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Optimum Hydropneumatic Tank Sizing to Protect Transmission Pipelines Supply System against Water Hammer

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Abstract: Water hammer is a phenomenon caused by flow disturbances in transmission pipelines, resulting in high positive and negative pressures that can cause pipe fracture. This phenomenon occurs due to a sudden pump stoppage or valve closure. There are many ways to protect transmission pipelines against the pressures caused by a water hammer, including hydropneumatic tanks (HT). In this paper, HT is utilized to protect transmission pipeline supply systems in El-Shorouk City, Cairo, Egypt against pump failure. The objective is to identify the optimum sizing of HT, including the inlet diameter and the liquid ratio inside HT, to avoid the harmful effects of the water hammer. The Bentley HAMMER model is used to simulate and analyze steady-state and transient flow conditions in the transmission pipeline. The results indicate that reducing the inlet diameter till reaching 1/5 times the transmission pipeline diameter decreases the maximum pressure. Further reduction in the inlet diameter leads to an increase in the maximum pressure. The study also concludes that the optimum liquid ratio inside HT is 60% (and 40% air). The study achieves approximately 75% savings in the inlet diameter of HT and assigns the optimum liquid volume in HT. Regression analyses are performed and 14 equations are developed to predict the maximum pressure according to the ratio of inlet diameter to the transmission pipeline diameter and liquid ratio in HT.

Keywords: Water hammer; transmission pipelines; hydropneumatic tank; Bentley HAMMER; and transient flow.

1. Introduction

1.1 Water Hammer Phenomenon

The water hammer phenomenon is the excessive pressure wave because of a sudden change in velocity in the transmission pipeline. Return wave speed causes excessive positive and negative pressure. Positive pressure causes pipe fracture and negative pressure causes a broken pipeline system because of suction forces. A water hammer is a transient surge pressure that occurs when a fluid in a pipeline is suddenly accelerated or decelerated due to a change in flow velocity or pressure [1]. This phenomenon can cause significant damage to pipeline components such as valves, pumps, and fittings, and can also lead to safety hazards, including pipe rupture and explosion. The water hammer can occur in a variety of fluid transport systems, including water supply networks, heating and cooling systems, and oil and gas pipelines. The water hammer phenomenon is caused because of the sudden change in flow through transmission pipelines from a steady state to transient flow. Transient pressures in transmission pipeline systems are usually high at pump stations [2]. Studying transient flow in transmission pipeline systems is as important as the steady state case. Because of pump shutdown or sudden valve closure, the rate of flow is changed rapidly, and a water hammer occurs [3].

1.2 Effects of Water Hammer on the Pipe

A water hammer is the transmission of pressure waves along the pipeline resulting from a change in liquid flow velocity. An unprotected transmission pipeline suffers huge damage due to water hammer surges inside the pipelines [4]. The effects of water hammer can be severe, including pipe rupture, valve failure, and damage to other pipeline components. The high-pressure spikes generated by the water hammer can cause cavitation, erosion, and fatigue of pipeline materials. The negative pressures generated by the water hammer can cause pipe collapse and cavitation damage to pumps and other components. The water hammer can also cause noise and vibration, leading to discomfort for occupants of nearby buildings [1] [5] [6].

1.3 Protection Methods to Resist Water Hammer

Various mitigation techniques are available to prevent or reduce the impact of a water hammer, including surge tanks, air valves, and control strategies. Most protection methods are designed to avoid sudden flow and velocity changes [7]. However, there is a lot of protection methods against water hammer such as surge tanks (open – closed – hydro-pneumatic tank with bladder), air valves (release – vacuum), relief valves (pressure – anticipator), check valves, and control valves [8]. Surge tanks are connected directly to the transmission pipeline systems. The main purpose of surge tanks is to reduce the excessive pressure due to sudden flow stoppage. Surge tanks may be classified into a lot of types [9]. Check valves are control valves for closing immediately when the flow stops suddenly. The valve must be closed quickly before the reverse flow becomes large [10]. Both air release and air vacuum valves are important in transmission pipeline systems to deal with air in the systems. Air release valves are used when filling an empty pipeline system. They are placed to remove air pockets out of the system slowly. But air vacuum valves are placed to suck air from the atmosphere into the pipeline systems [11].

[12] studied solutions to avoid water hammers due to pump failure in a pump station on the Tigris River in Iraq employing Bentley Software. It was found that surge tanks in the place of the highest point of pressure decreased the pressure from 22 to 7 bar. [13] presented a method to calculate five risk factors of water hammer hazards including a composite risk factor. A real case of CD City of China was used to illustrate the assessment method. The developed pipe rupture risk prediction and classification maps could be used to provide technical guidance for the water distribution network design and operation maintenance.

[14] investigated the impacts of transient flow in pipeline systems due to pump power failure employing Bentley HAMMER V8.0 Edition. For protection with an air vessel, it was concluded that the value of 40% of the original diameter for the inlet pipe diameter of the air vessel, and the value of 2/3 of the original pipe diameter were critical values for transient pressures. For protection with an air vessel and two surge tanks, as the inlet pipe diameter increased the maximum pressure increased and the minimum pressure decreased. Regression analyses were performed obtaining equations to predict the pressure according to the inlet pipe diameter, the area of the surge tank, and the pipe diameter.

[15] performed a simulation approach to protect the pipeline systems in hydropower plants against water hammer negative effects using pressure-regulating valves and hydropneumatic tanks. Four scenarios were studied. The results showed that a combination of the pressure regulating valve and the hydropneumatic tank was an adequate appliance to lessen the effect of water hammer/transient flow in a hydropower plant system. The results showed that pipeline diameters had crucial factors that influence hydraulic transient in hydropower plant systems. [16] studied the negative pressure due to the transient flow created by pump failure of the 31 km water transmission pipeline of Kerman City in Iran. It was shown that installing hydropneumatic tanks along the pipeline length in the right places prevented negative pressure.

[17] explored the design of surge protection devices considering different conditions for various pipeline systems. Dimensionless equations of fluid motion and continuity were introduced, and their solutions were developed in the dimensionless frequency domain. The integration of a dimensionless approach into a metaheuristic engine provided a general platform for surge tank design in the comprehensive bounds of flow and pipeline conditions. [18] performed a sensitivity analysis to show the effect of pump and pipeline parameters on the maximum and minimum head just downstream of the pump after pump power failure. A new approach was introduced to finding the required gas volume in a hydropneumatic tank to protect the pipeline using artificial neural networks.

In this paper, a simple transmission pipeline supply system in El-Shorouk city to transmit water from an underground reservoir to another higher reservoir is proposed. The Bentley HAMMER model is used to simulate this transmission pipeline in the steady-state and transient cases. A hydropneumatic tank is the optimum protection method to resist the water hammer phenomenon. Inlet diameter to HT and the ratio between liquid and air inside HT are studied as variable parameters to determine the optimum hydropneumatic tank sizing.

2. MATERIALS AND METHODS

2.1 General Definitions

The pressure wave's speed is a function of the parameters related to two important constraints (fluid type and pipe material type). Fluid type is the first parameter such as (K: liquid elasticity module, **ρ**: fluid density) and pipe material type is the second parameter such as (D: pipe diameter, C: pipe restraint case, E: pipe elasticity modulus, and e: wall thickness of the pipe). The relation for calculating the pressure wave speed is shown in the following formula No. (1):

$$\boldsymbol{\alpha} = \frac{\sqrt{\mathbf{k}/\boldsymbol{\rho}}}{\sqrt{\mathbf{1}+\frac{K}{E}\cdot\frac{\mathbf{D}}{e}\cdot\mathbf{C}}} \tag{1}$$

Joukowsky and Allievi predicted pressure rise through transmission pipelines which caused water hammer due to valve closures or pump stoppage [19]. Pressure rise (ΔH) through a transmission pipeline due to the water hammer phenomenon (bar) is an excessive pressure that can affect pipe material. The pressure wave's speed ($\boldsymbol{\alpha}$) and difference in velocity (ΔV) are measured in m/s, and (g) is the gravity acceleration in m/s^2. Pressure rise is calculated by using the following formula No. (2):

$$\boldsymbol{\Delta}\mathbf{H} = -\frac{\alpha.\Delta v}{g} \tag{2}$$

2.2 Case Study Description

This paper is concerned with the water hammer phenomenon study inside the transmission pipeline supply system in El-Shorouk City that transmits water from an underground reservoir to another higher reservoir. El-Shorouk is a satellite city in the Eastern Area of Cairo Governorate, Egypt. It is one of the so-called Third Generation new cities allocating 11,000 acres of public land, in addition to further allocations totaling 53,000 acres by 2017. According to the 2017 census, it had 87,285 residents. The transmission pipeline is 5000 m in length with 800 mm inner diameter (ductile iron) to transmit 50000 m^3/day by using a pumping station with 2 pumps

(290 l/s) with hydraulic booster lift = 65 m from underground reservoir (Reservoir 1) to two elevated tanks (Reservoir 2), South-east of El-Shorouk City, as shown in Figure (1).

The minimum and maximum pressures inside the transmission pipeline are studied and a protection method is recommended comprising technical data for protecting the system by using software Bentley HAMMER V8i. The transmission pipeline supply system transmits 50000 m^3/day from Reservoir 1 with a normal water level of 160.0 m by using two working pumps (Q = 290 l/s) along the transmission pipeline to Reservoir 2 with a normal water level of 210.0 m for a total static lift of 50 m, as shown in Figure (2). The level of the pumps is 155.0 m, and its speed is 1500 rpm. All pipes in the transmission pipeline have an 800 mm inner diameter and are made of ductile iron. The transmission pipeline consists of 2 air valves, and it is simulated in the Bentley HAMMER program with data as shown in Table (1).

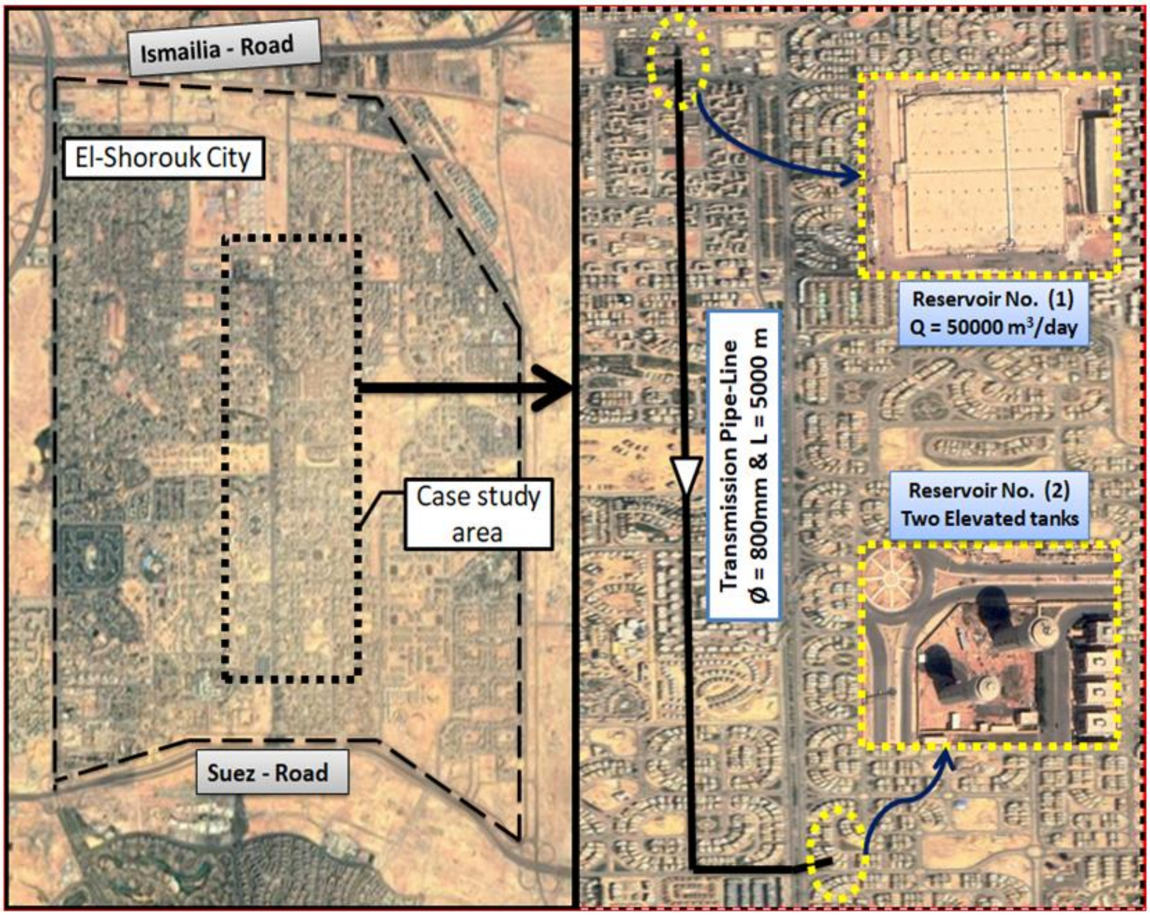

FIGURE 1. Transmission pipeline supply system in El-Shorouk City (case study)

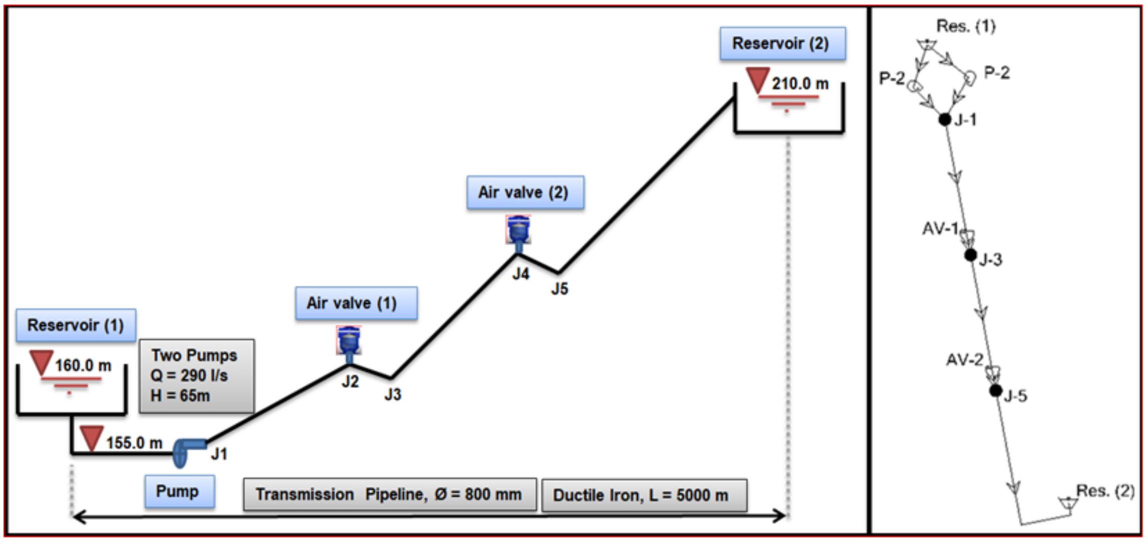

FIGURE 2. Schematic diagram of transmission pipeline supply system and system from Hammer Bentley

TABLE 1. Node's elevations and pipes' lengths

Node	Elevation (m)	Pipe			Length (m)
		ID	**from**	**to**	
Reservoir (1)	160	-	-	-	-
Pump	155	P 1	Reservoir (1)	Pump	10
J 1	169	P 2	Pump	J 1	10
J 2 (Air valve 1)	175	P 3	J 1	J 2 (Air valve 1)	1390
J 3	172	P 4	J 2 (Air valve 1)	J 3	200
J 4 (Air valve 2)	188	P 5	J 3	J 4 (Air valve 2)	1200
J 5	185	P 6	J 4 (Air valve 2)	J 5	200
Reservoir (2)	210	P 7	J 5	Reservoir (2)	1990

3. RESULTS AND DISCUSSION

3.1 HT Design (Protection System)

Figure (3) shows the steady state hydraulic grade line (HGL) and elevation along an unprotected transmission pipeline supply system employing the model software. The transmission pipeline hydraulic model was created by using the Bentley HAMMER program. Steady-state analysis was performed considering the pump characteristic data and pipeline information. Pumps have a flow rate of 315 l/s and a head of 60.0 m, so pumps will work within a safe range.

The transient analysis for this pipeline system was carried out without any protection to assess the potential for high/low transient pressure due to pump failure, which is a common condition (problem) in the pumping system at Reservoir (1), as shown in Figure (4). Also, as seen in Figure (5), maximum pressure reached 214.5 m (21.45 bars) at the beginning of the pipeline with an elevation of 369.5 m and minimum pressure reached to cavitation head of -9.98 m through the transmission pipeline. Maximum pressure can cause pipe fractures because pipe material can withstand only pressure of 160 m (16 bars).

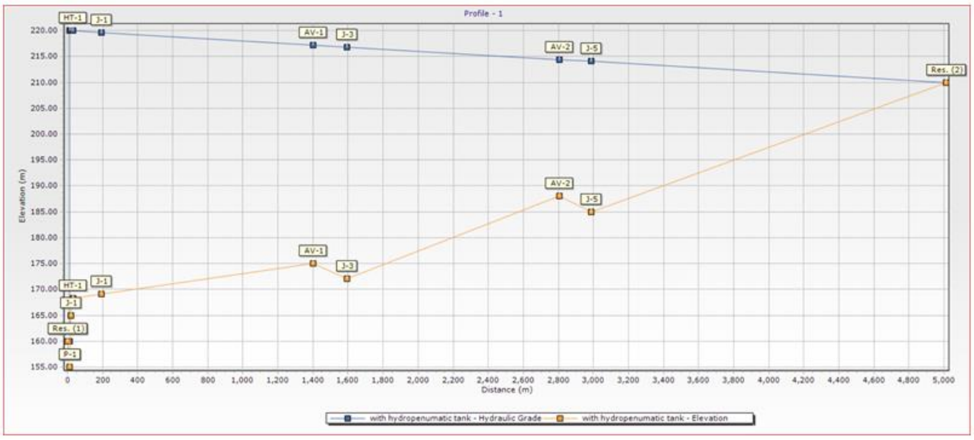

FIGURE 3. Hydraulic grade line and elevations along unprotected transmission pipeline supply system

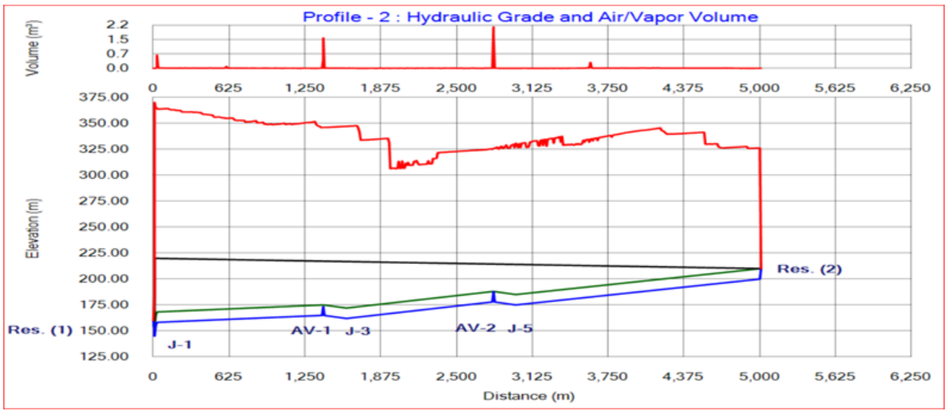

FIGURE 4. Hydraulic grade (max, min, and initial) and elevations for the transient state along unprotected transmission pipeline supply system

In Figure (4), the red line represents the maximum transient head, the green line represents physical pipe elevation, the blue line represents the minimum transient head, and the black line represents the initial conditions head.

3.2 Alternatives of HT Sizing

For protecting the long transmission pipeline system, a hydropneumatic tank (HT) was used with an initial design volume of 20 m^3 with a liquid volume of 12 m^3 and an inlet pipe diameter of 400 mm (these values are common for most designs). The transient analysis for this pipeline system was carried out after using a hydropneumatic tank. As shown in Figures (6) and (7), the maximum pressure became 125.34 m (12.53 bars) and the minimum pressure became positive to avoid cavitation head through the transmission pipeline.

Figure (8) shows the variation of pressure and air volume inside HT during the transient time after pump failure. The initial gas volume in HT was 8 m^3, which gradually increased to a maximum volume of 18 m^3, while the remaining 2 m^3 was in liquid form. After 40 seconds, the gas volume decreased to a minimum of 5 m^3, while the liquid volume reached 15 m^3.

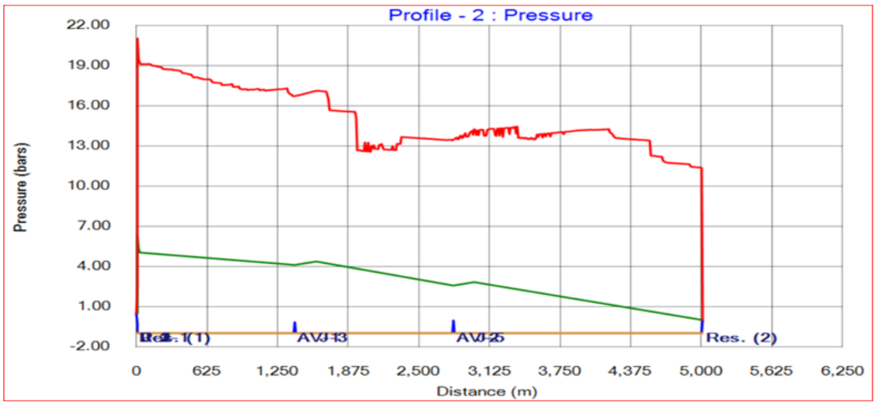

FIGURE 5. Pressure (max, min, and initial) for transient state along unprotected transmission pipeline supply system

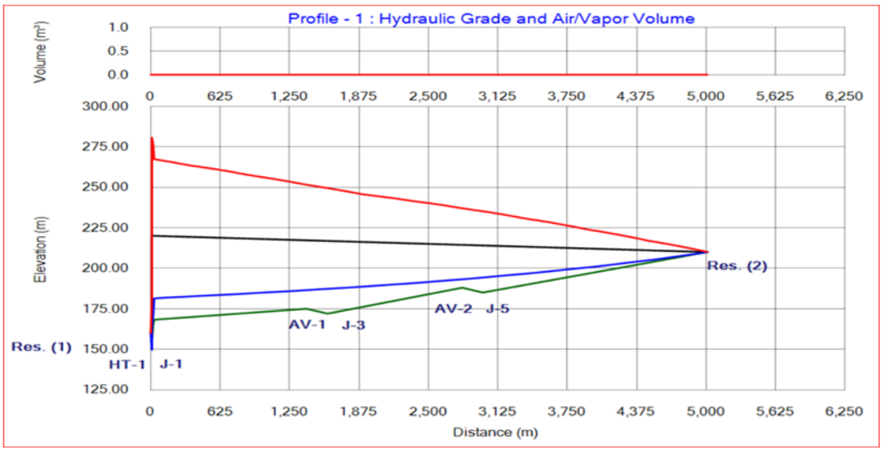

FIGURE 6. Hydraulic grade (max, min, and initial) and elevations for transient state along protected transmission pipeline supply system using HT

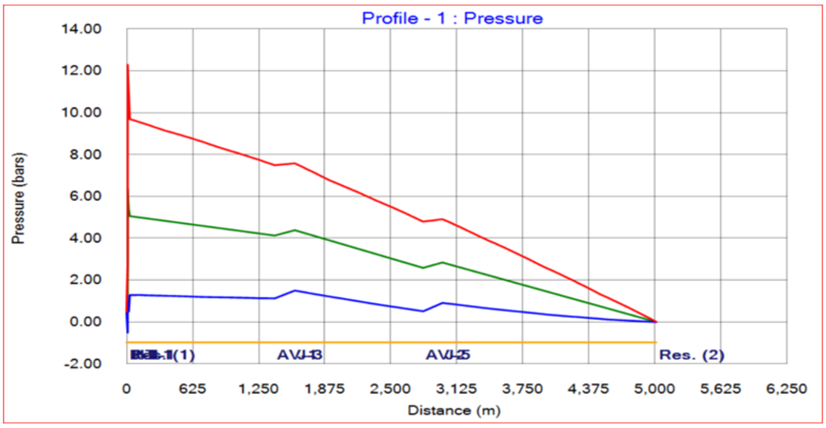

FIGURE 7. Pressure (max, min, and initial) along the protected transmission pipeline supply system using HT

Following the pump failure, the maximum and minimum pressures in HT were 10.94 bars and 2.35 bars, respectively, as indicated in Figure (9). The maximum velocity was 1.29 m/s, and there was no vapor volume present.

To determine the optimal sizing for HT, including the inlet orifice diameter (d) and liquid-to-air ratio (L_R), numerous variable parameters were analyzed, and the best alternatives were compared. The alternatives were tested individually and in combination to arrive at the optimal HT sizing.

The main parameters of HT design are tank inlet orifice diameter (d) and liquid volume/air volume ratio (L_R). These parameters were studied against the two main categories for the transmission pipeline supply system: max pressure through the transmission pipeline and vapor volume.

The inlet orifice diameter varied with different ratios relative to the pipe diameter, while the liquid ratio (L_R) was tested with ratios ranging from 0.50 to 0.75, as presented in Table 2.

FIGURE 8. Variation of gas volume inside HT during the transient time after pump failure

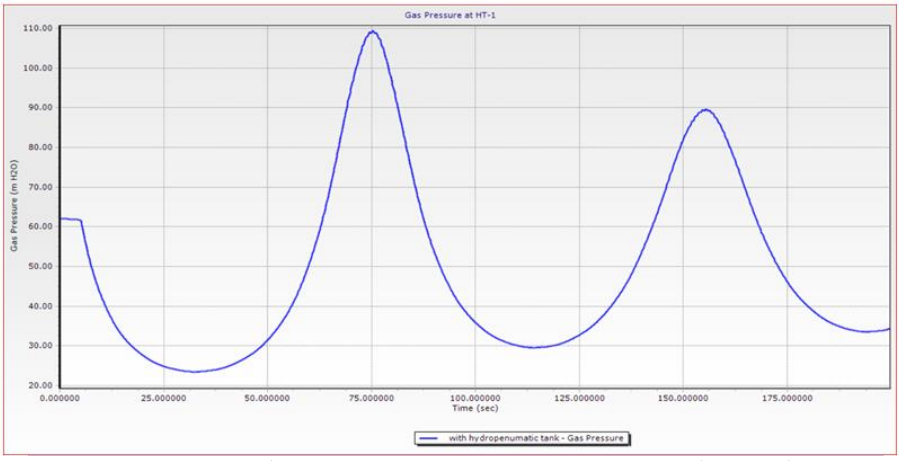

FIGURE 9. Variation of gas pressure inside HT during the transient time after pump failure

TABLE 2. All different alternatives (48 alternatives) for determining optimum HT sizing

Inlet orifice diameter "d" (mm)	**d/D; (D: Pipe Diameter)**	**Liquid ratio (L_R) in HT**					
		0.50	**0.55**	**0.60**	**0.65**	**0.70**	**0.75**
600	0.75	√	√	√	√	√	√
500	0.625	√	√	√	√	√	√
400	0.50	√	√	√	√	√	√
300	0.375	√	√	√	√	√	√
250	0.3125	√	√	√	√	√	√
200	0.25	√	√	√	√	√	√
150	0.1875	√	√	√	√	√	√
100	0.125	√	√	√	√	√	√

Tables (3) and (4) show the results obtained for various HT designs employing Bentley HAMMER V8i after carrying out all different alternatives. The results concerned two main categories: max pressure (bars) through the transmission pipeline and vapor volume (liter). Also, the important transient aspect to determine the optimum HT size is air (gas) pressure in HT, as illustrated in Table (5).

TABLE 3. Transient results for maximum pressure of HT design

Inlet orifice diameter "d" (m)	d/D; D: Pipe diameter	Liquid ratio (L_R) in HT					
		0.50	0.55	0.60	0.65	0.70	0.75
		Maximum pressure, bar					
600	0.75	18.0	16.0	13.4	13.0	14.4	17.1
500	0.625	17.9	15.6	12.9	12.8	14.3	17.0
400	0.50	17.7	15.2	12.5	12.7	14.1	16.9
300	0.375	17.5	14.8	12.0	12.5	13.8	16.8
250	0.3125	17.1	14.4	11.9	12.4	13.7	16.8
200	0.25	16.7	13.9	11.3	12.2	13.6	16.7
150	0.1875	16.3	13.5	11.0	12.1	13.5	16.6
100	0.125	18.5	15.9	13.3	12.2	13.7	16.9

TABLE 4. Transient results for vapor volume of HT design

Inlet orifice diameter "d" (mm)	d/D; D: Pipe diameter	Liquid ratio (L_R) in HT					
		0.50	0.55	0.60	0.65	0.70	0.75
		Vapor volume, lit.					
600	0.75	13.3	0	0	0	2.2	36.0
500	0.625	15.2	0	0	0	2.6	37.4
400	0.50	19.9	0	0	0	3.2	38.4
300	0.375	22.5	0	0	0	5.1	40.5
250	0.3125	27.0	0	0	0	6.7	42.9
200	0.25	32.2	0	0	0	7.2	43.2
150	0.1875	39.0	2.1	0	0.1	10.9	44.7
100	0.125	42.7	5.8	0	0.3	12.3	46.1

TABLE 5. Transient results for gas pressure inside HT for different ratios between inlet orifice diameter and pipe diameter (d/D)

Pressure (bar)	Liquid ratio (L_R) in HT					
	0.50	0.55	0.60	0.65	0.70	0.75
Maximum pressure ($P_{max.}$, bars)	98.3	102.6	109.8	133.2	153.2	106.9
Minimum pressure ($P_{min.}$, bars)	36.2	29.1	22.5	18.8	15.8	15.8
Differential pressure (ΔP, bars)	62.1	73.5	87.3	114.4	137.4	91.1

From these transient results from Tables (3), (4), and (5), the following are concluded:

a) The max pressure through the pipeline decreases as the inlet orifice diameter decreases until the diameter of 150 mm (≈ 1/5 times the transmission pipeline diameter). Further decreasing the inlet orifice diameter, the max pressure increases.
b) There is no vapor for only the liquid ratio 0.60. HT with a vapor volume of zero means that the tank is filled with water and has no space for compressed air or gas.
c) The max pressure decreases as the liquid volume increases until the liquid ratio of 0.70.
d) The max pressure decreases as the ratio d/D decreases until the ratio of d/D = 0.1875.
e) Differential pressure (ΔP) inside HT is small from the liquid ratios 0.50 to 0.60, so these results deduce these ratios for liquid in HT are preferred. Small ΔP is a good indicator for filling and emptying because this means that HT volume is appropriate due to small ΔP and not more than what is required.

3.3 Regression Analysis

Regression analysis is performed to investigate the relation between the ratio of the inlet diameter to the pipe diameter d/D and the maximum pressure H_{max} for different liquid ratios in HT, as shown in Figure (10). This figure excludes the ratio d/D = 0.125 because the maximum pressure increases for all liquid/gas ratios. Six equations are developed to predict the maximum pressure H_{max} according to the inlet diameter to the pipe diameter ratio d/D for different liquid ratios L_R in HT, as tabulated in Table (6).

Also, the relation between the maximum pressure H_{max} and the liquid ratios L_R in HT is studied through regression analysis for different ratios of the inlet diameter to the pipe diameter ratio d/D, as shown in Figure (11). Eight equations are developed to predict the maximum pressure H_{max} according to liquid ratios L_R in HT for different ratios of the inlet diameter to the pipe diameter d/D, as presented in Table (7).

TABLE 6. Equations to predict Hmax for different liquid ratios LR in HT

L_R	Developed equation	R^2
0.50	$H_{max} = -0.0571\left(\frac{d}{D}\right)^2 + 2.886\left(\frac{d}{D}\right) + 16.06$	0.8814
0.55	$H_{max} = -0.0861\left(\frac{d}{D}\right)^2 + 4.3531\left(\frac{d}{D}\right) + 12.905$	0.9661
0.60	$H_{max} = -0.0824\left(\frac{d}{D}\right)^2 + 4.1634\left(\frac{d}{D}\right) + 10.366$	0.9773
0.65	$H_{max} = -0.0311\left(\frac{d}{D}\right)^2 + 1.5709\left(\frac{d}{D}\right) + 11.852$	0.9808
0.70	$H_{max} = -0.034\left(\frac{d}{D}\right)^2 + 1.7165\left(\frac{d}{D}\right) + 13.175$	0.9914
0.75	$H_{max} = -0.0153\left(\frac{d}{D}\right)^2 + 0.7747\left(\frac{d}{D}\right) + 16.526$	0.9844

TABLE 7. Equations to predict Hmax for different ratios of the inlet diameter to the pipe diameter d/D

d/D	Developed equation	R^2
0.75	$H_{max} = 285(L_R)^2 - 362.48(L_R) + 128.39$	0.9562
0.625	$H_{max} = 298.57(L_R)^2 - 378.07(L_R) + 132.57$	0.9717
0.5	$H_{max} = 306.43(L_R)^2 - 387.09(L_R) + 134.85$	0.9773
0.375	$H_{max} = 315.71(L_R)^2 - 396.41(L_R) + 136.51$	0.9835
0.3125	$H_{max} = 320.71(L_R)^2 - 404.32(L_R) + 139.65$	0.9769
0.25	$H_{max} = 325(L_R)^2 - 406.25(L_R) + 138.65$	0.9759
0.1875	$H_{max} = 329.29(L_R)^2 - 409.55(L_R) + 138.81$	0.9752
0.125	$H_{max} = 324.29(L_R)^2 - 414.33(L_R) + 145$	0.9659

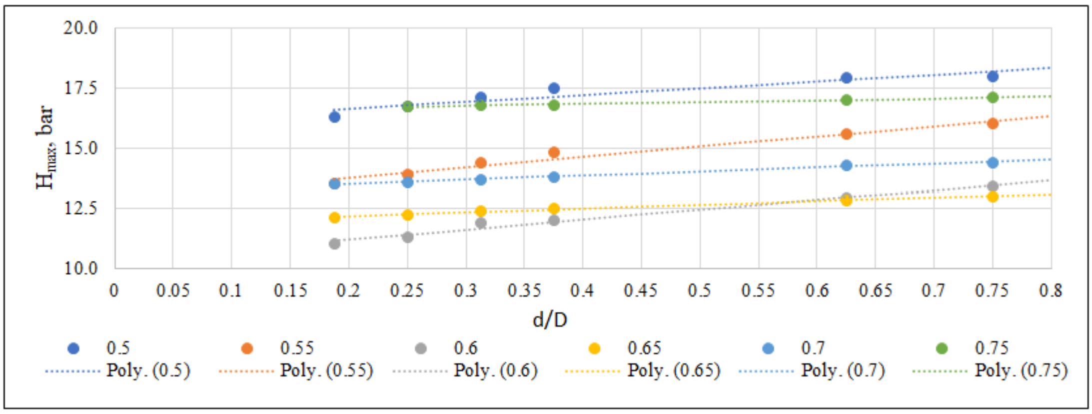

FIGURE 10. Regression analysis for Hmax versus d/D for different liquid ratios of (LR) in HT

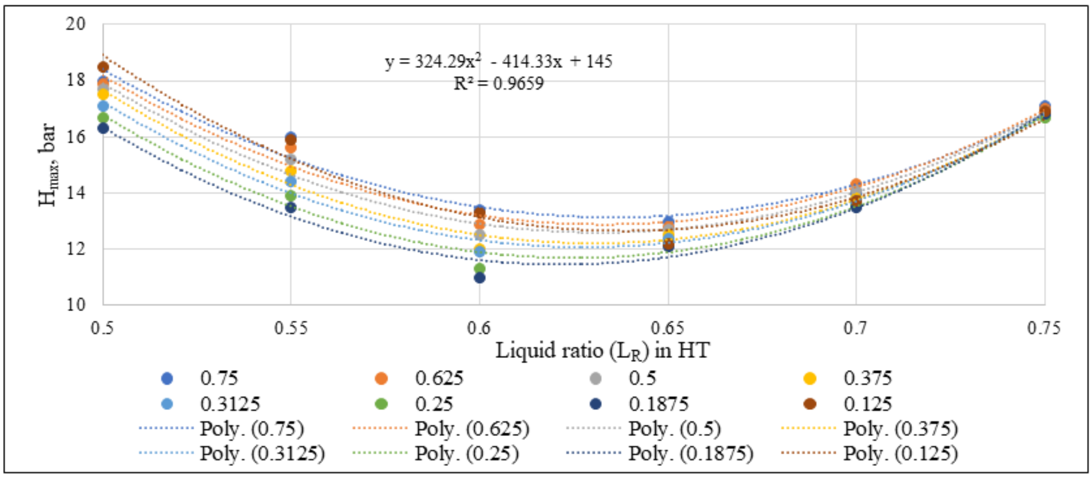

FIGURE 11. Regression analysis for Hmax versus liquid ratio (LR) in HT for different ratios of d/D

4. CONCLUSIONS

This paper is concerned with the water hammer phenomenon study inside a transmission pipeline supply system of 5000 m length with 800 mm inner diameter (ductile iron) to transmit 50000 m^3/day by using a pumping station with 2 pumps (290 l/s) with hydraulic booster lift = 65 m from underground (Reservoir 1) to two elevated tanks (Reservoir 2), Southeast of El-Shorouk City, Cairo Governorate, Egypt.

HAMMER Bentley is used for the analysis of water hammer pressure in the transmission pipeline in El-Shorouk City and analytical methods are used for determining the optimum hydropneumatic tank sizing to control the water hammer phenomenon. The optimum HT sizing is according to liquid ratio in HT and inlet orifice diameter d. The following conclusions are concluded from this study.

It is concluded that the optimal liquid ratio inside the HT is 0.60, with an inlet orifice diameter of 150 mm (0.1875 times the pipeline diameter). There is no vapor for the liquid ratio in HT of 0.60, which means that the tank is filled with water and there is no space for compressed air or gas.

A small (ΔP) inside the HT is a good indicator for filling and emptying, particularly for the liquid ratios in HT in the range of 0.50 to 0.60.

Savings of 75% in the inlet orifice diameter (only 150 mm instead of 600 mm) is accomplished for the obtained optimal liquid ratio inside the HT of 0.60.

Six equations are developed to predict the maximum pressure H_{max} according to the inlet diameter to the pipe diameter ratio d/D for different liquid ratios L_R in HT.

Eight equations are developed to predict the maximum pressure H_{max} according to liquid ratios L_R in HT for different ratios of the inlet diameter to the pipe diameter d/D.

COMPETING INTERESTS

The authors have declared that no competing interests exist.

References

[1] G. Wang, and S. Chen, "Control of water hammer in pipelines: a review of recent advances", Journal of fluid mechanics, 2020, 899, A22.

[2] Y. Xu, Y. Zhang, and Y. Wang, "Numerical simulation of water hammer in pipelines: a review", Journal of hydraulic research, 2021, 59(3), 413-428.

[3] Wood D.J., "Water hammer analysis - Essential and easy and efficient", J. Environmental Eng., 2005, 131(8):1123-1131.

[4] Joyanta Kumar Roy, Priti kumar, and Pijush Basak, "Water hammer protection in water supply system: a new approach with practical implementation", 2011, IEEE ICCIA https://www.researchgate.net/publication/254051250 .

[5] Ashish Kumar Patel, “Experimental Study of Water Hammer Pressure in a Commercial Pipe”, IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN: 2278-1684, 2015, p-ISSN: 2320–334X. Special Issue - AETM'16.

[6] Abuiziah I, Oulhaj A, Sebari K, and Ouazar D., “Sizing the protection devices to control water hammer damage”, International Scholarly and Scientific Research & Innovation, 2013, 7(11):558-563.

[7] Alaa Nabil EL-HAZEK, “Hydro-pneumatic Tank Design for Surge Protection of Irrigation Pipeline System”, Journal of Scientific Research & Reports, 18(6), 2018, 1-15. DOI: 10.9734/JSRR/2018/40253.

[8] Anton Bergant, Jernej Mazij, and Uroš Karadžić, “Design of water hammer control strategies in hydropower plants”, Applied Engineering Letters, Volume 3, 2018, No.1, 27-33. https://doi.org/10.18485/aeletters.2018.3.1.5 .

[9] Abuiziah I, Oulhaj A, Sebari K, and Ouazar D., “Controlling transient flow in Pipeline systems by surging tank with automatic air control”, World Academy of Science, Engineering and Technology International Journal of Physical and Mathematical Sciences, 2013, 7(12): 1775-1781.

[10] EL-Turki A., “Modeling of hydraulic transients in closed conduits”, M. Sc. Thesis, Colorado State University, Fort Collins, Colorado, USA, 2013.

[11] Larock BE, Jeppson RW, Watters GZ., “Hydraulics of pipeline systems”, New York: CRC Press, 2000.

[12] Afreen Emad, “Solutions for Water Hammer Phenomenon in the Low Lift Pump Station Located on Tigris River”, Eng. &Tech. Journal, 2013, Vol.31, No.1.

[13] R. Wang, Z. Wang, X. Wang, H. Yang, and J. Sun, “Water Hammer Assessment Techniques for Water Distribution Systems”, Procedia Engineering, Volume 70, 2014, 1717-1725. https://doi.org/10.1016/j.proeng.2014.02.189.

[14] Alaa N. EL-HAZEK, Menna F. AHMED, and Neveen Abdel-Mageed BADAWY, “Transient flow simulation, analysis, and protection of pipeline systems”, Journal of Water and Land Development, 2020, No. 47 (X–XII) p. 47–60. DOI: 10.24425/jwld.135031.

[15] Bagaragaza Romuald, Zhang Jian, Yu Xiao Dong, and Dusabemariya Claire, “Assessment and Performance Evaluation of Water Hammer in Hydroelectric Plants With Hydropneumatic Tank and Pressure Regulating Valve”, J. Pressure Vessel Technol., 2021, 143(4): 041401 https://doi.org/10.1115/1.4049148.

[16] Mohammad Hossein Arefi, Mahnaz Ghaeini Hessaroeyeh, and Rasoul Memarzadeh, “Numerical modeling of water hammer in long water transmission pipeline”, Applied Water Science, 2021, 11:140. https://doi.org/10.1007/s13201-021-01471-9.

[17] Sanghyun Kim and Dooyong Choi, “Dimensionless Impedance Method for General Design of Surge Tank in Simple Pipeline Systems”, Energies 2022, 15, 3603, 2022, https://doi.org/10.3390/en15103603.

[18] Ahmed Tawfik, “Air vessel sizing approach for pipeline protection using artificial neural networks”, Journal of Engineering and Applied Science, 2023, 70:34. https://doi.org/10.1186/s44147-023-00206-8.

[19] Arris, S. Tijsseling and Anderson Alexander, “The Joukowsky equation for fluids and solids”, 2015.