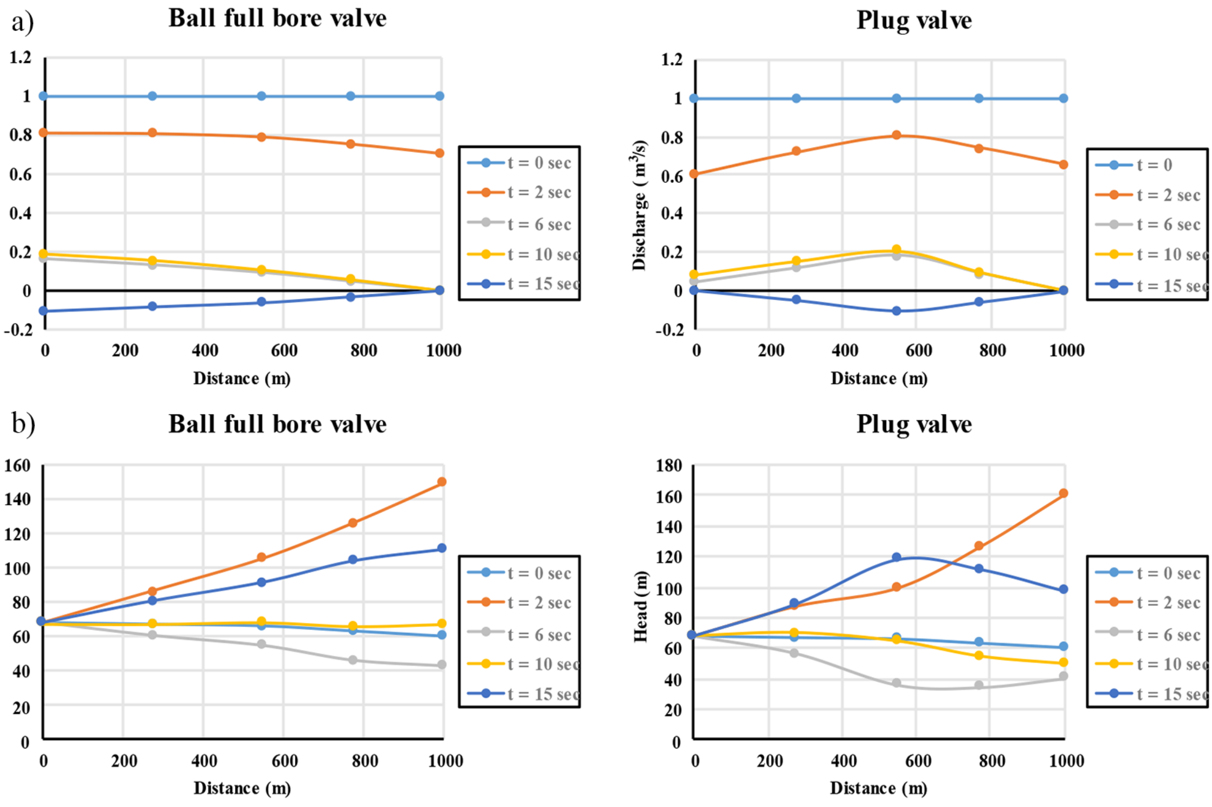

Figure 13. (a) Discharge and (b) head variation with the distance for selected time intervals of ball full bore and plug valves

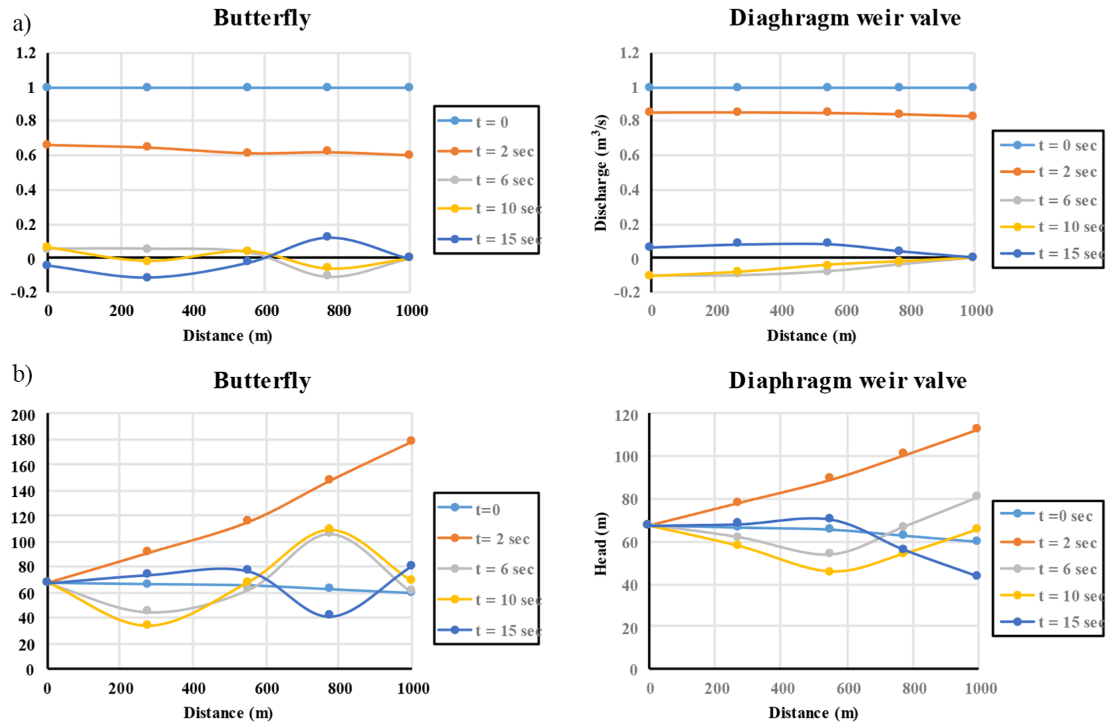

Figure 14. (a) Discharge and (b) head variation with the distance for selected time intervals of butterfly and diaphragm valves

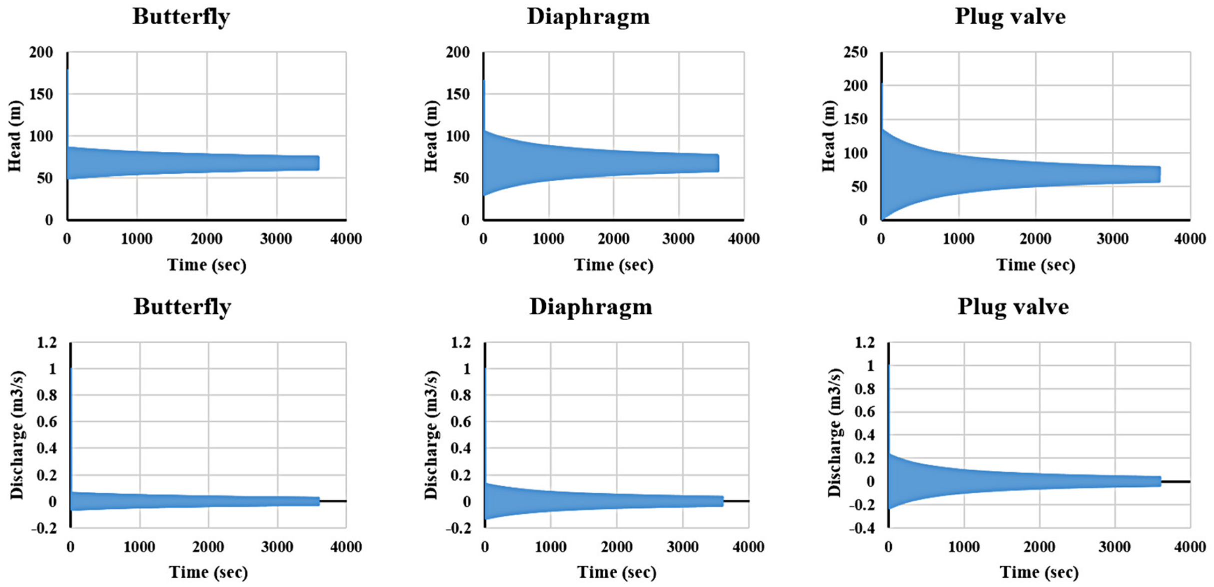

Figure 15. Results of the model runs for 1 hr of time duration

and min pressure at the valve and when it takes place during the calculation time (see Table 2). Figures (12) through (14) present the model run to compute the discharge and head along the modeled pipe for each valve for different periods of 0, 2, 6, 10, and 15 sec. In turn, the runs for long time calculation (1 hr) are presented in Figures (15 and 16). The pressure variation and the discharge variation were showing the same trends for all the

Table 2. Max and min pressure head for the studied valves

Valve	Max head (m)	Min head (m)
Ball full bore	195.34	15.44
Butterfly	178.83	39
Cone	214.19	11.15
Diaphragm weir	165.743	30.012
Plug	210.867	21.94
Globe	182.56	10.19

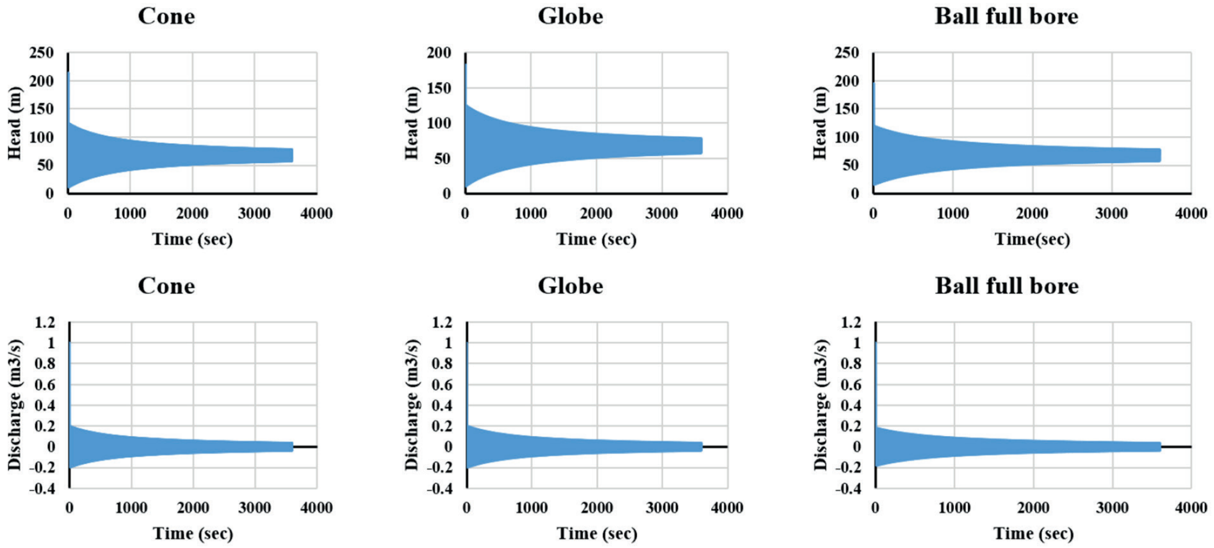

Figure 16. Results of the model runs for 1 hr of time duration

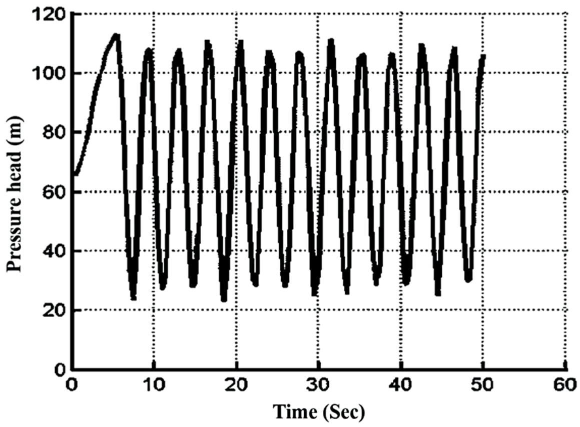

Figure 17. Pressure variation at the junction location for a time of 50 s

five types of selected valves. Figure (17) shows the pressure variation at the junction location which has a maximum of 105.108 m after 5.75 sec, and a minimum of 23.184 m after 18.5 sec.

CONCLUSIONS

In this study, several types of valves were taken to study the effect of valve kinds on transient conditions, where the effective valve opening differs with the type of valve. The following conclusions were drawn from the results and findings of this study. The variations in discharge and pressure head with the time vary with valve type. The most effective valve on transient conditions is the one with the lowest values of effective opening, i.e., the valve with the low slope of effective opening (higher values of t) has less effect on discharge and pressure, and then on transient conditions. The less effective valve on transient conditions is the one of small pressure wave propagation in the system. The pressure wave propagation depends on the valve closure and increases with decreasing the closure time of the valve. For the same operation time and even for a similar type of valve, the effective valve opening charts may be different for different designs.

Valve geometry and closure characteristics can have a substantial impact on transients in closed conducts. To reduce transients, additional work is needed to determine the effects of optimizing valve type and closure schedule and in sequences on the system costs where the head loss is the dominant valve choice, and this will be the future work of this study.

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