Control of Hydraulic Transients in the Water Piping System in Badra – Pumping Station No. 5

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Abstract

In this paper, the surge tank utilization method was used to prevent the water hammer. The study was conducted on a practical problem at pipelines and pumping station of Badra – pumping station No. 5, which is possessed to Iraqi General Company for Execution and Irrigation. For this purpose, Surge2012 transient analysis software was used to achieve the best design and checking parameters.

The study recommends installing 2x14m^3 closed surge tanks near to lifting station. The outlet/inlet nozzle has to be of 300 mm diameter. The initial air volume must be 5 m^3 for each one. All these parameters must be achieved to maintain a positive and negative pressure waves in pipe network system within accepted values.

Keywords: water hammer, surge, pipeline profile, pumping system.

Introduction

The terms as hydraulic transient, surge pressure or water hammer in water applications are familiar for most of the designers or planners of pumping systems. Under unsuitable conditions, damage due to water hammer may occur in long pipelines measuring more than one hundred meters and transfer only several tenths of a liter per second [1].

Water hammer (or hydraulic surge) occurs due to water sudden change in direction or velocity that increases pressure [2]. The reasons of the disturbances are pressure and flow changes that cause propagation of pressure waves throughout the piping system in the opposite direction.

The pressure waves transfer with acoustic or sonic speed (the velocity of sound). The transient velocity depends on the water and the pipe walls elasticity [3]. The wave's intensity reduces due to damp actions and friction until the system stabilizes at a new steady state. In general, any change in water flow conditions initiates a sequence of pressure waves in the water distribution system.

These changes normally generate from variable actions that affect hydraulic devices or boundary conditions [4]. The following typical cases must be recognized and addressed to prevent serious consequences for water utilities [5]:

1. Pump startup or shutdown.
2. Variation in cross-sectional flow area (valve opening or closing).
3. Cases like changing the adjustments in the water level at reservoirs, losing overhead storage tank, and pressure changes in tanks.
4. Rapid changes in water demand (e.g., hydrant flushing).
5. Changes in delivery conditions due to pipeline break or freezing of a part of the line.
6. Pipe filling or evacuating-air release from pipes.
7. Check valve or regulator valve action.

Hydraulic transients in closed conduits study characterize by its complexity and significance in practice. The study of hydraulic transients can be said to have started with the works of Joukowsky at 1898 [6] and Allievi [7]. Ref. [8] introduced a historical development of this subject. Ref. [9] simplified and edified the graphical calculation method. Ref. [10] combined the method of characteristics with computer modeling. Ref. [11] investigated the stability of hydropower plants to provide realistic data information and approaches for controlling transients in hydropower plants. Ref. [12] studied the elasticity effects. They studied the water column in water hammer effects on the pipe walls. Also, they tested the stability of a hydropower station unit and derived an analytical stability standard. Ref. [13] used pressure relief valves and safety membranes in place of a surge tank in a small hydropower plant. Ref. [14] analyzed the effects of water hammer in a hydropower plant supplied with safety membranes and developed mathematical models for these cases.

Ref. [15] presented a novel technique that parameterizes the water hammer effects in small hydro projects to improve the dynamic behavior of their turbines. Vakil [16] studied the effects of different valve closure laws on water hammer pressures and turbine speed. Although several published articles on the water hammer, a wide field remains open for further research.

Inaccurate designs and planning led to accidents that may cause life loss in addition to installations

In USA, At the Hydroelectric Power Plant Station of Oneida, a faulty operation of turbine valves caused a serious damage. Failures took place and resulted in five lives lost. Also at 1997 in Poland, the penstock of Lapino Station Hydroelectric Power burst during the acceptance tests of its new controlling tool (governor) [17].

Also, at Oigawa Hydropower Station in Japan, the rapid valve closure resulted in the penstock erupted, and three workers lost their lives [18].

The aim of this paper is to study a practical case of the water hammer treating in the piping system, to prevent system damage due to transient pressure fluctuation using the best scientific and engineering solutions.

Case Study

Water hammer analysis must receive the attention and the consideration required for safe and effective design and operation of piping systems. In this paper, a study was conducted on pumping station and pipeline 7500 m that is subjected to damage and many fractures due to faulty design that didn't take into consideration water hammer. Fig. 1 shows some of the water hammer traces on a part of the studied pipe.

This study based on technical data of the piping system provided by General Company for Execution of Irrigation Projects, Iraq. It was directed to deal with transient analysis study (Surge Analysis) conducted on water pumping station and piping system in Badra – pumping station No. 5. This station is pumping potable water through 7500 m of bending land using two pumps for six hours per day. However, three pumps prepared to operate in the future. Thereby, this study considered the operation of three pumps together. Table 1 represents the details of physical and hydraulic characteristics of the devices used in the pipe network. Figure 2 shows the pipeline profile.

Because of the intermittent of electricity supplying system in Iraq after 1991, electrical shutdown became familiar causing sudden pumps stopping. This unpredicted interruption causes high positive and negative pressure rates. After many years of usage, the pipeline unexpectedly exposed to several fractures. It required changing the pipeline with reconsideration of transient pressure effects.

Table 1: Details of physical and hydraulic characteristics of the devices used in the pipe network

Pipelines	
Pipe material	Ductile Iron
Pipe length	7500 m
Pipe diameters	500 mm
Pipe thickness	9 mm.
Wave speed	1135 m/s
Transmitted fluid	Potable Water
Applied Equation	Hazen William
Pipe Roughness	C_H: 140
Pumps	
Number of pumps	3 working +1 standby
Rated discharge per pump	500 m^3/h
Rated pump head	80 m
Pump and Motor Inertia	46.09 $N\text{-}m^2$ (estimated)
Pump rated speed	1500 rpm
Pump efficiency	70- 80%
End point	Main transmission pipeline ended to the storage reservoir higher than pump elevation by 32 m and 7.5km faraway from the pump room.

In this study, the water flow inside the mentioned pipeline network system has to be analyzed. The positive and negative pressure waves inside pipeline system must be defined and compared. The same must be done to the permissible values of hydraulic parameters for the network elements. If the encountered pressures inside the pipeline are within the design pressures of the network element, in this case pressures are safe, and no protection system is required. However, if pressures are beyond the design magnitude so protecting the network is a must. Many alternative solutions for water hammer like using soft starters, open-ended pipe with 80 m height or using surge tank. Surge tank with air chamber was selected to be added to the pipeline system as an acceptable method facing water hammer. So, the proper size of adequate surge tank for protecting the whole system and detailed description for this tank will be represented.

Surge Tanks

Surge tanks (or surge chambers) are open top tanks connected to the penstock. For appropriated sized, surge tanks deviate water hammer in a way that only the section of pipe between the surge tank and the pump station or valve is subject to the transient pressures. The ideal location for a surge tank is as close to the pumps as possible, although often the topography precludes this. The sizing and design of the surge tank should ensure that pressure waves are dampened and that the tank does not drain or overflow. Surge tanks can be of a simple connection, orifice or differential type. A simple surge tank involves a direct connection to the conduit. An orifice tank is similar to the simple surge tank, except that a throttling orifice is used to induce a pressure loss as water flows in and out of the tank. A differential tank uses a vertical pipe to dampen high-frequency pressure fluctuations and a surge tank to dampen the low-frequency oscillations. A surge tank must be high enough so that the top is above the static water level of the reservoir.

Air Chambers or Accumulators

Air chambers are tanks containing air at the top and water at the bottom, separated by a diaphragm. Their advantage is that their location close to the pumps is preferable, where a surge tank would not be practical. The air in the chamber expands or contracts as water flow out and in and out. While the air chamber is smaller than a surge tank and can save costs (particularly for underground powerhouses), the air slowly leaks out, so the air compressor must be installed and maintained. These devices are rarely used on small hydro systems.

Pressure Control Valves

Valves can be used in conjunction with surge tanks and air chambers or by themselves, depending on the arrangement of the hydropower plant. A pressure regulating valve is a spring operated valve that opens when the pressure reaches a pre-set level. They allow the rapid discharge of water to relieve excess pressure. These valves are normally installed in parallel with the pumps, and discharge via an energy dissipating valve into a stilling basin or the tail-race. Figure 3 represents a flow chart for surge control in water distribution systems. The chart clarifies that the general and detailed understanding for transients need a quantitative description.

The fundamental equations for describing transients are Newton's second law (equation of motion) and conservation of mass (kinematic relation). A series of nonlinear hyperbolic partial deferential equations can be derived from these equations; when they are applied on specific control volume. The dominant equations for transient flow can be set as:

Continuity

$$H_t + \frac{c^2}{gA} Q_x = 0 \qquad \text{….. (1)}$$

Momentum

$$H_x + \frac{1}{gA} Q_t - f(Q) = 0 \qquad \text{….. (2)}$$

The solution can be obtained numerically for transient-flow by solving equations 1 and 2 with appropriate boundary conditions. The pressure and flow depend on position and time. Ref. [19] described many solutions schemes like Lagraingian solution, Eulerian method, and the characteristic method. The justification of the employment of any method depends on its efficiency and stability in solving problems by mean of computer implementation. Using surge modeling to identify the weak spots and negative effects of transients flow can be considered very effective. The knowledge of the piping system behavior under the worst cases can give a reasonable evaluating of the possibilities of avoiding these water hammers and controlling it. For further details one can refer to References 20, 21 & 22]

The study was performed by using the latest version of the popular software Surge2000 developed at University of Kentucky, USA. This software program is the most widely used in the world and has advanced graphical interface to handle transient analysis of large complex pipeline systems. More than 2000 packages in circulation worldwide and the program have been successfully used for protecting thousands of pipeline systems (transmission main and distribution networks) over the last 35 years.

Results and Discussion

The study has simulated the pipe network system with all elements as per given technical information provided. Figure 4 shows the parameters used on the surge analysis. Figure 5 shows the arrangement of pumping station. Some assumptions have been considered as the required data are missing. It is assumed that the end point is a water reservoir with minimum water depth 0.5 meter.

Steady State Analysis

For steady state analysis a baseline hydraulic model was created by using technical information and the pipeline data provided into the Pipe2012 program, which is a graphical interface for the Surge2012 transient analysis software. Steady state analysis was performed considering the pump characteristics data and pipeline information. Figures 6 & 7 show steady state hydraulic grade line (HGL) for the system when 3 pumps were running at a normal speed. Below is the pump data as per steady state run.

Pump line	Flow rate (l/s)	Pump head (m)
Pump-1	136.82	80.98
Pump-2	136.83	81.98
Pump-3	136.84	80.97

Transient Model Runs (Surge Analysis)

The transient analysis for this pipeline system was carried out without any protection to specify the potential for high/low transient pressures subsequent a pump trip. It considered that the worst case scenario would be the power failure situation wherein all the running pumps get stopped at the same time. Figure 7 declares the pressure envelope following pump trip during the 800 seconds transient simulation without any surge protection system.

Figure 8 indicates the worst scenario would happen. A power failure situation when all the pertaining pumps tripped at the same time. A very high elevated pressure created which can damage the system; it is almost 429.3 m. Also, it encountered negative pressures reaches the cavitation head in the long portion of the transmission main. In the figure, the green line indicates the maximum pressure and the red line indicates the minimum pressure during an 800 seconds simulation, and the blue line indicates pipeline profile. Figure 9 illustrates pressures variation at one of the tripped pumps. As evident from these figures, the highest positive and negative pressures are beyond permissible pressures of the pipeline system and call protection system to suppress these pressure waves to design values.

For suitable protection achievement to the studied pipeline, Surge2012 transient analysis software indicates that 28 m^3 closed surge tanks, compressor type is suitable and sufficient to suppress pressure waves to design values. Figure 10 manifests that pressure envelope follows pumps trip after adding closed surge tank. Figure 11 illustrates pressures variation on tripped pumps after adding protecting surge tank. A maximum pressure of 146.70 m and minimum pressure of +1.40 m achieved, and both are occurring inside pump room.

Also, Figures 12 shows the variation of pressure inside (red line) the surge tank; the external pressure (green line) outside the surge tank. Figure 13 illustrates the air volume inside surge tank during the transient time 800 sec after pump trip.

Additional Scenarios

Additional transient cases based on pump operating scenarios with surge protection system were studied. These cases are:

- **a)** Three pumps are running while one pumps tripped; Figure 14 shows the pressure envelope when one pump tripped and two pumps still in operating, the maximum and minimum pressures are acceptable.
- **b)** Three pumps are running while two pumps tripped. Figure 15 shows the pressure envelope when two pumps tripped, and the other one pump stays in operating, the maximum and minimum pressures are acceptable.
- **c)** One pump is running and gets tripped. Figure 16 reveals the pressure envelope when one pump is running and gets tripped. The resulted maximum and minimum pressure are acceptable.
- **d)** Two pumps are running and get tripped. Figure 17 clarifies the pressure envelope when two pumps are running and get tripped. The resulted maximum and minimum pressure are acceptable.
- **e)** All pumps are off, and suddenly all started up. Figure 18 illustrates the pressure envelope when all pumps are stopped and suddenly get started up. The resulted maximum and minimum pressure are acceptable.

Because of high positive and negative pressures created while all pumps tripped simultaneously, so surge protection system is important to alleviate pressure waves at transient state. The chosen 28 m^3 closed surge tank is capable of protecting this piping system against high and low pressures and has good advantage to retaining a long life for the equipment better than other protection elements. NRV (non-return valve) characteristics at the pump discharge have a significant bearing on the modeling results. In particular, how quickly the NRV closes following a flow reversal in the pipeline is an important parameter that may affect the maximum pressure in the pipeline during a transient event. Since surge pressure might reach 146.7 m, thereby it is wise to select valves and fittings near the pumping station to be PN 16 (nominal pressure=16 bar).

Design Guideline for Surge Tank Dimension

Hydraulic transient calculations can yield reasonable results when compared to actual measurements provided. In addition to characterizing the pump, motor and valve, there has to be sufficient knowledge regarding the piping and flow demands. Since total required surge tank volume is about 28 m^3, it is, therefore, the selection was made to use two tanks each with a volume of around 14 m^3. Since the volume is relatively big, the choice is a horizontal pressure tank. The tank might have a diameter anywhere between 2.0 – 2.5 meter and length between 4.4 and 3.0. Example: if the diameter (D) is about 2.3 m then length (L) is 3.4 m.

Conclusion

In this study, a treatment for water hammer effects on a system of pipelines and pump is conducted. Surge2012 transient analysis software was used to achieve the best design and dimensions of the surge tank in addition of calculating transient pressures at several operating conditions. Several scenarios tested the momentum disturbances in transient pressure due to sudden stopping of one or two pumps out of three operating ones.

The study recommends the following considerations to maintain a positive and negative pressure waves in pipe network system within accepted values. Installation of 2x14m^3 closed surge tanks near to lifting station. These tanks must be equipped with outlet/inlet nozzle 300 mm and initial air volume 5 m^3 for each one. The results of additional tests indicated that the recommended design can fulfill all system requirements in preventing water hammer effects.

References

1. Çalmark M. & Bozus Z., “Protective measures against water hammer in run-of-river hydropower plants”, Digest 2012, pp: 1623-1636, (2012).
2. Petry B., Baumann A., Tomasson G. G. & Stefansson B., “Control of hydraulic transients in the power waterways of the Kárahnjúkar HEP in Iceland: Design challenges and solutions”, Proceedings, Hydro 2006, Porto Carras, Greece, September (2006).
3. Hachem F. E. & Schleiss A. J., “Monitoring of steel-lined pressure shafts and tunnels”, Hydro power and Dams, Issue 3, (2011).
4. Hachem F. E. & Schleiss A. J., “A review of wave celerity in frictionless and axisymmetrical steel-lined pressure tunnels”, J Fluid and Structures, vol. 27, (2011).
5. Don J., Wood D. J., “Water hammer analysis-essential and easy and efficient”, J Environmental Engineering ASCE, pp: 1123-1131, (2005).
6. Joukowsky N., “Water hammer”, Proc. Am. Waterworks Assoc., vol. 24, pp: 341-424, (1904).
7. Allievi L., “The theory of water hammers”, (English translation by Halmos EE, 1929), Trans. ASME, (1913).
8. Wood D. J., Dorsch R. G. & Lightner C., “Wave plan analysis of unsteady flow in closed conduits”, J. Hydraul. Div., Am. Soc. Civ. Eng., vol. 92, No. 2, pp: 83–110, (1966).
9. Parmakian J., “Water hammer analysis”, Dover Publications, Inc., New York, New York, (1963).
10. Wylie E. B. & Streeter V. L., “Fluid transients in Systems”, Prentice-Hall, Englewood Cliffs, New Jersey, (1993).
11. Hovey L. M., “Optimum adjustment of hydro governors on Mantoba hydro system”, American Institute of Electrical Engineers, vol. 81, No. 3, pp: 581-586, (1962).
12. Jimenez O. F. & Chaudhry M. H., “Stability limits of hydroelectric power plants”, ASCE Journal of Energy Engineering, vol. 113, No. 2, pp: 50-60, (1987).
13. Peicheng H., Pusheng Z. & Elkouh A. F., “Relief valve and safety membrane arrangement in lieu of surge tank”, ASCE

Journal of Energy Engineering, vol. 115, No. 2, pp: 78-83, (1989).

14. Ni F., Hu P. & Wang Q., "Numerical simulation of hydraulic transients in hydropower plant using safety membranes", ASCE Journal of Hydraulic Engineering, vol. 122, No. 6, pp: 298-300, (1996).
15. Ramos H. & Almeida B., "Parametric analysis of water-hammer effects in small hydropower schemes", ASCE Journal of Hydraulic Engineering, vol. 128, No. 7, pp: 689-696, (2002).
16. Vakil A. & Firoozabadi B., "Investigation of valve-closing law on the maximum head rise of a hydropower plant", Scientia Iranica Mechanical Engineering, vol. 16, No. 3, pp: 222-228, (2009).
17. Adamkowski A., "Case study: Lapino Power plant penstock failure", ASCE Journal of Hydraulic Engineering, vol. 127, No. 7, pp: 541-555, (2001).
18. Bergant A., Simpson A. R. & Tijsseling A. S., "Water hammer with column separation: a review of research in the twentieth century", Centre for Analysis Scientific Computing and Applications, Eindhoven, (2004).
19. Poulos P. F., Karney B. W., Wood. D. J. and Lingireddy S., "Hydraulic transient guidelines for protecting water distribution systems", American Water Work Assoc-iation Journal, vol. 97, No. 5, pp: 111-124, (2005).
20. Ramalingam D., Lingireddy S. and Wood D. J., "Using the WCM for transient modeling of water distribution network", American Water Work Association Journal, vol. 101, No. 2, pp: 75-89, (2009).
21. Benser M. C., "Risk evaluation of drinking water distribution system contam-ination due to operation and maintenance activities", PhD Thesis, University of Montreal, Quebec, Canada, (2007).
22. Abd El Kawi O. S., Elbakhshawangy H. F. and Elshazly M. N., "Simulation of water hammer oscillations in single pipe line due to sudden valve closure", Journal of American Science, vol. 9, No. 12, pp: 374-380, (2013).

Figure 1: Some of the water hammer traces on a part of the studied pipe

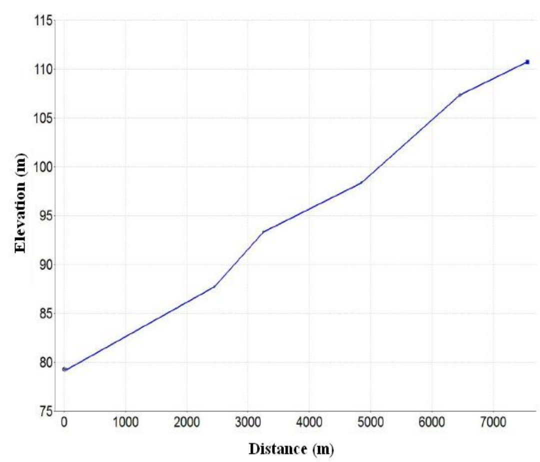

Figure 2: Pipeline profile

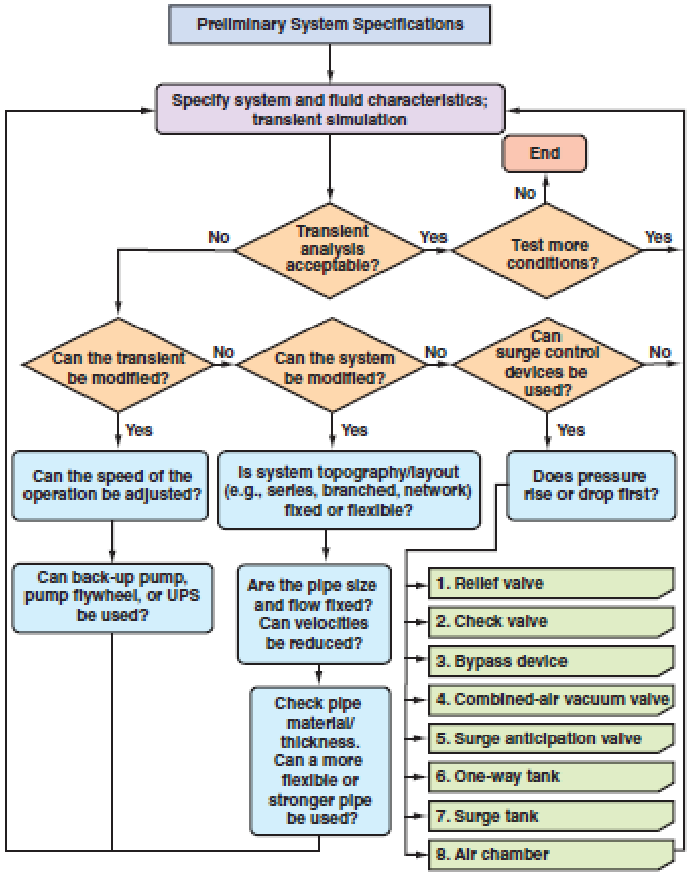

Figure 3: Flow chart for surge control in water distribution systems [19]

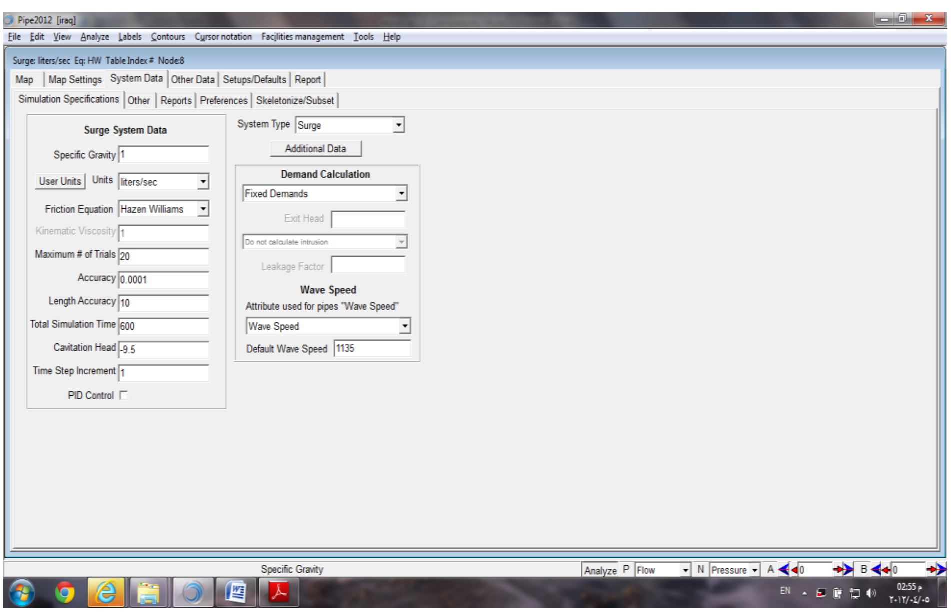

Figure 4: Parameters used on surge analysis

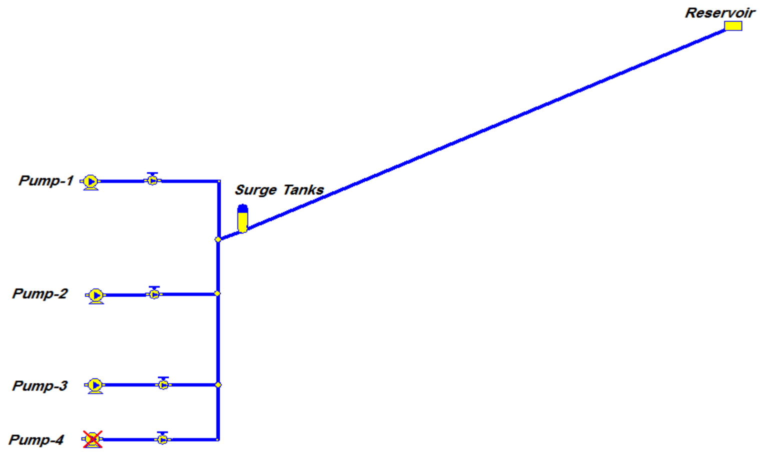

Figure 5: Pumping station arrangement

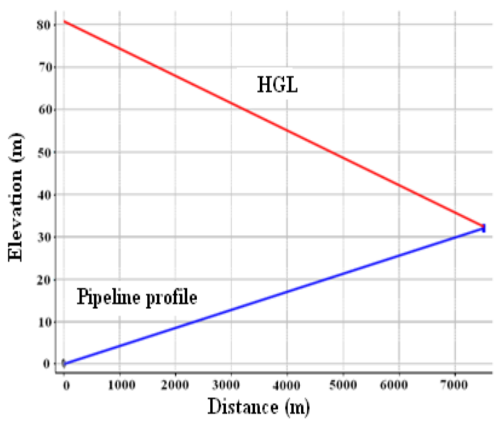

Figure 6: Hydraulic Grad Line (HGL) at steady state when 3 pumps running at the normal speed

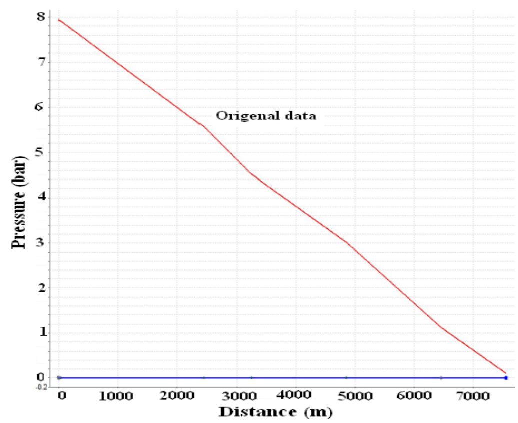

Figure 7: Pressure magnitude along pipeline at steady state operation

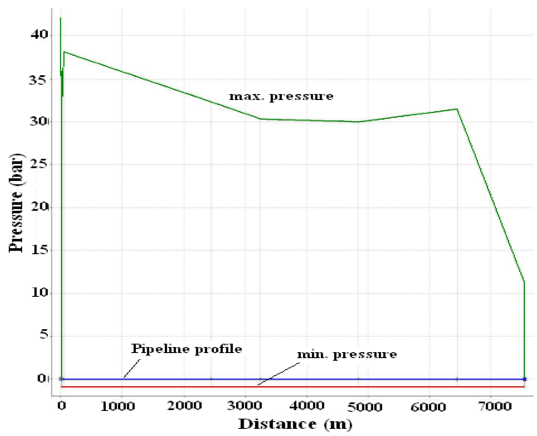

Figure 8: Min and max pressures along the pipeline when pumps tripped without surge protection system

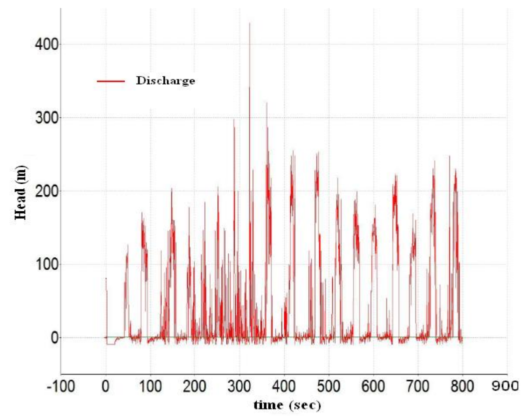

Figure 9: Pressure variation at one of tripped pump- without surge protection system

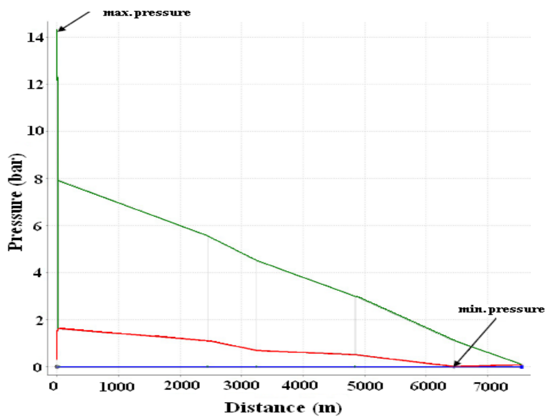

Figure 10: Min and max pressures along pipeline when 3 pumps tripped-with protection system

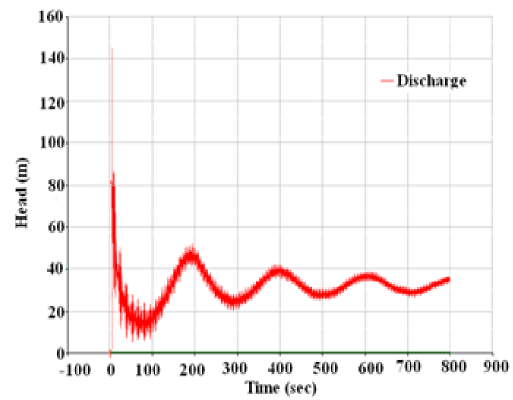

Figure 11: Pressure variation at one of tripped pumps with surge protection system

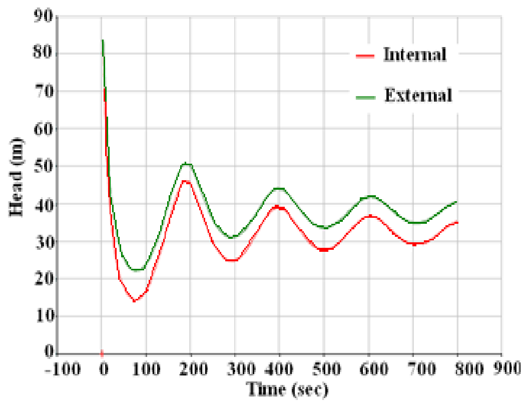

Figure 12: Pressure variation inside surge tank during 800 sec transient time after the pump tripped

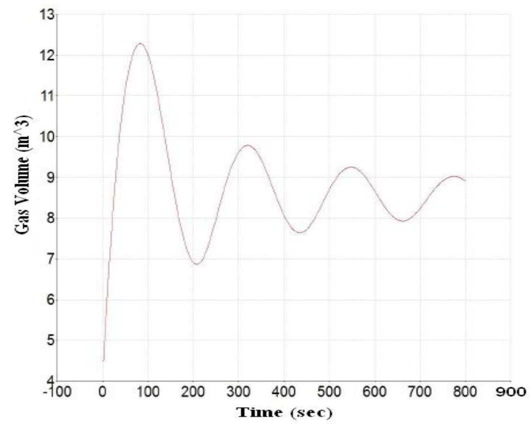

Figure 13: Air volume variation inside surge tank during 800 sec transient time

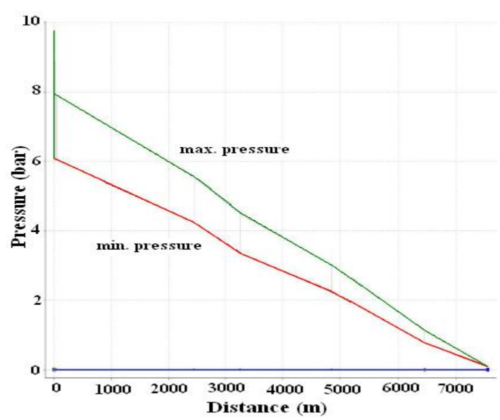

Figure 14: Max & min pressures when one pump is tripped from three running pumps – with protection system

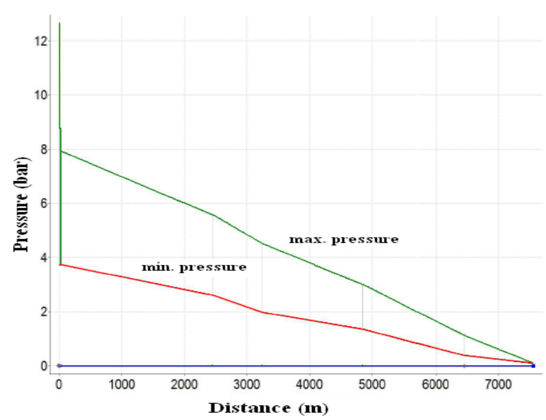

Figure 15: Max & min pressures when two pumps are tripped from 3 running pumps – with protection system

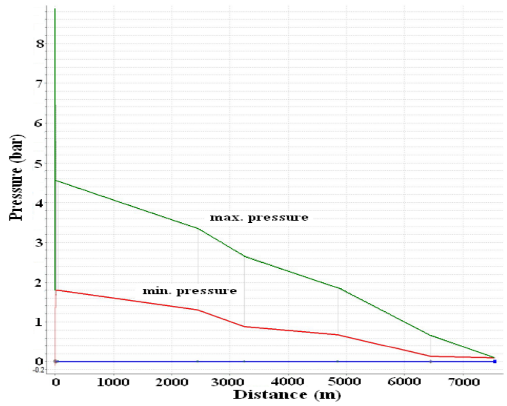

Figure 16: Max & min pressures when one pump running and tripped**-with protection system**

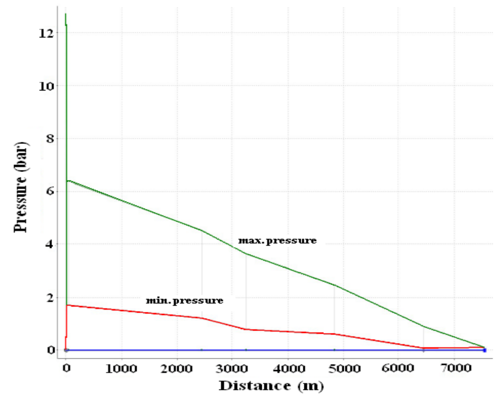

Figure 17: Max & min pressures when two pump running and tripped**-with protection system**

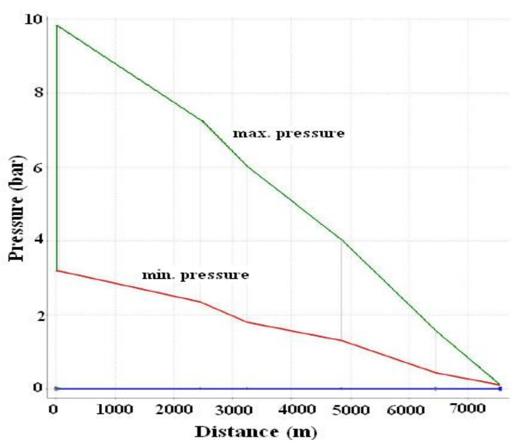

Figure 18: Max & min pressures when all pumps are stopped and get started up-with protection system

التحكم بتأثيرات المطرقة المائية في منظومة أنابيب الماء لمحطة ضخ بدرة رقم 5

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الخلاصة:
استخدم في هذا البحث اسلوب خزان الأندفاع لأخماد تأثيرات المطرقة المائية. تمت الدراسة على مشكلة عملية في خطوط انابيب لمحطة ضخ بدرة رقم 5 والتابعة للشركة العامة لتنفيذ مشاريع الري في العراق. وقد استخدم لهذا الغرض برنامج حاسوبي لتحليل الضغوط العابرة يسمى "Surge2012" للتأكد من الحصول على أفضل تصميم وتحقيق العوامل الهيدروليكية. أوصت الدراسة بالأخذ بالأعتبار النقاط التالية للمحافظة على موجات الضغط الموجبة والسالبة في الأنبوب ضمن قيم مقبولة: نصب خزانين مغلقين بقياس ($2x14m^3$) بجوار محطة الضخ وبحجم هواء 5 م^3 لكل خزان وتكون مجهزة بمنفث ادخال/اخراج بقطر 300 مم.