STUDYING OF WATERHAMMER PHENOMENON CAUSED BY SUDDEN VARIATION OF WATER DEMAND AT WATER SUPPLY PIPES NETWORK

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Water hammer in water-supply networks and irrigation networks may give rise to high pressures, due to the superposition of reflected pressure waves. The problem is relevant nowadays for the common use of automatic valves in networks regulation. When large variations in user demand happen often, as in distribution networks, water hammer occurs daily. In irrigation networks, its effect was found to concur to high rate of pipe failures, which these networks usually suffer. This paper investigates the effect of sudden variation of water demands in pipes network on transient pressures variations through the network. WHAMO software was used in the analysis which uses the implicit finite difference scheme for solving the momentum and continuity equations at unsteady state case. The study was applied on a two loops pipe network composed of eight pipes of different diameters and elevations. The flow is fed in the network by elevated storage tank. The results showed that rapidly changing the demand could significantly increase or decrease the pressure head in distribution system and cause flow reversal in a network system. In this simulation, shorter increasing/decreasing time of demand change causes the greater magnitude of transient fluctuation. Therefore, it is very obvious that the operations of distribution system should be done with very careful caution. The slower opening rates significantly reduce the impact of hydraulic transients. When the distribution system is designed, many different cases of simulation with different scenarios should be performed for the economical and safe design.

KEYWORDS: *Water Hammer, Pipe Network, Demand Variation.*

1- INTRODUCTION

Potable water distribution system is one of the most significant hydraulic engineering accomplishments. Potable water can be delivered to water users through distribution system. However, variable water demands and water usage patterns can produce the significant variations of pressure in distribution system, especially when the changes are sudden such as main breaks occur or during fire fighting activities. These sudden changes of water demand can create transient flow that could make so many undesirable consequences such as backflow, negative pressure, or excessive high pressure. Therefore, it is very important for engineers to explore the various transient

flow effects and to develop the emergency response strategies in order to minimize the negative impacts (Kwon [11]). The abrupt change to the flow that causes large pressure fluctuations is called water hammer. The name comes from the hammering sound that sometimes occurs during the phenomenon (Parmakian [13]). Many researchers studied the water hammer phenomenon along the last decades with different viewpoints, among of them Abd el-Gawad [1], Ali et al. [2], Burrows and Qiu [5], Jones and Bosserman [9], Jönnsson [10], Richard and Svindland [15] , Sharp and Sharp [17], Stephenson [19], Yang [20] and many others.

Al-Khomairi [3] discussed the use of the steady-state orifice equation for the computation of unsteady leak rates from pipe through crack or rapture. It has been found that the orifice equation gives a very good estimation of the unsteady leak rate history for normal leak openings. Fouzi and Ali [8] studied water hammer in gravity piping system due to sudden closure of valves, using both the most effective numerical methods for discretizing and solving the problem; the finite difference method using WHAMO program and the method of characteristics with software AFT Impulse. They showed that pressure fluctuations vary dangerously especially in the case of pipes has variable characteristics (section changes with a divergence, a convergence or a bifurcation).

Mohamed [12] introduced the effect of the different parameters such as time of valve closure, pipe material rigidity and pipe roughness on the pressure damping. He indicated that pipe friction factor and the time of valve closing have a significant effect in pressure transient reduction and the elastic pipe such as PVC are better than the rigid pipes in pressure damping. However, his study is restricted to valve closing at the end of pipeline and this case may be differ than the case of water hammer due to pump shut down.

Ramos et al. [14] carried out several simulations and experimental tests in order to analyze the dynamic response of single pipelines with different characteristics, such as pipe materials, diameters, thicknesses, lengths and transient conditions. They concluded that being the plastic pipe with a future increasing application, the viscoelastic effect must be considered, either for model calibration, leakage detection or in the prediction of operational conditions (e.g. start up or trip-off electromechanical equipment, valve closure or opening).

Samani and Khayatzadeh [16] employed the method of characteristics to analyze transient flow in pipe networks. They applied various numerical tests to examine the accuracy of these methods and found that the method in which the implicit finite difference was coupled with the method of characteristics to obtain the discretized equations is the best compared to the others.

According to the aforementioned studies, water hammer in pipes networks have been studied extensively by many investigators from different view points. However, every water supply network has its own special characteristics which makes it different from the other networks. Also, due to a lack of field measurements which are costly, it becomes important to use numerical models to gain an indication about the behavior of network under transient effect. This study aims to investigate the effect of sudden change of demand in pipe network on transient pressure head. Four operating scenarios were introduced and discussed through the following sections.

2- THEORETICAL CONSIDERATIONS

Because of difficulty in solution of governing equations, engineers in pipelines design usually neglect this phenomenon. Recently, a number of numerical methods suitable for digital computer analyses have been reported in the literature (Chaudhry and Yevjevich [6]), which may be used to solve these equations. In the following, the governing equations were solved by one of these methods.

2.1 Governing Equations

The governing equations for unsteady flow in pipeline are derived under the following assumptions (1) one dimensional flow i.e. velocity and pressure are assumed to be constant at a cross section; (2) the pipe is full and remains full during the transient; (3) no column separation occurs during the transient; (4) the pipe wall and fluid behave linearly elastically and (5) unsteady friction loss is approximated by steady state losses.

   The unsteady flow inside the pipeline is described in terms of the unsteady mass balance (continuity) equation and unsteady momentum equation, which define the state of variables of V (velocity) and P (pressure) given as (Simpson and Wu [18]);

$$\frac{\partial \rho}{\partial t} + V \frac{\partial \rho}{\partial x} + \rho \frac{\partial V}{\partial x} + \frac{\rho}{A} \frac{dA}{dt} = O \tag{1}$$

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

Where x=distance along the pipeline; t=time; V=velocity; P=hydraulic pressure in the pipe; g=acceleration due to gravity; f = Darcy-weisbach friction factor; ρ = fluid density; D=pipe diameter; α= pipe slope angle and A=cross sectional area of the pipe.

       Equation (1) is the continuity equation and takes into account the compressibility of the water and the flexibility of the material. Eq. (2) is the equation of motion.

In Eq. (1) we replace $\frac{1}{\rho} \left[\frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial x} V \right] = \frac{1}{\rho} \frac{dP}{dt}$

where $V = \frac{dx}{dt}$, $\frac{d\rho}{dt} = \frac{\rho}{k} \frac{dP}{dt}$ and K = bulk modulus of the fluid

Therefore, we have

$$\frac{dP}{dt} \left[\frac{1}{K} + \left(\frac{1 - v^2}{E} \right) \frac{d}{e} \right] + \frac{\partial V}{\partial x} = 0 \tag{3}$$

Putting $\frac{1}{\rho c^2} = \left[\frac{1}{K} + \left(\frac{1 - v^2}{E} \right) \frac{d}{e} \right] = \frac{1}{K} \left[1 + \frac{k\, c_1\, d}{Ee} \right] \tag{4}$

where: C = wave speed $C_1 = \left(1 - v^2 \right)$ and dividing the result by γ yields

$$\left[\frac{\partial H}{\partial t} + \frac{\partial H}{\partial x} V \right] + \frac{c^2}{g} \frac{\partial V}{\partial x} = 0 \tag{5}$$

The term $\dfrac{\partial H}{\partial x}$ is small compared to $\dfrac{\partial H}{\partial t}$ and it is often negligible. In terms of discharge, Eq. (5) becomes

$$\frac{\partial H}{\partial t} + \frac{\partial Q}{\partial x}\,\frac{c^2}{gA} = 0 \tag{6}$$

2.2 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. The implicit finite difference method is a numerical method used for solving the water hammer equations. The implicit method replaces the partial derivatives with finite differences and provides a set of equations that can then be solved 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, [7]).

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)* as shown in fig. (1).
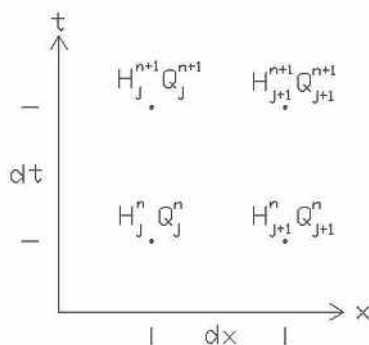

Fig. (1): Finite difference grid.

The momentum equation and the continuity equation can be represented in a short 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:

$$\alpha j = \frac{2\,\Delta t\,c^2\theta}{g\,Aj\,\Delta xj} \tag{7}$$

$$\beta j = \left(H_{nj+1} - H_{nj}\right) + \frac{(1-\theta)}{\theta}\alpha_j\left(Q_{nj} - Q_{nj+1}\right) \tag{8}$$

$$\gamma_j = \frac{\Delta x_j}{2g\,\theta\,A_j\,\Delta t} \tag{9}$$

$$\delta_j = \frac{(1-\theta)}{\theta}\left(H_{nj} - H_{nj+1}\right) - \frac{\Delta x_j f_j}{4g\theta D_j A_J^2}\left(Q_{nj}|Q_{nj}| + Q_{n.j+1}|Q_{nj+1}|\right) \tag{10}$$

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 (Batterton [4]:

Momentum: $-H_{nj+1} + H_{n+1j+1} + \gamma_j\left(Q_{n+1j} + Q_{n+1j+1}\right) = \delta_j \tag{11}$

Continuity: $H_{nj+1} + H_{n+1j+1} + \alpha_j\left(Q_{n+1j+1} - Q_{n+1j}\right) = \beta_j \tag{12}$

Now, with equations for the all 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.

3- CASE STUDY

The analysis of transient flow was performed for a small city pipe network. The sketch of a pipe network is shown in Fig.(2). This simple network has eight pipes, six junctions, and one reservoir. The demand at the Junctions #1, #2, #3 is 31.5 l/s, at the Junctions #4, #6 is 94.6 l/s and at Junction #5 is 63.1 l/s. Table (1) provides the junction report showing the demand and hydraulic grade at six junctions. Table (2) shows the steady state discharge in each of eight pipes. Somehow, the pipe network is modified by the change in demand at Junction #6. Four scenarios were studies in this research. In scenario 1, demand at junction #6 is linearly decreased from 94.6 l/s to 0 l/s within three different periods, 25, 50 and 75 second respectively. In scenario 2, demand at junction #6 is linearly increased from 0 l/s to 94.6 l/s within three different periods 25, 50 and 75 seconds respectively. In scenario 3, time of demand variation was kept constant at 10 s and the demand was decreased from 94.6 l/s to a ratio of 75%, 50% and 25% respectively. In the fourth scenario, the time of demand variation was kept constant at 10 second and the demand was increased from 0 to 25%, 50% and 75% of its value at steady state case.

Table 1: Elevations of hydraulic grade and demands at the different junctions.

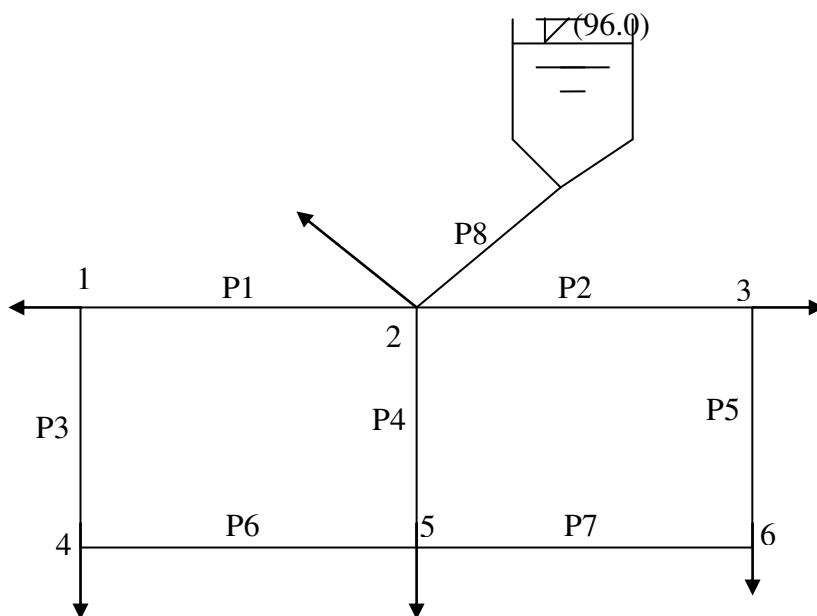| Junction node	Hydraulic grade m	Ground elevation m	Demand lit/s
1	87.6	51.8	31.5
2	89.7	54.9	31.5
3	88.4	50.3	31.5
4	87.6	47.3	94.6
5	88.2	45.7	63.1
6	81.5	44.2	94.6

Fig. (2): Schematic sketch for the used pipes network under study.

Table 2: Steady flow rates and pipe characteristics of the network.

Pipe number	Flow rate lit /S	Length (m)	Internal Diameter (mm)	Friction factor
A	31.1	1220	254	0.024
B	45.3	1829	254	0.024
C	0.00	1829	305	0.022
D	206.7	1982	610	0.018
E	14.2	2134	254	0.024
F	96.3	915	457	0.020
G	48.1	1524	254	0.024
H	314.3	91	305	0.022

4- RESULTS AND DISCUSSIONS

To show the effect of changing in demand on transient pressure in water supply pipe network, the pressure variation with time at two different junctions, one is located far from the point of variation in demand and the other at the point of variation as example, is discussed in the following sections.

4.1 Influence of Time of Decreasing Demand on pressure Head

Figure.(3) shows the variation of piezometric head with time at node 1 after decreasing of demand at junction 6 from the steady state value to zero in three different time intervals, 25, 50, and 75 s respectively. It is noticeable that as the time of demand variation decrease, the fluctuations in pressure head increase. Also, it can be seen that

the pressure head arrive to constant value after 70 s for the three cases and due to reduction of demand the pressure head at node 1 increased to more than 3 m.
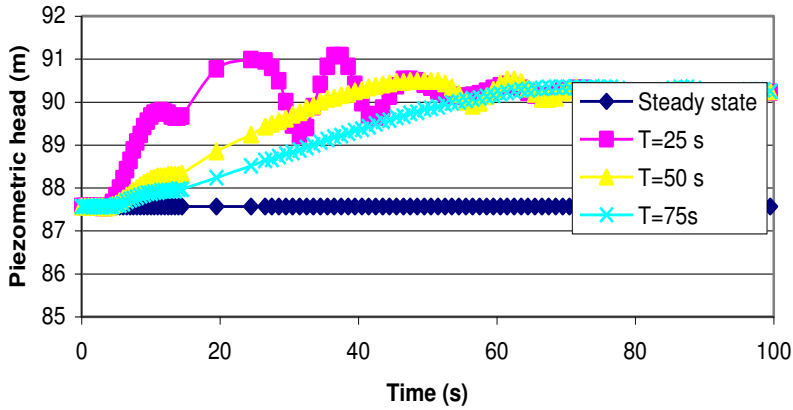

Fig. (3): Transient pressure fluctuation at Junction 1 due to decreasing of demand at junction 6 at different times.

Figure (4) shows the variation of piezometric head with time at node 6 after decreasing of demand at junction 6 from the steady state value to zero in three different time intervals, 25, 50, and 75 s respectively. It is noticeable that as the time of demand variation decrease, the fluctuations in pressure head increase. Also, it can be seen that the pressure head arrive to constant value after 75 s for the three cases and due to reduction of demand, the pressure head at node 6 increased to more than 16 m. Due to changes in demand at junction 6, the flow direction at some pipes is changed into the opposite direction as shown in the time dependent discharge curves shown in Fig. 5. From Fig. 5, it is seen that the flow direction is reversed in pipe P7 after about 6 seconds and return another to the same direction after 23 seconds before the complete implementation of change in demand at junction 6. However there is no change in flow direction in pipe P1 because it is far from the point of demand change.
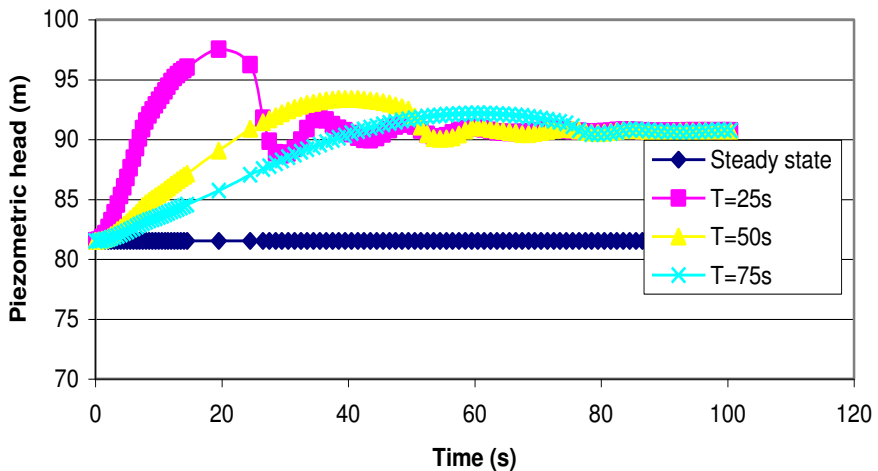

Fig. (4): Transient pressure fluctuation at Junction 6 due to decreasing of demand at Junction 6 at different times.
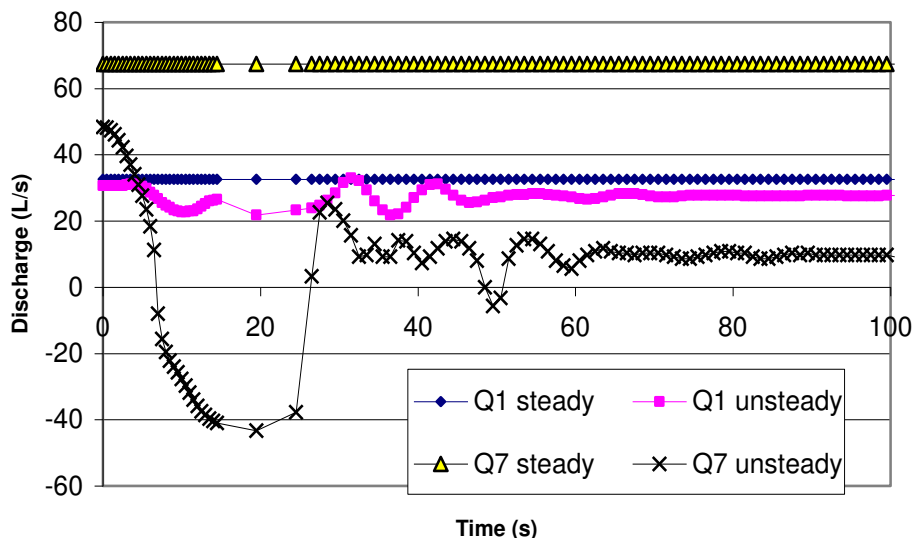
Fig. (5): Transient changes of flow rate at pipe P1 and P7 due to decreasing of demand at Junction 6 at time interval 25 s.

4.2 Influence of Time of Increasing Demand on Pressure Head

Figure(6) indicates the variation of piezometric head with time at node 1 after increasing of demand at junction 6 from zero to a value of 94.6 L/s in three different time intervals, 25, 50, and 75 s respectively. It is noticeable that as the time of demand variation decrease, the fluctuations in pressure head increase. Also, it can be seen that the pressure head arrive to constant value after 70 s for the three cases and due to increase of demand the pressure head at node 1 decreased to about 3 m.
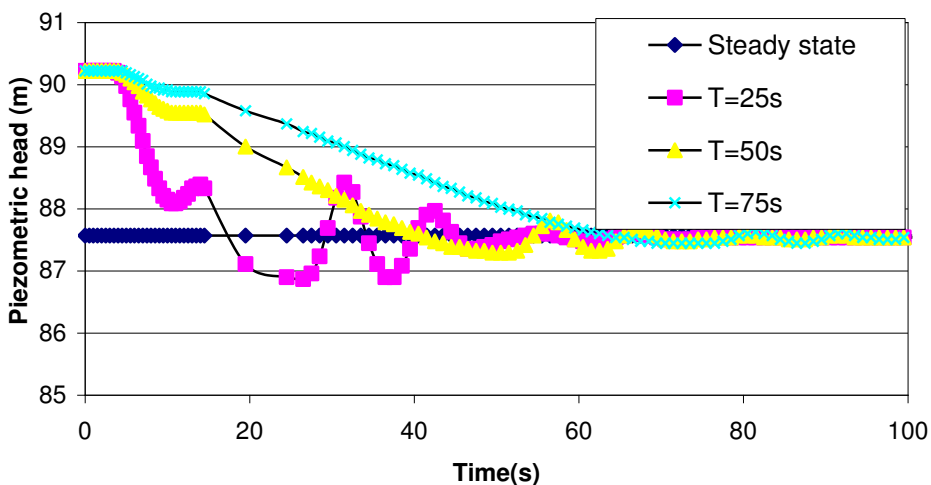

Fig. (6): Transient pressure fluctuation at Junction 1 due to increasing of demand at junction 6 at different times.

Figure (7) indicates the variation of piezometric head with time at node 6 after increasing of demand at junction 6 from zero to a value of 94.6 L/s in three different time intervals, 25, 50, and 75 s respectively. It is noticeable that as the time of demand variation decrease, the fluctuations in pressure head increase. Also, it can be seen that the pressure head arrive to approximately constant value after 80 s for the three cases and due to increase of demand the pressure head at node 6 decreased to about 15 m. Also, Fig. 8 shows the transient flow rate at pipe P1 and P7 due to increasing of demand at junction 6. It is clear that the fluctuation in flow rate increases at pipes near from point of demand variation and in contrary to the pervious case there is no change in flow direction.
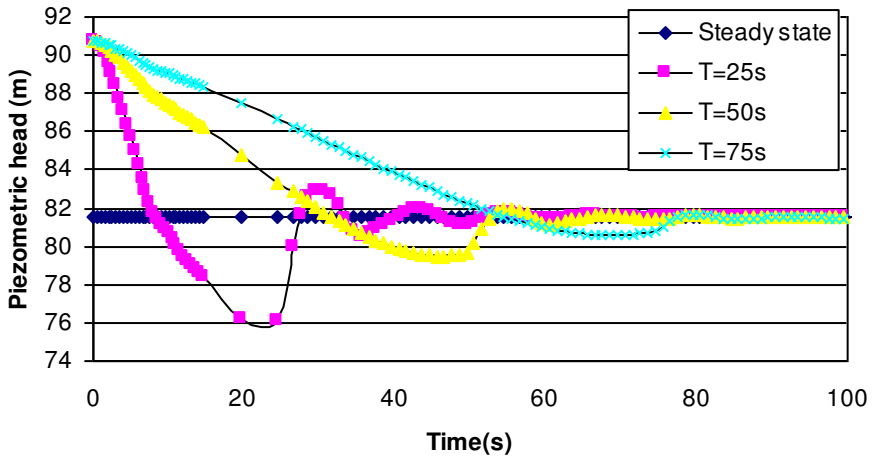

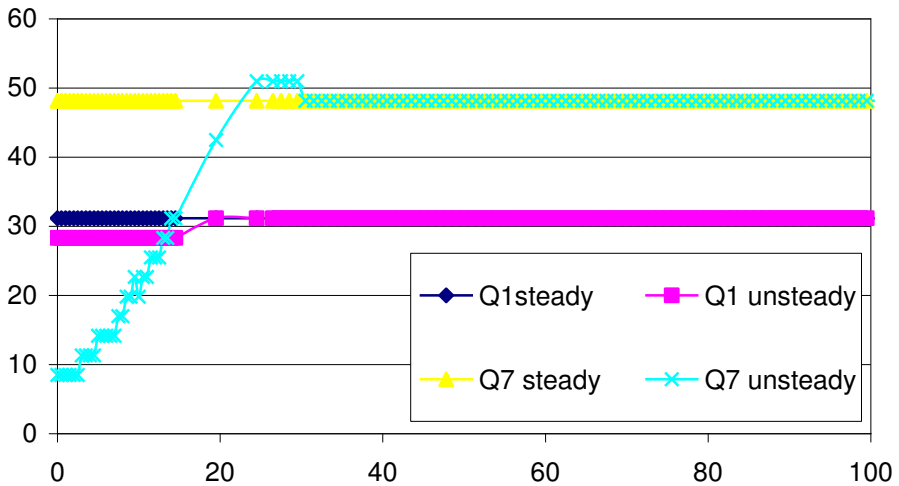Fig. (7): Transient pressure fluctuation at Junction 6 due to increasing of demand at junction 6 at different times.

Fig. (8): Transient change of flow rate at pipe P1 and P7 due to increasing of demand at junction 6 at time interval 25 s.

4.3 Influence of Ratio of Demand Decreasing

Figure(9) depicts the variations of piezometric head with time at node 1 due to decreasing of demand at junction 6 with different reduction ratios, 25%, 50%, and 75% percentage from the original case at ten seconds, respectively. It is noticeable that as the percentage of decreasing demand increases, the fluctuations in pressure head increase. Also, it can be seen that the pressure head arrive to constant value after 70 s for the three cases and increases to about 6 m than the original pressure for steady state .
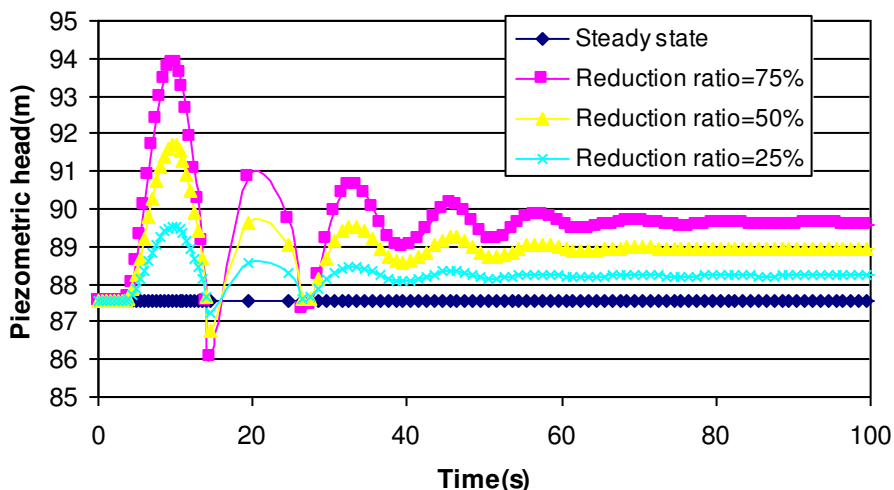

Fig. (9): Transient pressure fluctuation at Junction 1 due to decreasing of demand at junction 6 with different reduction ratios.

Figure (10) depicts the variations of piezometric head with time at node 6 due to decreasing of demand at junction 6 with different reduction ratios, 25, 50, and 75 percentages from the original case at ten seconds, respectively. It is noticeable that as the percentage of decreasing demand increases, the fluctuations in pressure head increase. Also, it can be seen that the pressure head arrive to constant value after 70 s for the three cases in case of high demand reduction, a sample fluctuations was accrued and increases to about 28 m than the original pressure for steady state.

4.4 Influence of Ratio of Demand Increasing

Figure (11) presents the variations of piezometric head with time at node 1 due to increasing of demand at junction 6 with different ratios, 25, 50, and 75 percentages from the original case at ten seconds, respectively. It is clear that as the demand ratio decreases, the fluctuations in pressure head increase with high amplitude. Also, it can be seen that the pressure head arrive to constant value after 60 s for the three cases.
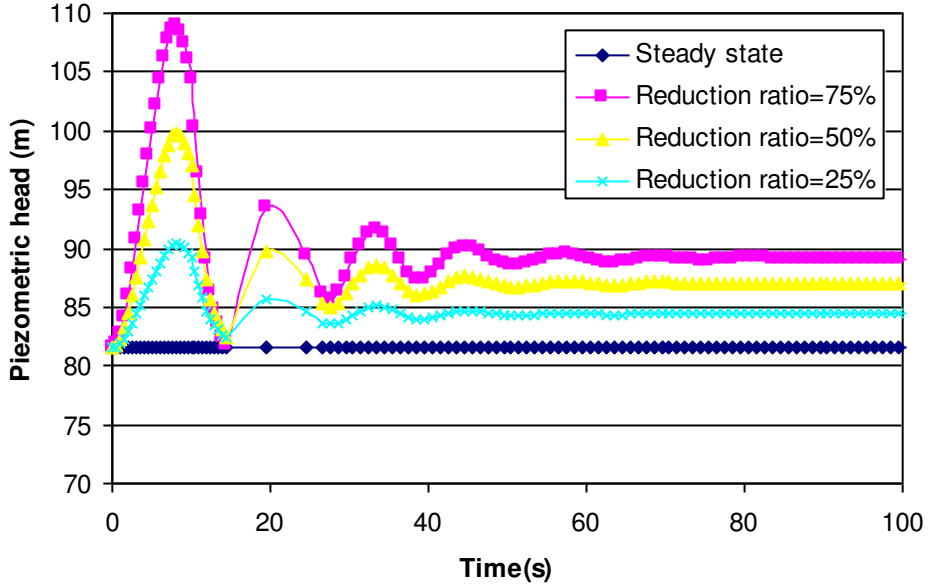
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Fig. (10): Transient pressure fluctuation at Junction 6 due to decreasing of demand at junction 6 with different reduction ratios.

Also, Fig. 12 presents the variation of piezometric head with time at node 6 due to increasing of demand at junction 6 with different ratios, 25, 50, and 75 percentages from the original case at ten seconds, respectively. It is clear that as the demand ratio decreases, the fluctuations in pressure head increase with high amplitude. Also, it can be seen that the pressure head arrive to constant value after 60 s for the three cases. In comparison with Fig. 9, it is obvious that the transient effect decreases as the location far from the change position.
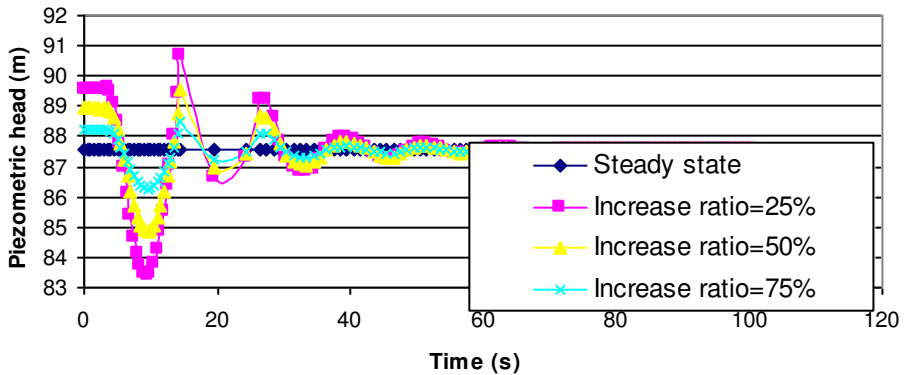

Fig. (11): Transient pressure fluctuation at Junction 1 due to increasing of demand at junction 6 with different increasing ratios.
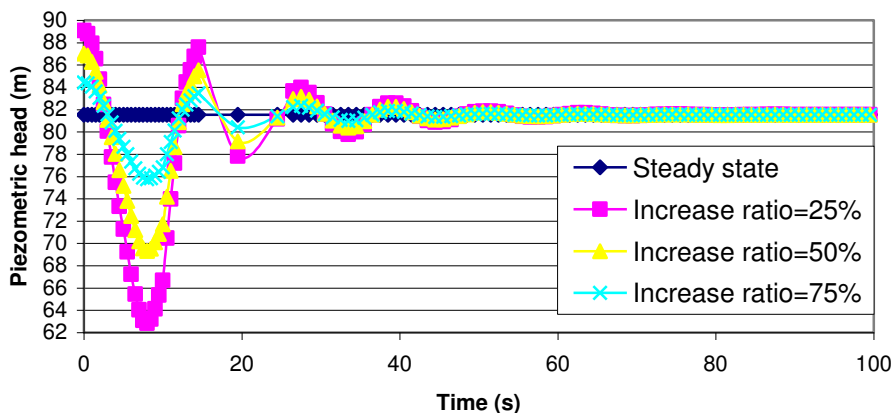
Fig. (12):Transient pressure fluctuation at Junction 6 due to increasing of demand at junction 6 with different increasing ratios.

5- CONCLUSIONS

Several cases of numerical simulation for transient flow in distribution system with different scenarios have been performed using WHAMO model in this study. The small pipe network with eight pipes, six junctions, and one reservoir has been simulated changing the demand at the specific junction. In this simulation, it is noticed that rapidly changing the demand could significantly increase or decrease the pressure head in the distribution system and cause flow reversal in a network system. In this simulation, shorter increasing/decreasing time of demand change causes the greater magnitude of transient fluctuation. Therefore, it is very obvious that the operations of distribution system should be done with very careful caution. The slower opening rates significantly reduce the impact of hydraulic transients. When the distribution system is designed, many different cases of simulation with different scenarios should be performed for the economical and safe design.

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دراسة ظاهرة المطرقة المائية الناتجة عن التغير المفاجئ في المتطلبات المائية

خلال شبكات المياه

تعتبر ظاهرة المطرقة المائية من الظواهر الغير مرغوب في حدوثها بخطوط توصيل السوائل المختلفة و شبكات مياه الشرب وشبكات الري , وتحدث هذه الظاهرة عند التوقف المفاجئ لطلمبات الضخ وكذلك تغير المتطلبات علي خطوط السريان من قفل مفاجئ أو كسر مفاجئ في المواسير ,لذا يلجأ المهندسون إلي العديد من وسائل الحماية علي خطوط الشبكات , يوجد العديد من الدراسات النظرية لدراسة بعض العوامل المؤثرة في هذه الظاهرة لصعوبة هذه الظاهرة وزيادة تكاليف إجرائها.

يقوم هذا البحث علي دراسة نظرية مستخدما برنامجWHAMO لتحليل دراسة التغير المفاجئ في المتطلبات المائية خلال شبكة مياه شرب مكونة من حلقتين بثمانية خطوط و ست نقاط تلاقي , يستخدم هـذا البرنـامج طريقـة الفروقـات المحـدودة لحـل معـادلتي الاسـتمرارية وتسـاوي القـوي فـي حالـة عـدم الاستقرار Unsteady.

وقد أجريت هذه الدراسة بحدوث تغير مفاجئ بنقص التصرف عند احدي نقاط الشبكة خلال أزمنة مختلفة وكذلك بقيم مختلفة عند زمن ثابت وكذلك الحال الزيادة في معدل التصرف عند نفس النقطة و دراسة هذه الحالات علي التغير في الضغط والتصرف عند بعض النقاط بالشبكة.

كان من أهم النتائج المستخلصة من هذا البحث انه بالنقص في زمن التغير بالزيادة أو النقصـان في التصرف بأحد نقاط الشبكة يزداد التغير في الضغط بالشبكة سواء بالنقصان أو الزيادة , أيضا قد تتأثر قيم و اتجاهات سريان المياه بالخطوط نتيجة لهذه التغيرات وخصوصا القريبـة مـن نقـاط الحـدث ,لذا يوصي بالحرص التام في تشغيل الشبكات , مع الأخذ في الاعتبار القوي الناتجة عن هذه الظاهرة في تصميم الخطوط ووصلاتها و كذلك عمل الحماية الكافية ضد هذه الظاهرة.