Water Hammer Phenomenon: Analysis and Solutions

ظاهرة الطرق المائى : التحليل والحلول

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الملخص :
تعتبر المطرقة المائية ظاهرة معقدة يجب التعرف على تأثيرها الضار حتى نجد الحلول المناسبة لمنع هذه الاضرار وتنشأ المطرقة المائية نتيجة التغير المفاجى فى سرعة المياه داخل الأنابيب نتيجة انقطاع المغذى لمحركات الطلمبات فجاة أو القفل المفاجئ للمحابس أثناء التشغيل وينتج عنها ارتفاع وانخفاض مفاجئ فى الضغط وظهور موجة ضغط موجبة وسالبة تتحرك بسرعة الصوت مما يسبب أضرار بالغة مثل (انفجار المواسير – تدمير الطلمبات – تدمير المحابس ....) وتهدف الدارسة إلى تحليل ووضع الحلول لظاهرة الطرق المائى أو منعها عن طريق تركيب أجهزة الحماية مثل(خزانات الفائض – خزانات المياه والهواء – محابس الأمان – محابس الهواء) تناول البحث تطبيق عملى على أحدى منظومات محطات الرى فى مشروع الصالحية الزراعى حوالى ٣٣٥٥١ فدان (محافظة الاسماعيلية) واشتمل العمل على القياسات العملية للتصرفات والضغوط داخل المواسير فى حالة السريان المنتظم وتم تسجيل أعلى ضغط وأقل ضغط على اللوحة الرئيسية للتشغيل عند انقطاع التيار وفى وجود خزان المياه والهواء تم التحليل باستخدام الطريقة النظرية الحسابية (AFT impulse **) للحصول على النتائج التسجيل وأسفرت النتائج إلى أن استخدام أجهزة الحماية مثل خزانات المياه والهواء أو خزانات الفائض تؤدى إلى حماية منظومة الرى من ظاهرة الطرق المائى كذلك كانت من النتائج أهمية وسهولة الطرق الحسابية** CFD **لحل مشاكل الطرق المائى باستخدام برنامج** AFT Impulse **بالمقارنة إلى التحليل النظرى أو العملى تطابقت النتائج العملية والنظرية والحاسبية إلى حد كبير .**

***Abstract*: Water hammer (hydraulic transient) is a complex phenomenon. The cause of a hydraulic transient is the rapid change in the velocity of the flow in a closed pipe due to sudden power failure or sudden valve closure which generates high and low pressure waves transmit through the pipe line with a speed of sound. The generated waves can cause serious problems in the pipeline system such as pipe burst, pumps and valves failure. The aim of the study is to analyze experientially, theoretically and computationally to find out a solution for this phenomenon. This was done through applying some practical methods techniques of water hammer control devices used in irrigation pumping systems. In Salhia Agriculture Project site, Ismailia 33551 feddan were selected to carry out the water hammer investigation. The steady state calculation was first executed to measure the flow rate and the head, unsteady state flow calculation was carried out to identify the maximum and minimum pressure during the sudden pump trips. The results showed that the control devices such as the air vessels or surge tanks would mitigate the pressure rise and prevent the formation of negative pressure. Water hammer analysis using AFT impulse program is an effective and reliable tool to choose the required surge protection device. Installation of surge control device in the system such as one air vessel 50 m3 air volumes provides an acceptable level of protection to the irrigation pumping systems, as there are no cavitations at the pipeline and the maximum pressure reduces from 11 bars to 6 bars. A good a agreement among the experimental, theoretical and computational associated results was found.**

I. INTRODUCTION

Water hammer is a pressure wave that occurs when there is a sudden momentum change of a fluid within an enclosed space. This may occur in pipelines when a valve is closed suddenly or when a pump is failed suddenly. The created pressure wave and the negative wave will propagate through the pipeline.

During the water hammer phenomenon, the high produced pressures can rupture the pipeline and its components, while the low negative pressures can collapse the pipeline, when the low pressure drops below the vapor pressure of the fluid, column separation and cavitations will occur. Several strategies have been developed to control the water hammer within the pipelines such as, changes of diameter, profile within the pipeline systems, reducing the wave speed, applying the optimal operational procedures and installation of control devices such as air vessels, surge tanks, air valves and pressure relief valves.

A comprehensive survey includes experimental, theoretical and computational investigations focusing on the aspects of water hammer control and control devices used in pipeline systems were made.

A. Review of Experimental Investigations

Tan, et al. [1] studied the water hammer effect through pipeline system. They provided that the first to successfully investigate the water hammer problem was the Italian engineer Lorenzo in 1898. They investigated experimentally the parameters affecting the water hammer phenomenon in PVC and steel pipes such as, pipeline diameter, pipeline length, pipeline material and the initial pressure in the pipeline. They concluded the following: Firstly, the larger diameter causes more water hammer effect compared to the small diameter. Secondly, the longer pipes produce more water hammer effect than the short pipes. Thirdly, PVC pipe reduces more water hammer effect than steel pipe. PVC (0.031 Pa), steel (0.021 Pa). Fourthly, higher pressure supply in pipe creates more water hammer effect compared with the smaller pressure supply in pipe. Finally, they concluded that installation of water hammer control devices cannot prevent completely the water hammer effects but it can only reduce its effects.

Weber, W. [2] studied the theory of flow of an incompressible fluid in an elastic pipe. He made some experiments to get the velocity of the pressure wave propagation (a). He deduced this velocity as:

$$a = \sqrt{\frac{K_p}{\rho}} \quad (1)$$

where: Kp , is the elastic modulus of pipe (N/m2), a, is the velocity of pressure wave propagation (m/s), ρ , is the Density(kg/m3).

Joukowsky [3] conducted a series of experiments on Moscow in 1897. Where the pressure change AP in a fluid caused by an instantaneous change in flow velocity AV are calculated by

$$\Delta p = \pm \rho .\ a.\ \Delta V \quad (2)$$

$$\Delta h = \pm \frac{a\Delta V}{g} \quad (3)$$

The positive sign indicates that the water hammer wave propagates in the downstream direction, while the negative sign indicates that the water hammer wave propagates in the upstream direction. The formula Δp is referred to the Joukowsky equation. The relation can be only applied to the period of time in which the velocity change ΔV is taking place. The equation (2) states that the pressure change Δp resulting from a fast closure of valve with time Tc smaller than critical time TCcr given by equation (4)

$$T_c < T_{Ccr} = \frac{2L}{a} \quad (4)$$

Where, Tc, is the valve closure or time for pump trips, TCcr, is the critical time, $\frac{2L}{a}$: is the return time of a water wave to travel from a valve at one end of pipeline to a reservoir at the other end and back to the valve and L : is the pipe length. Therefore, the Joukowsky equation can be used simply as estimator for a pressure surge in pipeline system. Joukowsky produced the best known equations (2) and (3) in transient flow theory water hammer. Polanco et al.[4] defined a water hammer phenomenon as the transformation of kinetic energy into pressure energy, this transformation occurs as the fluid conditions change inside the pipe in a quite short time. This transformation happened due to the closure of valves or stopping of pumping equipment. They provided that water hammer can initiate serious damages on the pipe system and involving leakage of the working fluid to the environment. They explained that water hammer effects can be controlled with focusing efforts on reducing the pressure increment that takes place once the phenomenon is presented. They added that some methods can reduce the time of closure or the rate of change before the closure using special non return valves. Some methods used additional elements to absorb the pressure surge and dissipate energy. Other methods install relief valves to release the pressure and others try to split the problem into smaller sections by installing check valves with dashpot. They studied the phenomenon numerically and experimentally to get the maximum and minimum pressure values at both ends of closed section. They compared the results with experiments. They concluded that the numerical pressure propagation results followed the experimental trends.

Adamkowski, et al. [5] studied experimentally the water hammer concerning the effect of pipeline supports. They introduced that dynamic interaction between the liquid and the structure influenced the transient pipe flow parameters in non-rigid systems. One can expect that due to basic energy conservation the energy outflow from the liquid to elastic structure would result in lowering of water hammer pressures. Experimental results acquired from measurements at special test rig at the institute of fluid flow machinery in Gdansk they concluded that lowering of tested supports stiffness causes high reduction of water hammer pressure oscillation mainly due to the amplitude damping effect. It was also found that lower supports stiffness caused mitigation and faster disappearing of the column separation effect.

B. *Review of Theoretical Investigations*

Parmakian, J. [6] proceeded to define water hammer as a very destructive force exists in any pumping installation, he provided discussion of some practical aspects of water hammer control devices used in pumping plants. He indicated various charts which provided ready water hammer solution for a variety of water hammer control devices. Anton, et al. [7] explained that column separation occurs in a water hammer event when the pressure drops to the vapor pressure at specific location in pipeline system as high points and knees. They mentioned that column separation was presented by Jaeger et al (1965), Wylie and Streater (1967, 1993), De Almeida (1987) and their scope of work included topics on mathematical modeling described by Joukowsky (1900). They indicated that mathematical modeling aims to predict the pressures that occur when large vapor cavity's collapse, predict timing of the events and might to predict the structural response of pipes and supports. Finally, they mentioned that column separation can be avoided by increasing pump inertia using high fly wheel and providing control devices as air vessel and surge tanks.

Sharp, et al. [8] indicated that, the wave velocity is found from the formula

$$a = \sqrt{\frac{1}{\rho\left(\frac{1}{k}+\frac{D}{Ee}\right)}} \quad (5)$$

where: k, is the fluid bulk modulus (N/m^2), E, is the pipe Young's modulus (N/m^2), e, is the pipe wall thickness (m) and D, is the pipe diameter (m). They provided that, the occurrence of a total vacuum, accompanied by the separation of water column leaving a vaporous space, which may have air that come out of solution, the pipe must be able to resist critical pressure by its strength. Bryan's formula for long tubes suggests the critical pressure as:

$$p = 2E \ \ [m^2 / (m^2 - 1)] \ \left(\frac{e}{D}\right)^3 \quad (6)$$

Mosab, et al. [9] provided that various methods of analysis were developed for the problem of transient flow in pipes. The methods ranged from approximate analysis to numerical solutions. They mentioned that the equation which is applicable for a wave propagating to define the change in pressure and the wave velocity by Joukowsky fundamental equation of water hammer, equations (2) and (3), where the wave propagated velocity through the fluid, a, is given by:

$$a = \sqrt{\frac{1}{\rho\left(\frac{1}{k}+\frac{Dc}{Ee}\right)}} \quad (7)$$

where c: constant which depends on the axial movement of the anchored pipe. In practical calculations c = 1. They provided that the full elastic water hammers equations (mass conservation and momentum conservation) by (Wylie and Streeter 1993)

$$\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial X}=0 \quad (8)$$

$$\frac{\partial Q}{\partial t}+gA\,\frac{\partial H}{\partial X}+\frac{fQ|Q|}{2DA}=0 \quad (9)$$

where, H: pressure head (m), Q: discharge flow (m3/s), |Q|: absolute value since the flow change direction during transient and f: pipe friction coefficient. They showed that one has to solve these equations for a wide variety of boundary conditions. However, the full elastic water hammer equations cannot be solved analytically except by some approximate methods.

Wuyi, et al. [10] provided that surge tank is common pressure control device for long pressurized pipeline. Three parameters are greatly affected to ensure safe operation: surge tank location, cross area of surge tank, connector area between the surge tank and main pipeline. In order to improve performance of water hammer protection, a kind of smart self- controlled surge tank is used, which can adjust the mentioned parameters to be suitable for different condition. They concluded that smart surge tank maintains a suitable discharge capacity due to the transient pressure condition in the system.

Mohamed et al. [11] studied the Fluid Structure Interaction (FSI) phenomenon. They described the complete cycle of pressure wave resulting from water hammer wave due to sudden valve closure. Figure 1 shows pressure head and wave velocity following sudden valve closure. They mentioned that the most important parameters which should be considered are firstly Poisson coupling, where fluid pressure waves cause elastic radial deformations (expansion, contraction) in the pipe wall which induce an axial stress wave in the wall. They added that the wave propagates along the wall with sonic velocity and produces a secondary fluid pressure wave. Secondly, friction coupling: where this effect accounts for the mutual friction between fluid and wall. Thirdly, junction coupling: where this effect is caused by pressure difference between specific points of the pipe system such as bends, tees and valves or pipe end. They mentioned that the plastic materials such as (PVC, PE and PP) can be used to reduce water hammer effects.

Bruce, et al. [12] described that surge relief valves open when the pressure exceeded the allowable pressure. The surge relief valve is generally located adjacent to the device that expected to cause the high pressure. They informed that large pipelines can be fitted with small surge relief valves because these valves can tolerate extremely high velocities for a short time period. The result will lead to water hammer control.

Meagher [13] developed an effective means of controlling and preventing the pressure spike as shown in Fig.2, which causes water hammer by using the water hammer arresters as shown in Fig. 3.

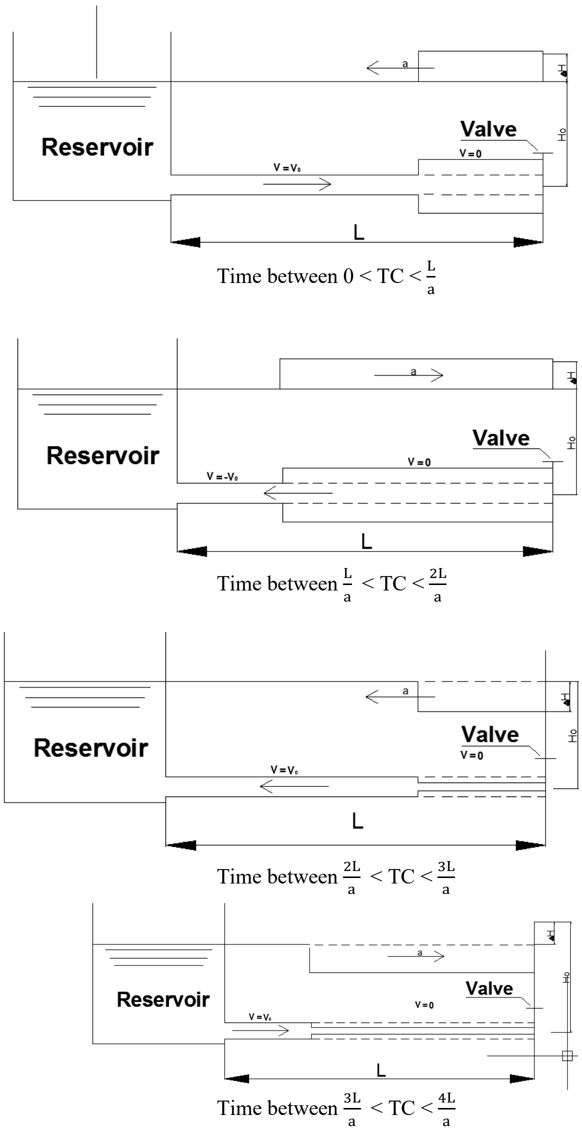


Figure 1. Pressure head and wave velocity following sudden valve closure [3].

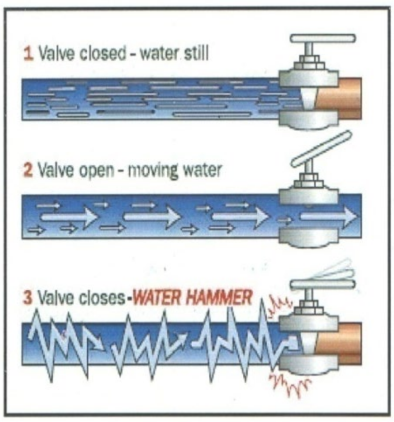
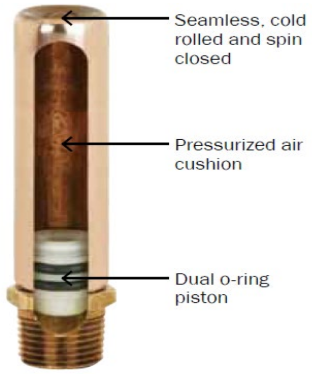


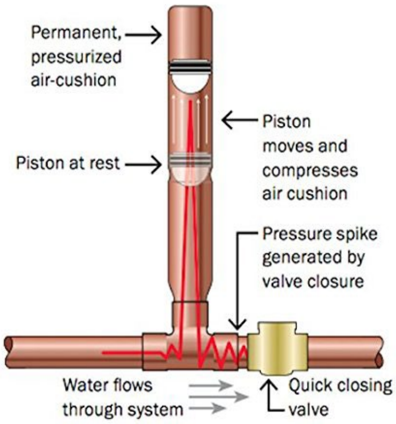
Figure 2. Water hammer description [13]

Figure 3.a shows the water hammer arrester section, while Fig.3.b describes the installation of water hammer arrester. The water hammer arrester has sufficient volume of air to dissipate the kinetic energy generated in the pipe system;

such arrester can be effective when installed at any angle. Meagher mentioned that the arrester produced with wide sizes (1.4 - 36cu in) according to the case required.



a. Section schematic



b. Installation schematic

Figure 3. Water hammers arrester [13].

The researchers at the pump manufacturing company Ksb, Germany [14], analyzed water hammer in pipe system as: a complex Phenomenon, where basic knowledge must be impaired without simplifying them. They concluded that the system designer and surge analyst have to be work closely to save time and money. Ksb researchers discuss the problem of water hammer in pipeline systems and provided that designers must start by determining the steady state operating pressures and volume rates of flow, Figure 4 shows a typical steady flow profile.

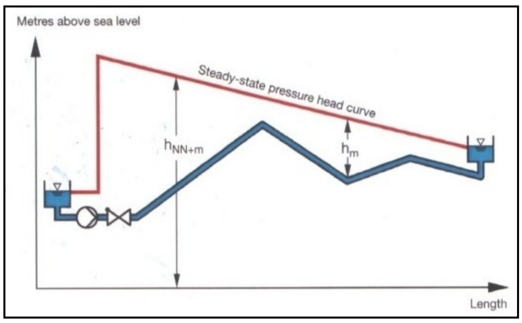


Figure 4. Steady –state pressure head curve of a pumping system [14]

They added that a pumping system can never be operated in steady state condition all the time, but the flow condition of this kind is commonly referred to unsteady flow or transient. They studied the photos taken of some accidents Fig. 5. They concluded that the damage caused by water hammer by far exceeds the cost of preventive analysis and surge control measures. They advised to solve problem of pressure transients following pump trip, an air vessel and non-return valve must be added to the pipeline system, Fig.6. As result maximum and minimum pressure will be within the permissible limit.

DN600 /12mm Destroyed | Support Destroyed | DN800 check valve destroyed

Figure 5. Damages caused by water hammer.

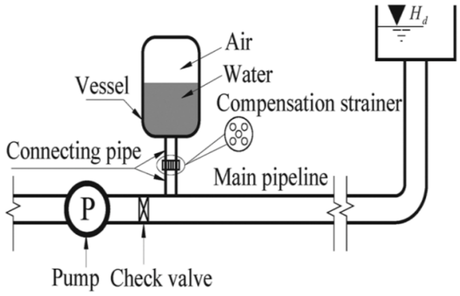


Figure 6. Pipeline system with air vessel [14].

Bassiouny, M. K.[15] provided that when water is flowing through a pipeline with certain velocity of flow ,and if the flow of water is suddenly brought to rest by closing a valve. This will generate a high pressure wave to be transmitted in whole length of the pipe which creates noise known as "water hammer". He introduced the pressure rise for gradual closing as:

$$\Delta h = \frac{\Delta P}{\gamma} = \frac{LV}{g\,Tc} \qquad (10)$$

where Δh: is the pressure head rise (m), ΔP: is the Pressure rise (N/m^2), γ :is the Specific weight of flowing fluid (N/m^3). And for sudden closure of valves:

$$\Delta p = V\sqrt{\frac{\rho}{\frac{1}{k}+\frac{D}{Ee}}} \qquad (11)$$

Crowley, M. [16] induced the maximum pressure rise due to water hammer by the same equation given by Joukwsky ($\Delta P = \rho.\ a.\Delta V$). He introduced the wave velocity (a) propagated in fluid as:

For rigid pipes where E = ∞ and compressible fluid

$$a = \sqrt{\frac{k}{\rho}} \qquad (12)$$

- For elastic pipes and compressible fluid, the wave velocity a is given by equation (5)

Blacoh, com. researchers [17] explained that the phenomenon of water hammer as uncontrolled hydraulic shock that occurs when there is rapid velocity change for fluid within an enclosed conduit. They compared between the sound wave propagated velocity in air and the wave propagated velocity in water, as in air equal 340m/s, but in water 1500 m/s. They introduced equation for pressure increase due to rapid change in velocity as:

$$P = 60\,\frac{V\gamma}{T_c} \qquad (13)$$

where p: pressure increase (psi), V : fluid velocity (ft/s), γ : specific gravity, T_c: time for valve close (s). They explained that the propagated wave will deal with plastic valve, plastic pipe, and gauges. The pressure wave will either break the system or dissipated in friction. They advised to control the rapid fluid velocity change (surge effect) by control valve closing time, slow liquid velocity 1.5m/s, use gate valve types, use strong pipes, use relief valves and surge tanks. These means will result in controlling the effect of hydraulic shock. They discussed the rapid pump start up and rapid pump shut down and advised controlling start / stop hammering by

- Slow start / stop (pump motor controller)
- Vacuum breaker valves added to the systems
- Slowly opening slowly closing valve at pump discharge
- Add surge tank

The use of these means will result in controlling the effect of hydraulic shock and prevent columns separation. They explained proper location for air valves, vacuum breaker and surge tank in case of high/low points in pipeline profile. They brief a review for water hammer as:

- Water hammer is acoustic pressure transient or wave.
- Water hammer can occur whenever fluid velocity changes rapidly.
- Sound wave travel in water at 1500m/s.
- Keep the flow velocity about 1.5 m/s.

C. *Review of CFD Investigations*

Kim, H. S. [18] has modeled the surge protection devices, such as surge tanks and air chambers using the impulse response method for transient analysis of water distribution systems. A modification is proposed so that transition between turbulent and laminar flows can be considered. The results of applying impulse response method in pipeline system had obtained a good agreement with respect to pressure and discharge variation.

The Fluid Hammer Consultancy Services Company, Ky pipe [19], concluded that the transient (surge) protection and analysis is essential for hydraulic distribution system. They introduced that transient analysis software is the state-of-the-art. Surge provides an advanced graphical interface and allows an easy transition between steady state and transient flow modeling. They offered software packages which include wave characteristic method, unique devices & elements, node & pipe emphasis, operational control setting, pipe profiling software, EAP (Employee Assistance Program) surge, pump station modeling, internet maps and data exchange. These software packages can grantee an integrated surge analysis that results to the water hammer solutions.

Izquierdo, et al [20] provided that it is a very well-known fact that calculations necessary to analyze transient conditions in hydraulic system are very difficult to organize. They mentioned that modeling the complex system can be generalized as a simple system. The analysis technique is based on the method of characteristics (MOC) used to solve numerically the elastic model known as water hammer. This model considers one-dimensional flow and is based on the continuity and momentum equations describing the general behavior of fluids in a closed duct in terms of two variables namely H, piezometric head and V, fluid velocity. They concluded that a mathematical model used to develop a computer program is able to simulate hydraulic transient in complex systems, and solve transient problems.

Applied Flow Technology AFT, [21] is a powerful fluid dynamic simulation tool used to calculate pressure transients in piping systems caused by water hammer. The company developed software "Impulse" to simulate and solve the water hammer phenomenon. AFT software is particularly useful for:

- Ensuring that pressure extremes are within design allowable
- Sizing and locating surge suppression equipment
- Determining imbalanced pipe forces and sizing structural supports
- Troubleshooting of existing systems to determine the cause of operational problems
- Evaluating the effect of pressure surge due to vapor cavity collapse.

Applied Flow Technology modeling is described by three equations representing continuity; momentum and energy, through AFT using MOC (Method Of Characteristics). They discussed AFT "Impulse" without any protection and with protection devices.

They concluded that AFT is cost effective and time reduction for testing and evaluating of fluid flow design stage for pipeline systems. Liquid Dynamic Company LDi. USA. [22] Investigated water hammer by CFD and theoretically. They introduced that shock waves are created in a pipe full of liquid when either a valve is closed too quickly, which forcing the liquid column to stop moving more quickly than it wants to, or when a pump is started up too quickly, which forcing the liquid column to start moving more quickly than it wants to. In either situation, the shock wave travels up and down the pipe through the liquid banging against each of the pipe. They provided that banging can be heard as water hammer. They added that in industry, the pipes can be very large, and water hammer may not just be heard as a bang, it can cause a great deal of damage, even rupturing pipes. LDi advised a range of hardware to prevent water hammer and advised a range of complete software to analyze water hammer and to recommend system modifications which remove the shock.

Abuiziah, et al. [23] introduced and used several methods to analyze water hammer problem like the energy, arithmetic, graphical, characteristics, algebraic, implicit and linear analysis. Euler and Lagrangian based method. They provided that the characteristics method converts the two partial differential equations of motion and continuity into four total differential equations. They provided an acceptable level of protection against system failure due to pipe collapse or bursting, and concluded that CFD with hydraulic transient analysis is an effective and reliable tool to determine the needs for protection systems against transient surges.

Lohrasbi, et al. [24] defined and investigated theoretically and CFD the water hammer problems as rapid changes in the velocity of fluid in closed conduits generate large pressure, which are transmitted through the system with the speed c sound. They provided that most water hammer analysi involves computer solution by the method of characteristics They added that for preventing water hammer defects it i recommended that valves should be open and close slowly Using the method of characteristics to model th phenomenon, it will lead to see the effect of water hamme by getting the function and draw a graphical output an derive equations of all points which will be calculated b characteristics method.

Lahane, et al. [25] said that water hammer phenomeno cannot be eliminated but can be reduced by using differer protection devices. They provided that the pipeline system can be modeled using GAMBIT software. They concluded that simulation will help the designers to have good understanding of water hammer phenomenon and work on the ways to reduce the surge, CFD tools will reduce cost and time consumption required to analyze the effect of surge than practical methods systems.

Kim, T.O.et al. [26] conducted transient analysis by CFD. They concluded that it is possible to reduce the effects of the water hammer pulses with an air chamber, surge tanks; surge relief valve. Among them, surge relief valve is more useful than others to reduce water hammering.

Mohamed et.al [27] explained that water hammer models are becoming wildly used for the design, analysis and safe operation of pipeline systems and protective devices. The application of digital computing techniques has resulted in a rapid increase in the range and complexity of problem being studied.

D. Scope and Purpose of Investigation

The aims of the analysis study are either to mitigate the pressure rise or to prevent negative pressures. The following questions will be tried to answer in this investigation.

- How can be known whether there is a risk of water hammer or not.
- How significant are approximation formula for calculating water hammer?
- How reliable is the available surge control equipment and how much does it cost to be installed?
- How reliable is the available CFD software packages?

II. Water Hammer Investigation (Case Study)

A. Case Study

Salhia irrigation project (station 3) at Ismailia Governorate Egypt was selected to carry out detailed the water hammer investigation. The field work has been used to measure the flow and the head during steady state condition and measure the maximum and minimum pressure during sudden pump trips when using an air vessel to control the surge events. The results have been compared with the AFT and the analytical results. The system consists of the upstream reservoir, irrigation pumping plant, pipeline arranged with air vessel and downstream reservoir. As shown in Fig .7 . a photo for the pipeline system is shown in Fig.8.

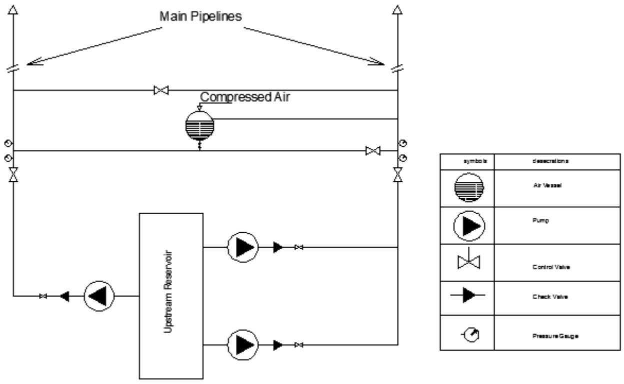


Figure 7. Layout pumping installation pipelines.

Figure 8. Irrigation pump plant photo.

A summary of the pumping plant specification data is listed in Table 1. The performance data of each pump is listed in Table 2. Figure 9 shows a photo for the irrigation pump plant, while Figure 10 shows a photo for the main operating panel.

TABLE 1
PUMPING PLANT SPECIFICATION SUMMARY

Manufacture	Peerless pump USA
Type	32 HXB- 2 stage, vertical
Number of pumps	(2 duty +1 standby) parallel connection
Duty Discharge	3600 m^3/h each
Duty Head	68m
Speed	985 RPM
Power	1000kW
Volt	11kV

TABLE 2
PUMP PERFORMANCE

Pump 32 HXB- 2 stage 985 RPM

Q L/S	H m	η %	P kW
842.2	73.8	0.78	781.5
926.4	73.2	0.82	811.7
1010.6	67.8	0.84	800.4
1094.8	63.7	0.83	824.9
1179	58.3	0.8	743.2
1263.3	50.2	0.78	797.3
1347.5	40.7	0.7	768.4

Figure 9. Irrigation pump plant photo.

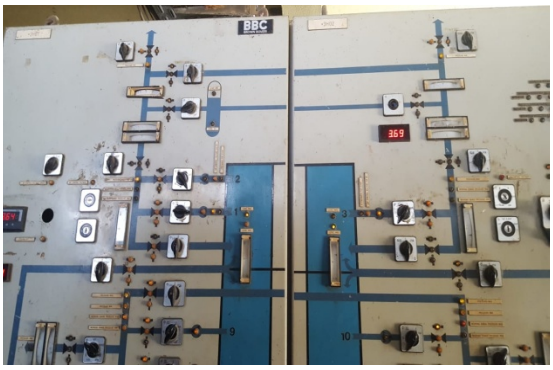


Figure 10. Main pumps operating panel photo.

The discharge pipeline data are listed in Table 3. The air vessel specifications are listed in Table 4. Fig 11 shows the air vessel equipped with discharge pipeline

TABLE 3
DISCHARGE PIPELINES DATA

Length , m	4600
ND diameter , mm	1000
Material	Steel and GRP PN10

TABLE 4
AIR VESSEL SPECIFICATIONS

Type	Horizontal
Air vessel diameter, m	3.5
Air vessel length, m	15
Air volume, m^3	50
Water air rated	2:1
Operating pressure, bar	4.50

Figure 11. Air vessel.

B. Instruments

The specifications of used instruments to carry out the water hammer field work are provided. They include the flow meter, thickness gauge, pressure meter devices.

a) The ultra-sonic flow meter

One of the basic steps in the field work is to measure the steady-state flow rate before transient event is generated using the ultra-sonic flow meter. The used flow meter model is ultra-sonic FUP1010 and accuracy from ± 0.5% 2% of flow rate, manufacture by Siemens with pair transducers.

b) The thickness gauge

The thickness gauge is used to measure the pipe wall thickness. The used thickness gauge model is AS-0209 manufacture by Siemens and has measuring range between 3mm and 30 mm.

c) The pressure meter devices

Two types are used to measure the pressure during steady-state flow and during transient state flow. One pressure gauge is sent signal to the main panel through pressure transducer to indicate pipeline pressure (steady and transient). The other one is a direct pressure gauge indicates the pressure reading. Figures 12, 13 show pressure gauges up to 10 bars.

Figure 12. Main panel with pressure gauge indicator.

Figure 13. Main pipeline with pressure gauge.

C. Measuring procedure

The discharge flow rates together and pump plant pressure are monitored during steady state operation. The following steps are done during water hammer investigation with an air vessel as surge protection means. Stop the pump suddenly then monitor and record the maximum and the minimum pressures from the main panel, in the same time pressure indicator device on the pipeline will record the gauged pressure.

Discharge measuring steady- state scenario

Results of discharge measurement are listed in Table 5 using the ultra-sonic flow meter.

Pump	Q m^3/s	Pressure bar
Pump 1	1.081	3.7
Pump 2	1.041	4.1
Pump 3	0.932	3.7

Transient scenario practical measuring

Transient scenario with air vessel protection device. Results are listed in Table 6.

TABLE 6
TRANSIENT WITH AIR VESSEL PRACTICAL MEASURING

case	P steady bar	P max bar	P min bar
Operating two pump Protected	4.50	5.50	2.90
Operating one pump Protected	4.20	4.60	2.10

D. Analytical investigation of water hammer 2.5.1 Head losses h_f

Head losses are calculated using Hazzen - William equation

$$h_f = 10.675 \left(\frac{Q}{C}\right)^{1.85} \frac{L}{D4.87}$$

Wave speed calculation and pipeline water flow velocity

The wave speed calculated using by equation (5) using the data: ρ : 1000 kg/m^3, E steel pipe: 120×10^9 Pa, K for water: 2.19×10^9 Pa and E GRP pipe: 12.5×10^9 Pa. As result a wave speed for steel = 877 m/s and a wave speed for GRP= 385 m/s. Pipeline velocity: One pump operating V_o = 0.64 m/s, two pumps operating V_o = 1.27 m/s Equation (2) is used to calculate the pressure change due to water hammer effect. Then the maximum and minimum pressure in the pipeline is calculated as:

$$P_{max} = P_o + \Delta P \text{ and } P_{min} = P_o - \Delta P$$

E. CFD water hammer analysis

Transient scenario using AFT impulse program without control device with two pumps & one pump operated are done Results are listed in Tables 7&8, respectively.

TABLE 7
AFT TRANSIENT WITHOUT CONTROL DEVICE (TWO PUMPS)

case	P steady bar	P max bar	P min bar	Vapor volume m^3
Non protected	4.55	11	-1	0.0149

TABLE 8
AFT TRANSIENT WITHOUT CONTROL DEVICE (ONE PUMP)

case	P steady bar	P max bar	P min bar	Vapor volume m^3
Non protected	4.15	9.60	-0.9969	0.0038

Transient scenario with air vessel protection Results are listed in Tables 9&10, respectively.

TABLE 9
AFT TRANSIENT WITH AIR VESSEL (TWO PUMPS)

case	P steady bar	P max bar	P min bar	Vapor volume m^3
protected	4.55	6	0.05	zero

TABLE 10
AFT TRANSIENT WITH AIR VESSEL (ONE PUMP)

case	P steady bar	P max bar	P min bar	Vapor volume m^3
protected	4.15	4.90	0.05	zero

F. Results and evaluation

Comparison of the practical, AFT impulse and analytical results is listed in Table 11.

TABLE 11
COMPARISON OF RESULTS

Case	Practical	AFT impulse	analytical	
			Steel pipe	GRP pipe
One pump with flow rate 1800 m^3/h				
P_o bar	4.20	4.15	4.20	4.20
Pump trip				
P_{max} bar without control	-	10	9.8	6.7
P_{mm} bar without control	-	-0.9969	-1.4	1.7
Control with air vessel				
P_{max} bar With control	4.60	4.90	-	-
P_{min} bar With control	2.10	+ 0.05	-	-
Two pumps with flow rate 3600 m3/h				
P_o bar	4.50	4.55	4.50	4.50
Pump trip				
P_{max} bar without control	-	11	15.3	9.4
P_{min} bar without control	-	-1	-6.5	-0.4
Control with air vessel				
P_{max}, bar With control	5.50	6	-	-
P_{min} bar With control	2.90	0.05	-	-

1- There is slightly difference in results obtained by practical, AFT and analytical for the steady state.

2- Results of (AFT and analytical) for transient without control device provided an occurrence of maximum and minimum pressures exceeded pipe strength which would lead to pipeline burst and collapse.

3- AFT and practical results for transient with air vessel control is nearly the same and the excessive pressure is prevented and don't exceeded pipe strength.

III. Practical ASPECTS of water hammer in irrigation water pipeline systems

A. Water Hammer

Any change of water flow velocity in a pipeline causes pressure fluctuation, water hammers or surge. Surge can produce large pressure forces and rapid fluid acceleration into the pipeline. The disturbances may result in: Pipe ruptures, column separation and device failure.

B. The Major Events That Cause Water Hammer in Irrigation Water Pipeline System

Pump shutdown or startup, valve closing or opening, changes in boundary pressure (water level at reservoirs, pressure changes in tanks...), rapid change in demand conditions, pipe filling or draining where air enters or release (into/from) pipes and check valve actions.

C. Technical Means for Water Hammer Reduction or Elimination

- Moderate and smooth profile pipeline. -Selection of pipeline material and fittings to with stand the anticipated pressure.
- Proper start-up, operation and shut-down procedure for the system.
- Lower fluid flow velocity, maximum 1.5 m/s.
- High pressure rating for pipeline.
- Smooth control valve closing or opening.
- Discharge piping with good practice installation of check valve, where both a check valve and gate valve are installed in the discharge line. To reduce water hammer effect, the check valve is placed between the pump and the gate valve and protects the pump from reverse flow either due to pump trip or reverse flow from another operating pump.
- Moderate value for pressure wave velocity.
- Closure Time T_c about 90 s.
- Selection and location of the proper control devices to alleviate the effects of transient, Fig 14.
- Two stages air valve includes close valve, Fig 15.
- Pressure relief valve is more useful than other to reduce water hammering, Fig 16.

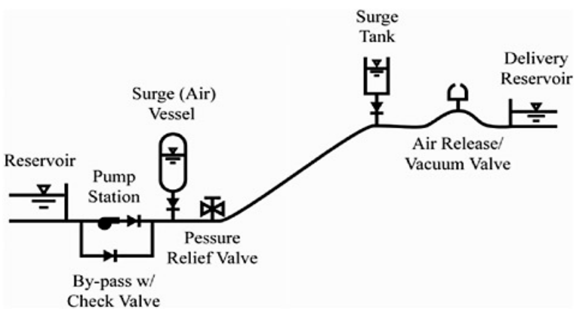


Figure 14. Typical locations for some water hammer control device.

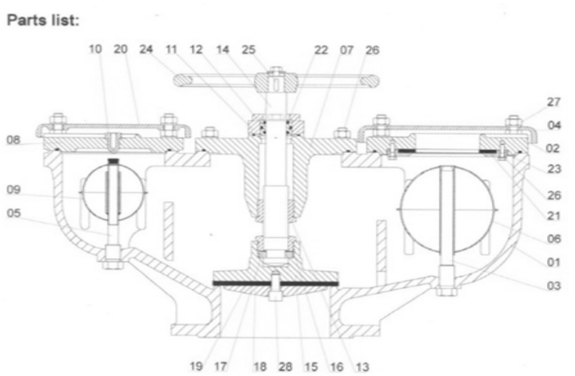


Figure 15. Two stage air valve [27].

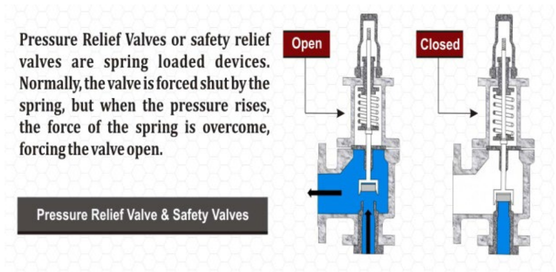


Figure16. Relief valve.

D. Water Hammer Control Devices Charts

Three principals for mitigation water hammer are:

- Pipeline profile & diameter. Pump and valve control procedures Design and installation of surge control devices.
- Water hammer control devices chart can be adopted concerning several criteria and to determine which surge devices are to be used.

Tables 12a, 12b and 12c represents the water hammer control devices charts which can be used in irrigation pipeline systems. Such chart summarizes some characteristic parameters of several water hammer control devices such as: protection aspects, pipeline system characteristic, and principle of operation, application, reliability, and required auxiliary equipment, operating problems, maintenance and cost.

IV. Solutions of Practical Problems of Water Hammer (Ismailia Projects)

Table 13 shows the problems and solutions for water hammer in the irrigation pipeline system.

V. CONCLUSIONS

Transient can introduce large pressure force into pipeline system. The undesirable water hammer effects may disturb overall operation of the system and damage components of the system, as pipe rupture. To mitigate water hammer effect three principals are must

- Alteration of pipeline properties such as profile and diameter.
- Implementation of improved valve with closure time control and pump control procedures.
- Design and installation of surge control devices. Simple calculations using joukowsky equation can predict and describe the water hammer effect.

Water hammer analysis using AFT is an effective and reliable tool to determine the required surge protection. AFT can be analyzed accurately and efficiently in large distance water pipeline system. AFT is the most widely used and trusted hydraulic modeling software on market today. Installation of surge control devices in the system as surge tank, air vessel, air valve and a pump by pass system, can provide an acceptable level of protection against system failure due to pipe collapse or bursting. Water hammer control devices chart can help to determine which surge devices are to be used.

TABLE 12a
DEVICES TO PROTECT HIGH PRESSURE AND COLUMN SEPARATION

Device	arresters	Open - end Surge tank	Air vessel	Controlled pump operation	bypass	Additional inertia
Protection aspects	Noise &vibrate	High pressure and column separation	High pressure and column separation	High pressure and Column separation	High pressure and Column separation	High pressure and Column separation
Pipeline system & effectiveness	small pipeline system	Long &very low head system	Long pipelines &medium to high system	Moderate head system	Low head system long suction line	Moderate pipeline
Principle of operation	Energy accumulator	Energy accumulator	Energy accumulator	Regulate starting and shut-off control	Maintains flow by relieving return flow	Keep flow state of motion to certain time
application	sometimes	sometimes	Very often	sometimes	sometimes	sometimes
reliability	good	excellent	good	excellent	poor	excellent
Auxiliary equipment	none	none	compressor	Soft starter &VSD	In line valve	Larger electric motors
operating problem	none	Check water level	Check air pressure	none	Check in line valve	none
maintenance	low	high	high	low	low	parts
cost	low	high	Very high	moderate	low	low

TABLE 12b
DEVICES TO PROTECT HIGH PRESSURE AND COLUMN SEPARATION

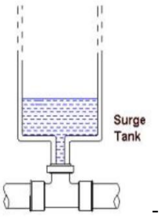
Device	Pressure relief valve	Controlled valve closure	Rupture disk
Protection aspects	High pressure	High pressure	Very high pressure
Pipeline system & effectiveness	High head systems	Long pipelines with high points	High head systems
Principle of operation	Reliefs pressure	Regulates discharge	Reliefs pressure
application	sometimes	often	sometimes
reliability	poor	moderate	excellent
Auxiliary equipment	Regular maintenance	Hydraulic control system	Water storage
operating problem	none	Check hyd. Control system	Replace rupture disc
maintenance	low	low	Repair
cost	moderate	high	low

TABLE 12c
DEVICES TO PROTECT HIGH PRESSURE AND COLUMN SEPARATION

Device	one way surge tank	Air valve
Protection aspects	Column separation	Column separation
Pipeline system &effectiveness	Long pipe with high points	Long pipelines with high points
Principle of operation	Provides flow	Air admission and air release
application	sometimes	often
reliability	moderate	poor
Auxiliary equipment	Check water level	none
operating problem	Refilling of tank	Remove air from pipeline
maintenance	high	low
cost	moderate	low

TABLE 13
PRACTICAL PROBLEMS AND THEIR SOLUTIONS FOR WATER HAMMER IN THE IRRIGATION PIPELINE SYSTEMS

No	Site	Problems	Solutions	Protection devices
1	Ismailia Sarabuim	3 "Vacuum breaker air valve installed at discharge pipeline but an air pockets not alleviated completely	It is important that any air enters the pipeline is expelled safely and the line is re-primed safely before full pumping restarts to prevent surge. Sizing the protection devices is must, so: Installed 2X3" air valve instead of one air valve to prevent negative pressure.	Air vacuum breaker valve
2	Ismailia Abo Sultan Fayed	High pressure water hammer caused pipeline rupture at point of two stage air valve installing	The effect of air valve in long distance water pipelines are: Firstly in the water filled stage. Secondly at the normal working stage. Finally during pump failure.	Two stage air valve

			- Check two stage air valve - Hand wheel in close position - Put the valve hand wheel in operation. Fig. 15	
3	Ismailia Fayed	- High-water hammer pressure ruptured a pipeline, although pressure - relief valve was installed pressure -relief valve not affected with the pressure rise, maximum pressure > pipeline strength	- Check pressure relief valve setting point -Pressure-relief returned to be in operation to protect the pipeline systems Fig 16.	Relief valve
4	Ismailia El-Salhia (satiation 1)	Large pumping system with pipelines around 8km long and 1500 mm diameter, discharge 4m^3 /s , concrete pre-stressed pipeline, protection devices (air vessel & surge tank) installed to control effects due to excessive and low pressure occurs in the system. High and low pressure wave surge ruptured the pipelines many times after pump trips	It is necessary to start Up and shutdown flow more slowly Air vessel to be checked and adjust water to air ratio Maintain surge tank Suggest to replace the pipeline by (GRP, P.E or PVC) pipes this can tolerate (-0.5 bar gauge) the results excellent controlled positive and negative surge Fig. 11 Where the used solution of surge tank and air vessel are shown in Fig. 17.	- Air vessel  - Surge Tank Figure 17. Salhia project-Ismailia pipeline systems with surge tank

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Nomenciature

Symbol	Description
A	Pipe cross sectional area, m^2
A_t	Tank cross sectional area, m^2
a	Wave speed, m/s
D , D_i	Pipe internal diameter, m
D_e	Outlet diameter of air vessel, m^2
ND	Pipe outer diameter, m
E	Modules of elasticity, Pa
e	Pipe wall thickness, m
F	Force, N
f	Friction coefficient
g	Gravitational acceleration, m/s^2
H	Pressure head, m
Ho	Initial pressure head, m
ΔH, Δh	Change in pressure head , m
H_f, h_f	Head loses , m
H_{max},h_{max}	Maximum head, m
i	Interest rate %
H_{min}, h_{min}	Minimum head, m
K	Fluid bulk modules, Pa

L	Pipe length, m
n	Life time, year
P	Power, kW
p	Pressure, Pa
p_{max}	Maximum pressure, Pa
p_{min}	Minimum pressure, Pa
P_{steady}	Initial pressure, Pa
ΔP	Pressure change, Pa
ΔP_{jou}	Joukwsky pressure change, Pa
Q	Discharge flow rate, m^3/s
$\vert Q \vert$	Discharge absolute valve, m^3 /s
S	Surge tank maximum elevation, m
Tc	Valve closure time or pumps trip time,s
T_{Ccr}	Critical time, s
T, t	Time, s
V	Pipe velocity, m/s

Symbol	**Description**
~~V_o~~	Air volume, m^3
~~V_w~~	Water volume that air vessel forces into pipeline, m^3
V_o	Initial pipe velocity, m/s
ΔV	Velocity change, m/s
X	Axial distance, m
Z	Elevation, m

Greek Symbol

Symbol	**Description**
Δ	Difference
∂	Partial change in value
γ	Specific weight, Pa
ρ	Fluid density, kg/m^3
$\varepsilon, \frac{1}{m}$	Poisons ratio
ϕ	Energy cost EGP/ Kwh
η	Pump efficiency %
τ	Daily working house, h
σ	Annual working days, day/year

Abbreviations

AFT	Applied Flow Technology
CFD	Computational Fluid Dynamics
CRF	Capital Recovery Factor
FSI	Fluid Structure Interaction
GRP	Glass Reformed Polyester
MOC	Method Of Characteristics
PE	Poly Ethylene
PN	Pipe Class, Pipe Strength bar
PP	Poly Propylene
PVC	Poly Vinyl Chloride
PWF	Present Worth Factor