Optimization of Irrigation Pipelines Design for Minimizing the Effects of Water Hammer Phenomenon

أمثلة تصميم شبكات الرى مع تقليل تأثيرات الطرق المائى

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الملخص :
تنشأ المطرقة المائية التغير المفاجئ فى سرعة المياه بسبب الإيقاف والتشغيل للطلمبات بأنقطاع التيار وعودته فجأة أو القفل والفتح السريع للمحابس على خطوط الرى نتيجة لذلك يحدث ارتفاع وأنخفاض مفاجئ للضغط داخل المواسير يتسبب فى أنفجار المواسير وتحطيم المحابس والطلمبات ولتلافى الإضرار بسبب هذه الظاهرة يتطلب التحكم فى طريقة التشغيل والإيقاف للطلمبات والتحكم فى طريقة القفل والفتح للمحابس على الخطوط وكذلك يتم إضافة أجهزة الحماية لتقليل تأثيرات الطرق المائى مثل خزانات المياة والهواء – خزانات الفائض – محابس الهواء – محابس الأمان – محابس التحكم ويهدف البحث إلى : دراسة وتحليل ظاهرة الطرق المائى لمنظومة رى عند انقطاع التيار فجاة ولا توجد أجهزة حماية لخط مياه FVC , FN4 طوله ٢٠٠٠ متر للاقطار من ٤٥٠ مم – ٨٠٠ مم مع تصرفات من ١٢٠٠ – ١٨٠٠ م٣ / س وفرق منسوب ٤٠ متر ثم لخط مياه FVC , FN6 ولخط مياه FVC , FN10 بنفس البيانات وتم حساب الضغط فى حالة السريان المنتظم ثم استخدمت الطريقة النظرية باستخدام معادلة JOUKWSKY لحساب أقصى ضغط موجب وأقل ضغط سالب فى حالة حدوث الظاهرة ومقارنته بقوة تحمل المواسير PN واحتياجها إلى أجهزة الحماية و كذلك اشتمل البحث على تصميم خط مياه PVC ٦ بار PN6 بطول ٢٠٠٠ وفرق منسوب ٤٠ م مع تصرف ١٢٠٠ م٣ / س واستخدام التحليل الحسابى CFD (AFT IMPULSE) والنظرى لايجاد أقصى ضغط موجب وأقل ضغط سالب عند انقطاع التيار واختيار أجهزة الحماية اللازمة . ونتيجة الدراسة الفنية الأقتصادية القطر الأمثل ٥٦٠ مم باستخدام أجهزة الحماية (خزانات الهواء والمياه أو خزانات الفائض) ثم التحكم فى أقصى ضغط موجب بحيث اصبح أقل من أقصى ضغط مسموح به والتحكم فى أقل ضغط سالب لتلافى ظاهرة التكهف .

***Abstract*: The rapid change in velocity of a fluid in a closed pipeline system can generate large pressure waves of large amplitudes which can propagates through the system with the speed of sound. This is called the water hammer phenomenon which causes the additional pressure in the pipeline system which may cause rupture of pipes and damage of pumps and valves. It creates also a reduction in pressure values which can argument the separation or the cavitations effects. This research aims to study and analyze this phenomenon during sudden power failure, pump trips without control devices the attached to PVC pipeline systems of pressure classes PN4, 2000m length with diameters 450,500,560,630,710 and 800mm and flow rates 1200,1350,1500,1650 and 1800 m3/h with elevation differences of 40m. The analysis will be done for the same pipeline data with PN6 and PN10. The steady state pressures were obtained and Joukowsky equation used to calculate the maximum and the minimum pressure, the results were compared with the permissible pressure classes for the pipeline PN4, PN6 and PN10, then the dissection for the need of control devices will be taken. This research provided complete design for PVC pipeline PN6. The pipeline length is 2000m, elevation difference of 40m and discharge 1200m3/h. Theoretical and CFD (AFT impulse) analysis provides to determine the values of transient pressure during power failure. Design criteria for system equipment and control devices such as (air vessel, surge tank...), at an adequate economical analysis had been done to estimate the optimum diameter that ensures a minimum total cost. A result led to 560 mm was found as the optimum diameter. The analysis shows that installing of air vessel or surge tank is must this can be mitigated the high pressure to be less than 6 bars and controlled the magnitude of the negative pressure to safe limits can be changed to positive pressure.**

I. INTRODUCTION

Ksb, [1] defined the water hammer as a pressure surge or wave caused when a fluid in motion is forced to stop or to change direction suddenly. The pressure changes during a transient period are often very large and occur very rapidly (within a few second). If the maximum pressure exceeds the pressure rating (mechanical strength) of the pipe then pipe will rupture. Also, when the minimum pressure drops below the vapor pressure of fluid, cavitations will occur then the pipe will collapse. If the mass inertia causes the fluid flow on the downstream side of the pump to collapse into separate columns, a cavity containing a mixture of water vapor and air coining out of solution will be formed. Figure 1 shows cavitations following the pump trip, as the separate liquid columns subsequently moves backward and recombine with a hammer like impact.

Bruce, [2] explained that systems in which static lift is large and pipeline profile rises rapidly immediately down of the pumps can be subjected to the most sever transients upon power failure. If the power is cut off from the pumps suddenly, the pressure just downstream of the pumps drops rapidly, and this pressure drop propagates downstream at the wave speed as shown in Fig. 2. This depression can easily reach the vapor pressure and then create cavitations in the pipe. It is necessary to equip the air valves in the piping system to prevent the gas liquid transient flow.

Wu, Xu, and wang [3] defined the operating principle of air valve in three areas: firstly, in water filled stage of the pipeline the air valve can discharge remain gas in the pipe. Secondly at normal working stage, the air valve can discharge the small amount of gas gathered in the pipe, finally during the pump failure stage, the air valve will replenish the gas into the pipe to break the vacuum.

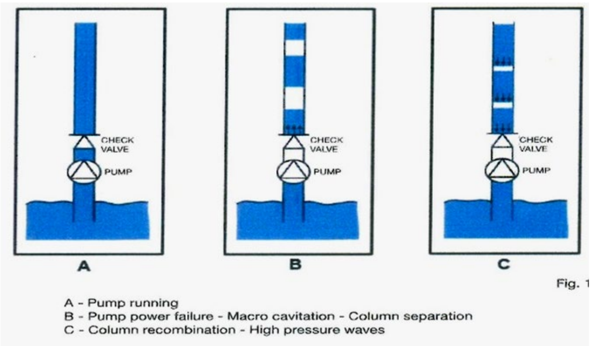


Figure 1. Cavitations following pump trip [1].

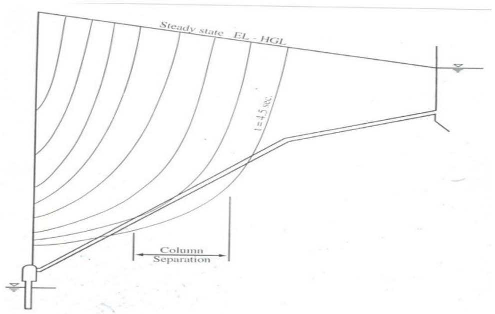


Figure 2. Pressure drop propagation [2].

Naik, and Bhat [4] explained the water hammer in the pipe due to the gradual closure and the sudden closure is studied. The pressure surge due to the gradual and sudden closure getting from CFD is satisfied with the manual calculations.

Kim, et.al. [5] Provided that it is possible to reduce the effect 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. Water hammer phenomenon can define as the transformation of kinetic energy into pressure energy, the transformation happened due to the sudden pump stop or sudden valve closure. Water hammer effects can be controlled with focusing efforts on reducing the pressure increment that takes place once the phenomenon is presented. Some methods try to reduce the rate of change before the closure through proper valve closure rates (with slow-closing valves).

Planco, et.al. [6] introduced the factors related to water hammer are: time rated of closing the valve, flow velocity, pipe length, elastic properties of the pipe material, and elastic properties of the flowing fluid. Water hammer analysis necessary either in the planning phase or in the operating condition. The ability to provide reliably surge control devices as (an air vessel, surge tank, etc...) has been state of the art.

Bassiouny. [7] provided that if water flowing in a long pipe is suddenly brought to rest by any obstruction, there will be a sudden rise of pressure as the momentum of the moving water being destroyed. The sudden rise of pressure in pipes is known as water hammer, consider a long uniform pipe of length L and diameter D provided with a valve as shown in Figure 3.

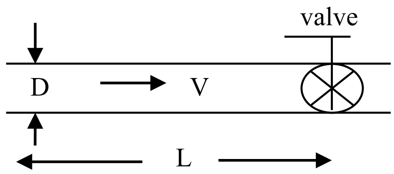


Figure 3. flow in pipeline

The pressure rise for gradual closing:

$$\Delta h = \frac{\Delta p}{\gamma} = \frac{LV}{gTc} \quad (1)$$

The pressure rise for sudden closing:

$$\Delta p = \sqrt{\frac{\rho}{\frac{1}{k}+\frac{D}{Ee}}} \quad (2)$$

where Δp, is the pressure rise (N/m^2), Δh, is the pressure rise (m) γ , is the Water specific weight (N/m^3), γ = ρ.g ,L, is the pipe length (m), V, is the flow velocity (m/s), T_c, is the time of closure (s), g, is the gravity acceleration (m/s^2), K, is the bulk modules (N/m^2), E, is the young's modules (N/m^2), e, is the wall thickness (m), ρ: Density (kg/m^3), D, is the pipe diameter (m).

Glover, [8] explained that if the resulting pressure is much higher than the static pressure in the pipe, which can be controlled by redesign the pipe material, the pipe diameter, air vessels, surge tanks, relief valves, pressure reducing control, fly wheels, valve selection, feed tanks, check valves control, vacuum breakers, air valves, variable speed drive (VSD) and variable frequency drive (VFD).

KY Pipe [9] provided Software packages which can supply an integrated surge analysis that results to water hammer solutions.

Izquierdo and Iglesias [10] explained that the main reason of a pipe rupture is water hammer caused by the hydraulic transient shock and cavitations. Four aspects are to be identified firstly high water pressure bursting pipes, secondly the vacuum flattening pipes and leading to water pollution, thirdly the cavitations damaging the pipelines and pump impellers, finally as well as the impact force losing the pipe joints. They explained that the computer model can not only improve work efficiency, but also can provide the technical support for the operation and maintenance of the water supply systems and monitoring and inspecting the severity level areas. They added that the velocity of pressure wave is closed the sound speed and can decrease quickly according to pipe material and pipe thickness. Table 1 shows the range of expected values for typical materials.

Pressure wave velocity

$$a = \sqrt{\frac{1}{\rho\left(\frac{1}{k}+\frac{D}{Ee}\right)}} \quad (3)$$

TABLE 1
EXPECTED VALUES OF PRESSURE WAVE VELOCITIES FOR DIFFERENT PIPE MATERIALS

Type of pipe	E (GPa) Young's modulus	a (m/s) Velocity of pressure wave
Steel	120-200	Up to 1485 m/s
Cast iron	80-170	900-1300 m/s
PVC	3.0-4.7	320 - 680 m/s
PE	0.7-1.2	200 - 400 m/s

The time taken by the wave to go to the reservoir and came back is designated as critical time, T_{Ccr} and is given by equation:

$$T_{Ccr} = \frac{2L}{a} \tag{4}$$

Ksb. [11] explained that the return time is important parameter of water system allowing setting closure time for valve or shutdown time for pump. A large size pipeline transfers high flow rates can be protected from water hammer by using open surge tank. For a cylindrical surge tank the maximum elevation (S) can be determined by equation:

$$S=V\sqrt{\frac{AL}{A_t\, g}} \tag{5}$$

Mahanna and Magalhaes [12] explained that surge tank is still a topic that sees active research and improvements are frequently proposed. The air vessel is one of the common methods of reducing water hammer. It is a relatively small pressurized vessel containing both air and water, which is connected to the discharge line from the pump station. The parameters control air vessel is: the top level of the tank, the water level in the tank, the water level in the pipeline and the cross section area for the air vessel are the minimum requirements to determine the air vessel initial volume.

Sharp and Sharp [13] provided that air vessel can be an excellent positive surge suppresser and can prevent negative pressures, column separation in the pipeline during power failure.

Salem [14] introduced that one of the main reasons that cause water hammer in pipeline systems is sudden pump trip due to power failure. In case of the power failure the initial wave is a negative which travel from the pump discharge side towards the end of pipeline, the air vessel generally alleviates negative pressure more effectively than other forms of the water hammer protection units, and can maintain a positive pressure in the line at all stages following the pump trip. Volume of water that the air vessel would force into pipeline behind the water column $\forall_w$ where:

$$\forall_w = \frac{ALV_O^2}{2gh} \tag{6}$$

$$\forall_o = \left(\frac{H_o}{h_{min}} - 1\right)\left(\frac{ALV_O^2}{2gh}\right) \tag{7}$$

$$\frac{D_e}{D_p} = \left(\frac{2V_O^2}{gHo}\right)^{1/4} \tag{8}$$

$$\frac{D_i}{D_p} = \frac{1}{\sqrt{2}}\left[\frac{V_O^2}{gh_{max}}\right]^{1/4} \tag{9}$$

The air vessel characteristics are defined to limit the minimum pressure head and to limit the maximum pressure head above the static pressure.

II. Prediction of the Occurrence of Water Hammer Phenomenon

It is possible to expect water hammer phenomenon though the following questions:

-Is the pipeline profile has high points which may cause column separation?

-Is the flow velocity increase than (1.2 - 1.5) m/s?

-Is the pipe strength decrease (3x operating pressure)?

-Is the check valve installed after the gate valve in the discharge line?

-Is the time of pump trip or valve closure less than the critical time T_{Ccr} i.e. $T_c<T_{Ccr}$?

Gradual and sudden stopping of Flow

Since the intensity of pressure rise depends upon the time rate of stopping the flow, hence the following two cases will be considered:

a) Gradual stopping of flow

Gradual stopping of flow where the moving liquid column in the pipe is brought to rest with uniform rate of retardation and $T_c > T_{Ccr}$ and the increase in pressure Δp can be described by the equations:

$$\Delta p = \frac{\gamma LV}{gTc} \tag{10}$$

$$\Delta p = p_o\left(\frac{N}{2} + \sqrt{\frac{N^2}{4} + N}\right) \text{where} \left(N = \frac{\rho LV}{P_o T_c}\right) \tag{11}$$

b) Sudden stopping of flow

Sudden stopping of flow where $T_c < T_{Ccr}$

and the increase in pressure Δp due to water hammer can be described by equations (2) and by Joukowsky equation. The Joukowsky equation is given by:

$$\Delta p_{Jou} = \rho.a.\Delta V \tag{12}$$

The wave velocity (a) can be described by equation (3) for elastic pipe, elastic fluid. The maximum and the minimum pressure can be described by equations:

- $P_{max} = P_o + \Delta p$

- $P_{min} = P_o - \Delta p$

where p_o ia the Steady flow pressure (P_a), and Δp is the Pressure change (P_a)

A. Water Hammer Analytical Parameters

The aim of the analysis is to study water hammer phenomenon and predict the pressure fluctuation during the surge events by sudden pumps trip. Figure 4 shows a typical layout pipeline system.

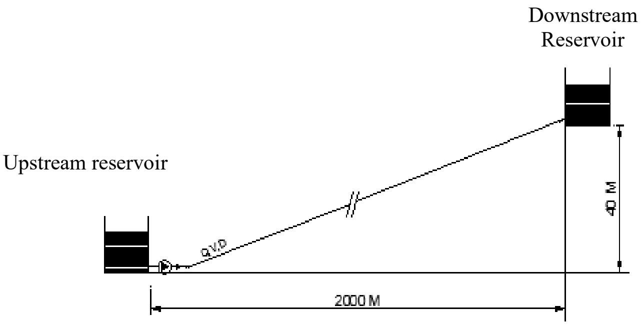


Figure 4. Typical layout pipeline system

B. Fluid

Irrigation water at 20°C, ρ, density 1000 kg/m3, K, bulks modulus 2.2 × 109 Pa.

C. Pipeline material and diameter

It is required to use a pipeline feeding a farm with irrigation water. The elevation difference between the water surface upstream reservoir and the downstream reservoir is 40m. The distance between the two reservoirs is about 2km. the proposed pipe material is polyvinyl chloride PVC (PN4, PN6 and PN10).

Table 2 shows PVC pipelines specification. Where: PN: pipeline pressure class (strength), ND: nominal outside diameter, e: wall thickness.

D. Wave speed

The wave speed can be calculated using equation (3).

E. Head loss

The head losses, h_L can be defined by Hazzen.
- William equation

$$h_L = 10.67\left(\frac{Q}{C}\right)^{1.85}\frac{L}{D^{4.87}} \qquad (13)$$

F. Water hammer transient

The maximum and minimum pressure due to water hammer events will be introduced by applying Joukowsky equation (12).

TABLE 2
P.V.C PIPES SPECIFICATIONS

Nominal outside diameter ND mm	PN4 (4bar) Pipe wall thickness mm	PN6 (6 bar) Pipe wall thickness mm	PN10 (10 bar) Pipe wall thickness mm
450	8.9	13.2	21.5
500	9.8	14.6	23.9
560	11	16.4	26.7
630	12.4	18.4	30
710	14	20.7	
800	15.7	23.3	
Young's modulus E	3.8×10^9Pa		

TABLE 3
SUMMARY OF ANALYTICAL ANALYSIS RESULTS FOR PIPELINE, a=240m/s, T_{Ccr} = 16.6 s

Q m^3/h	Data and Results \ ND/mm	PN4 450	500	560	630	710	800
1200	P_o bar	5.8	5.1	4.6	4.3	4.2	4.1
	P_{max} bar	11.3	9.45	8.1	7.1	6.4	5.8
	P_{min} bar	0.3	0.6	0.5	1.5	2	2.4
	Pipe burst	√	√	√	√	√	√
	Pipe collapse	-	-	-	-	-	-
1350	P_o bar	6.18	5.31	4.75	4.42	4.24	4.13
	P_{max} bar	12.35	10.28	8.71	7.54	6.69	6.07
	P_{min} bar	0.01	0.34	0.79	1.30	1.79	2.19
	Pipe burst	√	√	√	√	√	√
	Pipe collapse	-	-	-	-	-	-
1500	P_o bar	6.7	5.6	4.9	4.5	4.3	4.2
	P_{max} bar	13.52	11.12	9.33	8	7.04	6.32
	P_{min} bar	-0.18	0.06	0.49	1.67	1.54	2
	Pipe burst	√	√	√	√	√	√
	Pipe collapse	-	-	-	-	-	-
1650	P_o bar	7.17	5.89	5.09	4.62	4.34	4.19
	P_{max} bar	14.68	11.96	9.94	8.44	7.53	6.57
	P_{min} bar	-0.34	-0.18	0.14	0.8	1.33	1.88
	Pipe burst	√	√	√	√	√	√
	Pipe collapse	-	-	-	-	-	-
1800	P_o bar	7.73	6.23	5.28	4.72	4.4	*4.2*
	P_{max} bar	15.94	12.86	10.59	8.9	7.7	6.8
	P_{min} bar	-0.48	-0.4	0.03	0.54	1.1	1.63
	Pipe burst	√	√	√	√	√	√
	Pipe collapse	-	-	-	-	-	-

G. Analytical analysis results and Discussion

Three scenarios are applied to investigate whether the used PVC pipelines with (PN4, PN6 and PN10) of different diameters producer (450 mm and 800 mm) the flow rates range producer (120 0m^3/h and 1800 m^3/h) are free or not against the water hammer due to pump trip without using control devices. The pipe diameter will affect slightly the sound speed and consequently affects slightly on the critical time. However, the sound speed increases with increasing the value of Young's modulus which leads to decrease the critical time. While the pipe diameter has great effect on the water flow velocity inside the pipeline depending on the flow rate and consequently the head losses and the elevation (Z=40m).

Analyzing Joukowsky equation it is obvious that transient pressure change for the same pipeline material and the same fluid depends on the value of the flow velocity inside pipeline. Therefore, its higher value would be corresponding to minimum pipe diameter and maximum flow rate. The results of the above mathematical analysis are given in Tables 3, 4, 5 Figures 5 to 7.

-Table 3 shows that for sudden pumps trip at time $T_c<T_{Ccr}$, the wave velocity ≅ 240 m/s and T_{Ccr}=16.6s for PN4 and no surge devices water hammer occurs, the result illustrates the pressure situations where the over pressure (P_{max}) exceeds the maximum PN4 allowed for the pipe for all ND diameters. Also the steady state pressure (P_o) exceeds the PN4 allowed for the pipe for all ND diameters so the pipes will burst and all the pipes are rejected.

TABLE 4

SUMMARY OF ANALYTICAL ANALYSIS RESULTS FOR PIPELINE, a=294.7m/s, T_{Ccr} = 13.6 s

Qm^3/h		PN6					
	Data and Results \ ND/mm	450	500	560	630	710	800
1200	P_o bar	5.9	5.2	4.7	4.4	4.2	4.1
	P_{max} bar	12.89	10.85	9.18	6.96	7	5.6
	P_{min} bar	-1.09	-0.45	0.22	0.84	1.4	2.6
	Pipe burst	√	√	√	√	√	√
	Pipe collapse	√	√	√	√	√	√
1350	P_o bar	6.41	5.44	4.83	4.47	4.26	4.15
	P_{max} bar	14.25	11.8	9.87	8.47	7.38	6
	P_{min} bar	-1.43	-0.92	-0.21	0.47	1.14	2.3
	Pipe burst	√	√	√	√	√	√
	Pipe collapse	√	√	√	√	√	√
1500	P_o bar	6.9	5.8	5.01	4.6	4.3	4.2
	P_{max} bar	15.63	12.9	10.61	9	7.8	6.3
	P_{min} bar	-1.83	-1.3	-0.59	0.2	0.8	2.1
	Pipe burst	√	√	√	√	√	√
	Pipe collapse	√	√	√	√	√	√
1650	P_o bar	7.49	6.09	5.21	4.68	4.38	4.21
	P_{max} bar	14.07	13.88	11.37	9.57	8.17	6.47
	P_{min} bar	-2.09	-1.70	-0.95	-0.21	0.59	1.95
	Pipe burst	√	√	√	√	√	√
	Pipe collapse	√	√	√	√	√	√
1800	P_o bar	8.1	6.5	5.4	4.8	4.4	4.2
	P_{max} bar	18.6	15	12.12	10.13	8.58	6.67
	P_{min} bar	-2.4	-2	-1.32	-0.53	0.22	1.73
	Pipe burst	√	√	√	√	√	√
	Pipe collapse	√	√	√	√	√	√

TABLE 5

SUMMARY OF ANALYTICAL ANALYSIS RESULTS FOR PIPELINE, a=379m/s, T_{Ccr} = 10.3 s

Qm^3/h	ND/mm — Data and Results	PN10			
		450	500	560	630
1200	P_0 bar	6.4	5.4	4.8	4.5
	P_{max} bar	16.18	13.28	11.05	9.42
	P_{min} bar	-3.38	-2.48	-1.45	-0.42
	Pipe burst	√	√	√	√
	Pipe collapse	√	√	√	√
1350	P_o bar	6.92	5.76	5.01	4.57
	P_{max} bar	17.91	14.64	12.05	10.09
	P_{min} bar	-4.07	-3.12	-2.04	0.95
	Pipe burst	√	√	√	√
	Pipe collapse	√	√	√	√
1500	P_o bar	7.6	6.1	5.2	4.7
	P_{max} bar	19.81	15.93	13.15	10.87
	P_{min} bar	-5.61	-3.73	-2.75	-1.47
	Pipe burst	√	√	√	√
	Pipe collapse	√	√	√	√
1650	P_o bar	8.25	6.55	5.47	4.82
	P_{max} bar	21.66	17.4	14.06	11.55
	P_{min} bar	-5.16	-4.3	-3.12	-1.91
	Pipe burst	√	√	√	√
	Pipe collapse	√	√	√	√
1800	P_o bar	8.98	6.99	5.72	4.96
	P_{max} bar	23.68	18.79	15.27	12.38
	P_{min} bar	-5.72	-4.81	-3.83	-2.46
	Pipe burst	√	√	√	√
	Pipe collapse	√	√	√	√

- Table 4 shows that for sudden pumps trip at time $T_c < T_{Ccr}$, the wave velocity≅294 m/s and T_{Ccr}≅13.6 s for PN6 and no surge devices water hammer occurs, the result illustrates the pressure situations where for all ND diameters except ND800 the over pressure (P_{max}) exceeds the maximum PN6 allowed for the pipe for all ND diameters and the under pressure (P_{min}) goes below vapor pressure which will break the water column with a cavitations' pocket. Control device is must, except in case of Q = 1200 m^3/h and Q = 1350 m^3/h with ND 800.

-Table 5 shows that for sudden pumps trip at time $T_C < T_{Ccr}$, the wave velocity=388 m/s and $T_{Ccr} \cong$ 10.3 s for PN10 and no surge devices water hammer occurs, the result illustrates the pressure situations where the over pressure (P_{max}) exceeds the maximum PN10 allowed for the pipe for all ND diameters and the under pressure (P_{min}) goes below vapor pressure which will break the water column with a cavitations pocket. Control device is must except in case of Q = 1200 m^3/h and Q = 1350 m^3/h with ND 630 appears with maximum pressure (P_{max}) = 9.42 bar and 10.09 bar which each is slightly less or equal to PN10 and P_{min} = - 0.42 bar and 0.95 bar where the PVC pipe manufacture permits till - 0.4 bar in this case no need to control device.

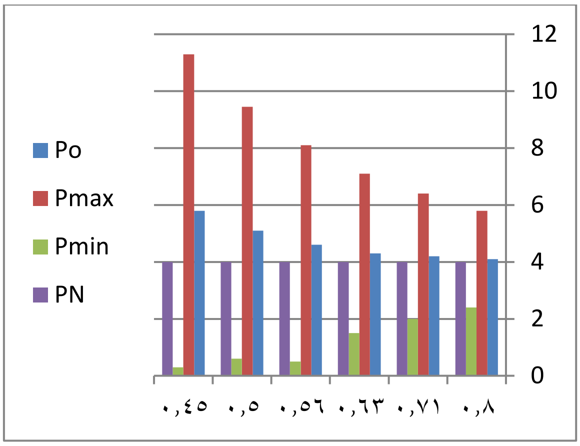
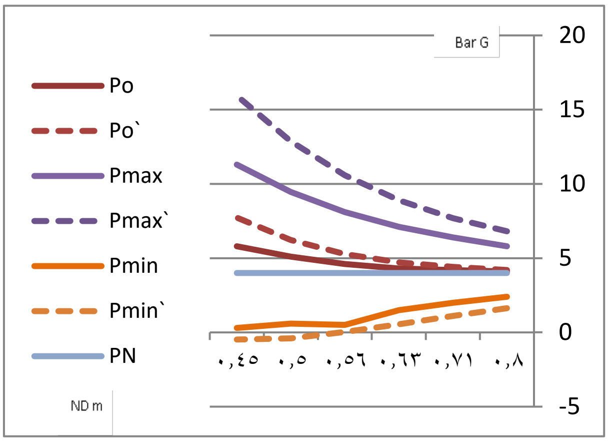


Figure 5a. Water hammer surge represented by bar chart ($Q=1200m^3/h$) (PN4).



Q ——— $=1200m^3/h$
Q............. $=1800\ m^3/h$

Figure.5b Water hammer surge represented by line chart ($Q=1200m^3/h$ & $Q=1800m^3/h$)

Figure.5 water hammer theoretical analysis results (PN4)

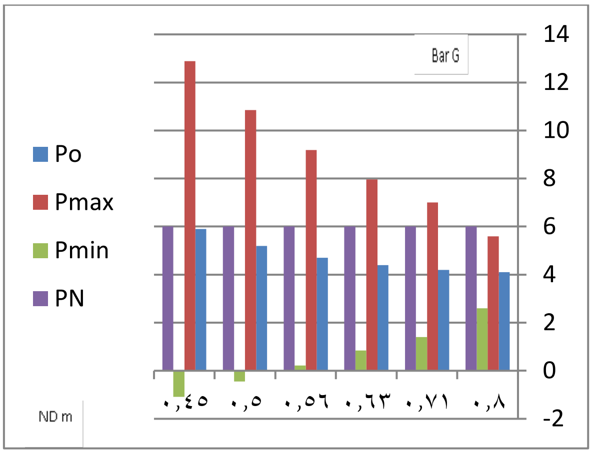
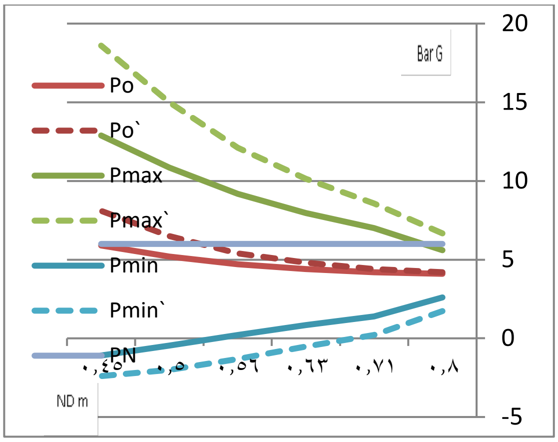


Figure 6a. Water hammer surge represented by bar chart ($Q=1200m^3/h$) (PN6)



Q ——— $=1200m^3/h$
Q............. $=1800\ m^3/h$

Figure 6b. Water hammer surge represented by line chart ($Q=1200m^3/h$ & $Q=1800m^3/h$).

Figure 6. Water hammer theoretical analysis results (PN6).

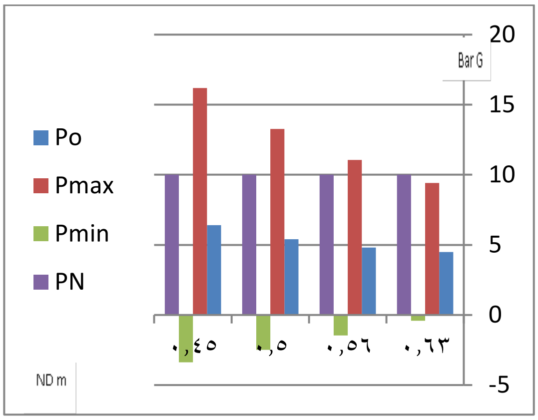


Figure 7a. Water hammer surge represented by bar chart ($Q=1200m^3/h$)

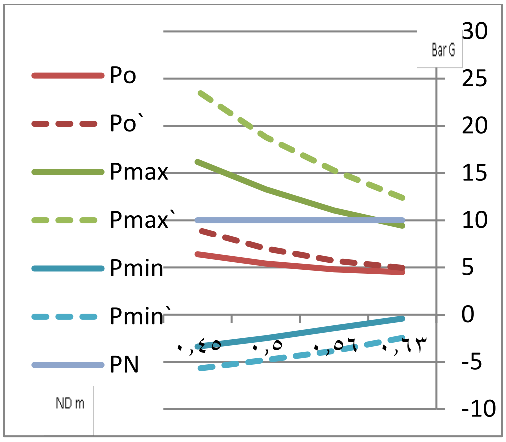


Figure 7b. Water hammer surge represented by line chart ($Q=1200m^3/h$ & $Q=1800m^3/h$)

Figure 7. Water hammer analytical analysis results (PN10).

III. Irrigation Pipelines Design Optimization With Reduction Of Water Hammer Effects

It is required to design a pipeline feeding a farm with irrigation water. The farm area is 1000 Feddan lies within Abu Sultan city, Ismailia. The design should include the optimum technique for protecting the pipeline against water hammer events caused by pump trip. The irrigation water is pumped from a channel to a reservoir built at the farm edge, Figure 8. The elevation difference between the water surface in the channel and the reservoir is 40m. The irrigation water requirement at peak demand is 1200 m^3 / h, the distance between the reservoir on the farm edge and the channel is to be 2km (pipeline length). Table 6 shows the profile of the pipeline.

A. Pipeline Selection

Pipeline data: Discharge Q = 1200 m^3/h, pipe length L = 2000 m, elevation diff. ΔZ = 40 m and pipe material = PVC 6 bar.

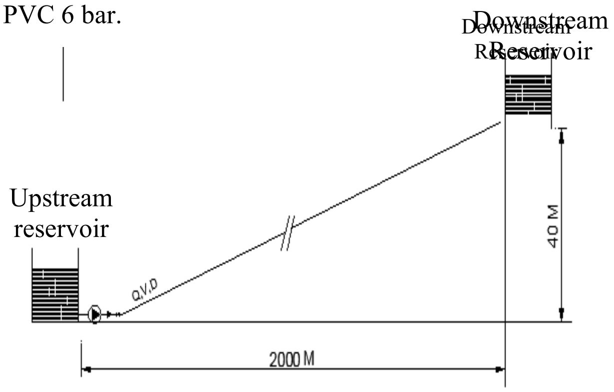


Figure .8 Layout for pipeline system

TABLE 6
THE PROFILE OF THE PIPELINE

Pipe segment	Segment length (m)	Pipe length at end of segment	Elevation inlet (m)	Elevation outlet (m)
1	10	10	0	0
2	10	20	0	0
3	200	220	0	0
4	300	520	0	10
5	100	620	10	15
6	200	820	15	20
7	300	1120	20	27
8	200	1320	27	30
9	100	1420	30	30
10	200	1620	30	35
11	200	1820	35	35
12	200	2020	35	40

The investigation is done using the standard pipe nominal diameters D mm 315, 355, 400, 450, 500, 560, 630, 710, 800, 900, and 1000. No. of pipes = 1 Hazzen William equation (13) is used for head loss calculation.

Energy consumption: Pump efficiency η = 0.65, Daily working hours τ = 18 h /day, Annual working days σ=240 days / year, Energy cost ϕ = 0.59 EGP/kWh. Power

$$P = \frac{\rho g Q H}{\eta\ 1000}\ \text{kW} \qquad (14)$$

Pump head H = h_L+ ΔZ m

The optimum pipe diameter will result by getting a minimum total annual cost for the pipeline where:

-Total annual cost = sum (annual energy cost + annual purchase cost)

-Annual energy cost = power (kW) × daily working hours × annual working days × energy cost

-Annual purchase cost = capital cost × CRF where:

-Capital cost = pipe length × pipe cost EGP/m

-(CRF) Capital recovery factor = $\frac{1}{PWF}$

$$\text{-(PWF)Present work factor} = \frac{[(1+i)^n - 1]}{[i(1+i)^n]} \qquad (15)$$

Capital recovery factor:

Life time n= 30 year, Interest rate i = 10 %

-CRF = 0.10608

The results have been presented in Table 7 and in Figure 9 where the optimum nominal diameter is 560mm, with inner diameter 527 mm and thickness e = 16.5mm.

B. Pump Selection

The required discharge Q 1200 m^3/h at the required head H 46.69 m. Choose No. of pumps = 3 + 1 (3 working with parallel connection and one stand by). Use Alwailer Farid pump model NT150/400/408 at the best efficient point where flow Q = 360 m^3/h, head H = 50 m, efficiency η = 80 %, speed N = 1450 RPM and power of electric motor drive75 kW /3ph/50HZ. Table 8 the characteristic points of 3 pumps operating in parallel, while their operating point is shown in Figure 10. The data of Q_p, H_p is obtained from Al wailer pump characteristic curve, H_{sys} is obtained by the analytical calculations of the sum of head loss and the elevation.

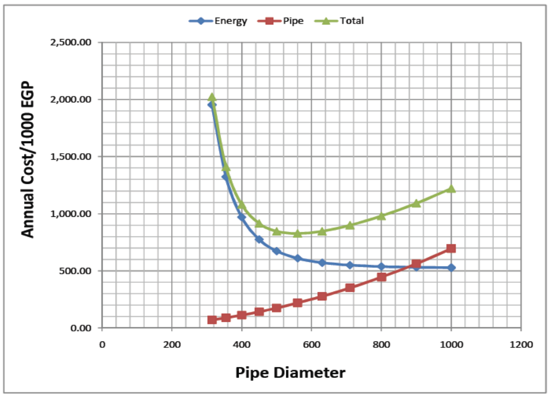


Figure 9. Annual cost vs. pipe diameter

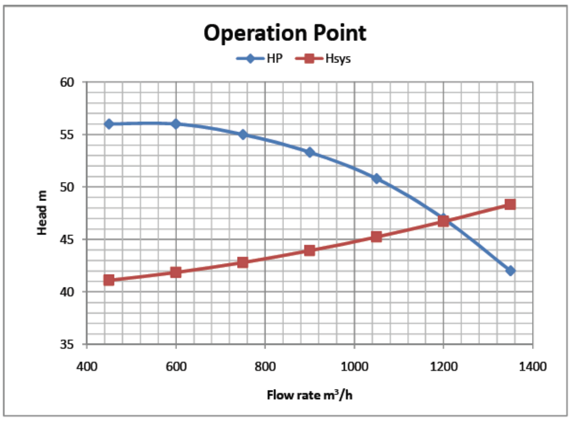


Figure 10. Operation point

TABLE 7

TOTAL ANNUAL COST VS. PIPE NOMINAL DIAMETER

Pipe Nominal Diameter mm	Pipe Inside Diameter	Pipe Cost LE/m	Flow Velocity m/s	Head Loss m	Pump Head m	Power	Initial pipe cost 1000LE	Annual Energy Cost 1000LE	Annual Pipe Cost 1000LE	Total annual Cost 1000LE
315	297	330	4.83	110.07	150.07	766.8	660.00	1953.71	70.01	2023.72
355	334	418	3.80	61.55	101.55	518.9	835.00	1322.05	88.58	1410.63
400	377	528	2.99	34.40	74.40	380.2	1055.00	968.64	111.91	1080.55
450	424	670	2.37	19.40	59.40	303.5	1340.00	773.35	142.15	915.49
500	471	823	1.92	11.60	51.60	263.6	1645.00	671.75	174.50	846.25
560	527	1035	1.53	6.69	46.69	238.5	2070.00	607.78	219.58	827.37
630	593	1035	1.21	3.76	43.76	223.6	2610.00	569.75	276.87	846.62
710	669	1653	0.95	2.10	42.10	215.1	3305.00	548.11	350.59	898.70
900	847	2650	0.59	0.66	40.66	207.8	5300.00	529.38	562.22	1091.60
1000	942	3275	0.48	0.40	40.40	206.4	6550.00	525.91	694.82	1220.73

TABLE 8

CHARACTERISTIC POINTS OF THE 3 PUMPS OPERATING IN PARALLEL

Q_P	H_p	H_{Sys}
450	56	41.1
600	56	41.9
750	55	42.8
900	53.3	43.9
1050	50.8	45.2
1200	47	46.7
1350	42	48.3

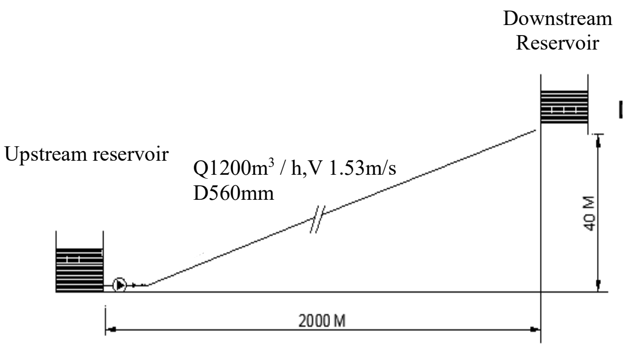


Figure 11. Layout for pipeline system with optimum nominal diameter

C. Water Hammer analytical solution

(ΔP, P_{max} and P_{min})

Figure 11 shows the layout for pipeline system with optimum nominal diameter.

Used technical data: D_{in} =527mm, e = 16.5 mm, K= 2.1 × 10^9 Pa, E= 3.8 × 10^9 Pa, L= 2000 m,

Q= 1200 m3/m, H= 46.7 m

ρ = 1000kg/m3.

As result of calculations: Wave speed a = 333 m/s critical time TCcr = 12.01 s , v = 1.53m/s Po=4.67bar,

ΔPjou=5.09bar

Pmax = 9.76 bar

P_{min} = - 0.42 bar (negative pressure)

V=1.53m/s

ΔPjou=5.09bar

-Pmin = - 0.42 bar (negative pressure)

The following are concluded:

- Calculated maximum pressure due to water hammer exceeds the allowable pressure for the pipeline.
- Calculated minimum pressure due to water hammer will create negative pressure (vacuum), leads to vapor accumulation.

D. Water Hammer CFD Simulation

AFT impulse is a powerful dynamic simulation and analysis tool used to calculate pressure surge transients in liquid piping systems caused by water hammer, AFT impulse has several advantages.

- Easily model includes a wide range of system components.
- Understand the transient response of the system.
- Evaluate the effect of pressure surge due to vapor cavity.
- Validate the design of safety features to produce safer, more economical pipe system.

AFT impulse can be used to advice the optimum solution to choose the suitable and control device to mitigate high pressure and to prevent negative pressure. In order to demonstrate the transient analysis, the same data from the analytical will provide to the AFT impulse program to simulate the system, at steady state, at pump trip (transient) without adding control device and at pump trip, (transient) when adding air vessel when adding surge tank. Figure 12 shows the static pressure VS. Flow length for steady state case. Figure 13 shows the profile of maximum and minimum pressures caused by a sudden pumps trip for water pipe without protection. In order to minimize the effect of over pressure and low pressure, the following devices have been provided: surge tank and air vessel. The results of installing protection devices will lead to mitigate the pressure rise and prevent negative pressures. An air vessel has installed with the following specification. Air volume 14 m^3 is suitable and will be taken 25 % increase to obtain total volume of the air vessel = 17.5 m^3. Figure 14 shows the profile of maximum and minimum pressure using air vessel to protect the system. An open-end surge tank of area = 0.20 m^2 are used to mitigate both high and low pressure. Figure 15 shows the profile of maximum and minimum pressure using surge tank to protect the system.

IV. Evaluation of Both Analytical and AFT Solution of Water Hammer Analysis

Some of the important results of both analytical and AFT solutions are:

a) From analytical, there is negative value of pressure - 0.42kg/cm^2, causing cavitations at pipeline while the maximum pressure 9.76kg/cm^2.

b) From AFT impulse, there is minus value about - 0.5:-1 kg/cm^2 pressure causing cavitations at pipeline and the maximum pressure has a value of 10.5kg/cm^2.

c) The pressures computed using AFT impulse is higher than what they are in analytical solution. However, the advantage of applying AFT impulse is always on the safe side. Generally, the results from AFT impulse and analytical are nearly led to the same results.

By installing air vessel or surge tank as protection devices for water hammer surge there are no cavitations at pipeline i.e. increase the minimum pressure of water. Also, the maximum pressure of water decreases below the maximum allowable working pressure. The results of installing protection devices will lead to mitigate the pressure rise and prevent negative pressure.

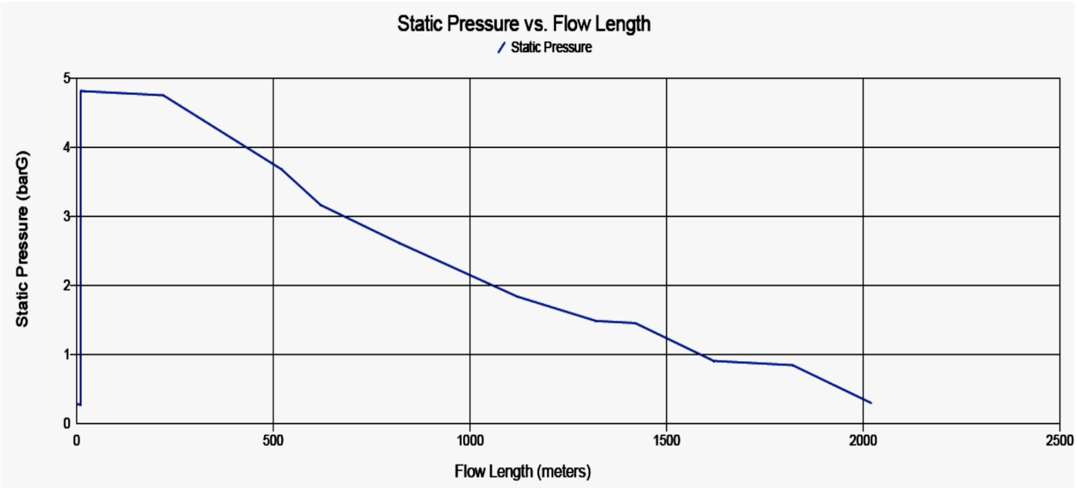


Figure 12. Static pressure vs. flow length.

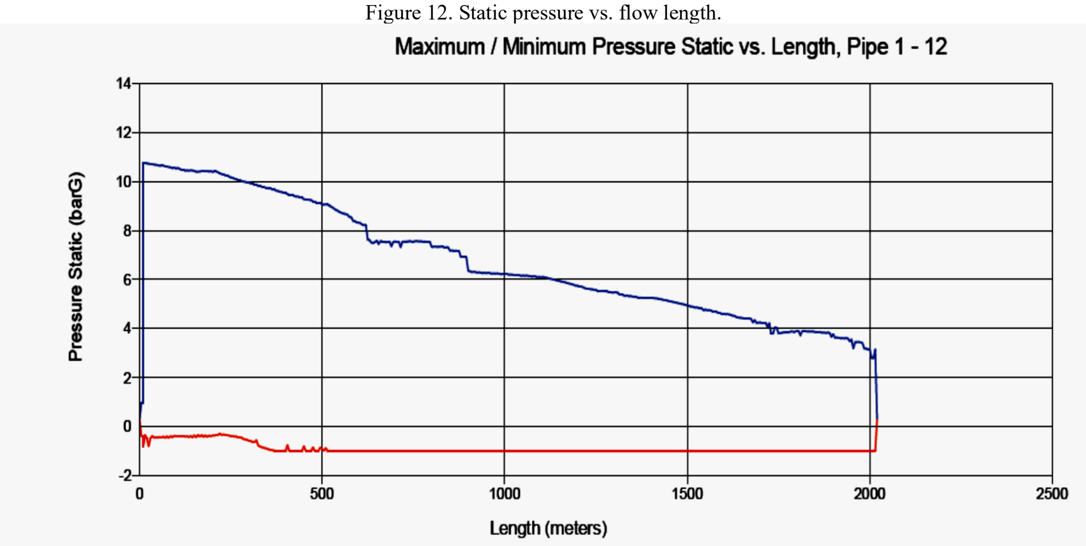


Figure 13. The maximum and minimum pressure static vs. length.

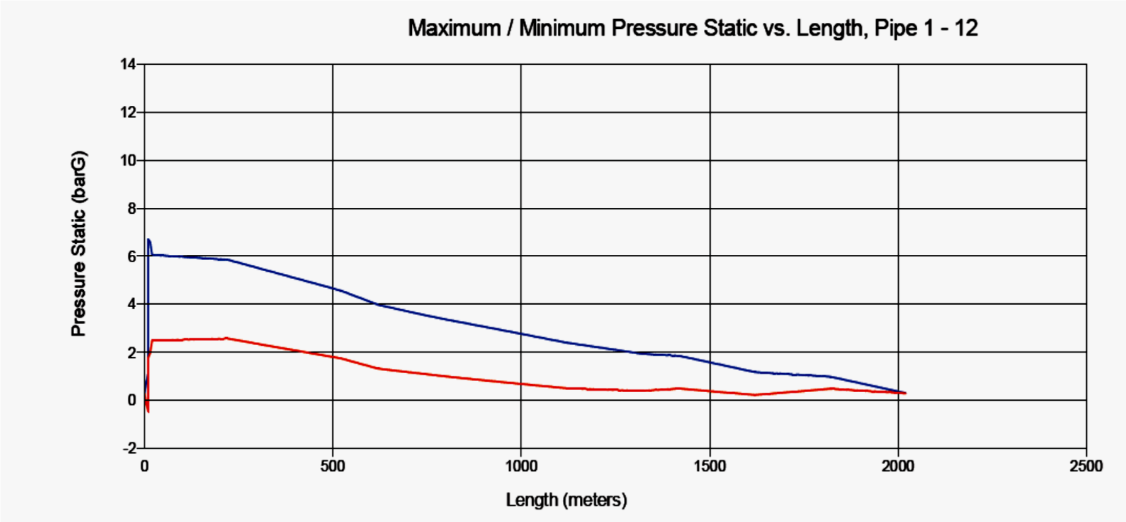


Figure 14. Maximum and minimum pressure static vs. length with air vessel.

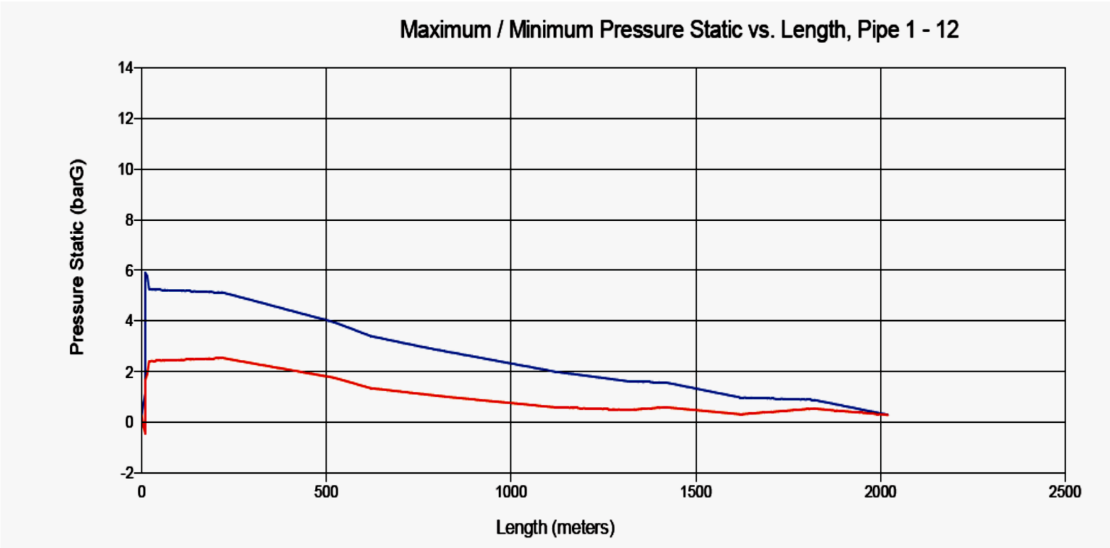


Figure 15. Maximum/ minimum pressure vs. length, pipe 1-12 with surge tank.

V. CONCLUSIONS

Water hammer can cause the pipe to rupture if the pressure is high enough and can cause pipe to collapse if the pressure drops below the vapor pressure. The results analysis show that the lower strength material pipe and smaller inner diameter pipe will deal with large water hammer effect. The design of a piping system required the following two important disciplines:

1-Economical analysis to estimate the optimum pipe diameter that ensures a minimum cost of the pipeline system

2- Flow transient analysis to select suitable protection devices, which can control the surge pressures and column separations occurring from water hammer. In this paper irrigation pipeline design optimization with reduction of water hammer effects is presented. The design included protecting the pipeline against water hammer upon sudden power failure. Both above mentioned disciplines are considered.

The pipeline diameter of 560mm is selected according to optimum cost analysis. The pumps are selected from real local market. The proposed pipeline solved analytically and is simulated using the computer AFT impulse program. Some of the important conclusions of both analytical and AFT solutions are:

-Both analytical and CFD solutions give coincide qualitative results for the maximum pressure and cavitations occurrence.

-The maximum pressure computed using AFT impulse is higher than that given by analytical solution by 7%, while the minimum pressure obtained using AFT impulse at the same pipe is lower than the analytical result by 19%.

-However the AFT impulse is in the safe side which is advantage from point of view of design.

-By installing air vessel or surge tank as protection devices for water hammer surge:

-There are no cavitations at pipeline i.e. increase the minimum pressure of water.

-The maximum pressure of water decreases below the maximum allowable working pressure.

-The results of installing protection devices will lead to mitigate the pressure rise and prevent negative pressure.

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Nomenciature

SymbolDescription	
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
| Q |	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

$\forall_o$	Air volume, m^3
$\forall_w$	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