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Transient flow simulation, analysis and protection of pipeline systems

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Abstract

This paper investigated the problems and impacts of transient flow in pipeline systems due to pump power failure. The impact of different protection devices was presented to assure surge protection for the pipeline system. A model via Bentley HAMMER V8.0 Edition was employed to analyse and simulate hydraulic transients in the pipeline system, and protection alternatives were studied.

Surge protection included using only an air vessel, using an air vessel and two surge tanks, and employing five air vessels and vacuum breaker. The obtained results for pressures, heads, and cavitation along the pipeline system were graphically presented for various operating conditions. Using five air vessels with vacuum breaker valve as surge protection proved to be more effective and economical against pump power failure.

Changing the flow density did not have a significant impact on the pressures.

For protection with an air vessel; it was concluded that the value 40% of the original diameter for inlet pipe diameter of air vessel, and the value of 2/3 of original pipe diameter were critical values for the transient pressures. Cast iron pipes proved to be the best pipe material for all studied volumes of the air vessel.

For protection with an air vessel and two surge tanks; as the inlet pipe diameters increased the maximum pressures increased and the minimum pressures decreased.

Regression analyses were performed obtaining equations to predict the pressures according to the inlet pipe diameter, the area of surge tank, and the pipe diameter.

Key words: *air vessel, Bentley HAMMER model, surge tank, unsteady flow, vacuum breaker valve, water hammer, water turbidity*

INTRODUCTION

Irrigation consumes increasing quantities of water due to increasing population all over the world. It was predicted that the demand for water in the agricultural of a studied commune in Poland would increase by about 5.5% by 2030 [KOPACZ *et al*. 2018]. A paper was presented to provide approach and universal solution to forecast the behaviour of urban catchment (including surface runoff or pipeline systems) for urbanization in terms of natural land-water cycles and its application in planning existing or new urban catchments that could be followed by the planners, engineers, and hydrologists [SHARMA 2019]. Pipeline systems that transport fluids through long distances are common in modern society [CARLSSON 2016]. For the most pipeline systems, the extreme pressures that occur during the transient operation of the system are considered as the most critical situations. It is fundamental for the design and operation of pipeline system to establish a transient analysis for normal startup and shutdown and for unplanned events [WOOD 2005]. A water distribution network is mainly a system of the dependent components valves and pipes, where the pipes are static elements and the valves are dynamic elements [LAKEHAL, LAOUACHERIA 2017]. Modelling based on a Static Bayesian Network (SBN) was implemented to analyse qualitatively and quantitatively the availability of water in the different segments of the network. Dynamic Bayesian networks (DBN) were then used to assess the valves reliability as function of time, which could allow management of water distribution based on water availability assessment in different segments.

For transient flow, the velocity and pressure can change suddenly affecting badly the pipeline, which may be relatively long with a quite large diameter. There are various causes of water hammer. The most common events that can produce large changes in pressure are pump startup, pump power failure, and valve opening and closing. Also, non-proper operation or incorporation of surge protection devices can cause more damage than providing protection for the system. The essential objective of transient flow analysis is to determine the values of transient pressures that can result due to sudden changes in flow velocity, and to establish suitable devices that provide an acceptable level of protection against system failure. Various techniques have been used to analyse water hammer phenomena such as the arithmetic, energy, graphical, algebraic, characteristics, Euler and Lagrangian based method, implicit and linear analysing, and decoupled hybrid methods [ABUIZIAH *et al*. 2013]. The elastic effects of the fluid and pipeline must be considered in order to obtain an accurate characterization of the transient flow conditions [LAROCK *et al*. 1999].

This excess pressure, known as water hammer pressure, is caused by momentary changes in flow velocity, and is identified as shockwaves moving through the liquid at the local speed of sound, celerity [PATTERSON, COVEY 2014]. Water hammer is the significant force which causes pounding noises and vibration in a pipeline system when the flow is suddenly stopped due to any unplanned event [SALEHI 2010]. Pump startup can induce the rapid collapse of a void space existed downstream the pump generating high magnitudes of pressures. The power failure of the pump can produce a flow disturbance, which causes a sudden increase in pressure on the suction side and a sudden decrease in pressure on the destination. The surge pressure on the discharge side is usually the main problem, where it might reach high values of negative pressure that probably reach vapour pressure resulting in vapour column separation. A valve closure at the downstream of a pipeline system in a time less than it takes causes a pressure wave that moves toward the reservoir, where velocity changes rapidly and producing a surge pressure. Improper operation or inappropriate surge protection devices can dramatically do more harm than good. For example, the oversizing of the surge relief valve, the vacuum breaker or air relief valve, which might cause column separation [LAHLOU 2009].

There are other factors that can cause water hammer in pipeline system such as: changes in water levels, changes in the flow transmission conditions, and pipeline filling or draining or sudden release of air [BERGANT *et al*. 2012]. Disturbances due to surge pressures may result in system fatigue, backflow of dirty water for wastewater pipeline, pipe collapse, vibration, excessive pipe displacements, pipe-fitting, support deformation and/or failure, water column separation, and vapour cavity formation, valve failures, overstress pressure gauges, and bend internal system mechanisms. That's why improved operations in piping systems is required [YU *et al*. 2015], devices such as surge tanks [VEREIDE *et al*. 2017], air vessels, and air valves [BERGANT *et al*. 2012] are strongly needed in some projects to ensure the running security. The surge pressure must be incorporated with the operating pressure in the design of the pipeline as the maximum pressure that can be produced, known now as the Joukowski pressure or Joukowski head [ORD 2006]. The dynamics of fluids is always described by the Navier Stokes equations [KUNDU *et al*. 2011] and [LOH, TIJSSELING 2014], which are mainly two partial differential equations that represented by the continuity and the momentum equations.

The maximum and the minimum pressure can be obtained through method of characteristics – (MOC), which converts the two partial differential equations into four total differential equations that were employed by KARNEY, MCINNIS [1992] and TEZKAN *et al*. [1998] for analysing transient events in simple and complicated pipeline systems, respectively. The obtained results of surge pressures were more accurate in the simple pipeline systems [JUNG *et al*. 2007]. A theoretical result that usually relates to actual system measurements was produced by solving the two partial differential equations for valid data and assumptions via numerical model [SALMANZADEH 2013]. It was recorded that decreasing the diameter till 1/6 times the pipeline diameter, the max pressure decreases. More decreasing the diameter, the max pressure increases [EL-HAZEK 2018]. Protecting irrigation systems from water hammer damage can be achieved by creating conditions in which a water hammer will not occur as a result of closing the end gate valve (EGV). To verify the effectiveness of a combined end gate valve closure of a pipeline [HERASYMOV *et al*. 2019] investigated processes occurring in the pipeline during a linear closure of the EGV, during a closure with one break point and during an intermittent closure. Based on experimental data and calculations, a linear closure of the EGV with one break point was recommended.

MATERIAL AND METHODS

A typical pipeline system is studied. The pump station is located at elevation (85.00 m) + msl, which consist of six parallel pumps (five pumps are in operation simultaneously and one is considered as a standby pump of similar type) to provide 6.00 $m^3 \cdot s^{-1}$ into the system from elevation (79.81 m) + msl at suction level to elevation (111.41 m) + msl at delivery side. The pumping station is followed by an 1800 mm main header diameter with 30 m length that is branched into two Glass fibre reinforced plastics (GRE) pipelines each of 1200 mm diameter with 1600 m length to deliver water to open channel at the end of the pipeline. The main header steel pipe extends from the pump station at elevation (85.00 m) + msl to (88.65 m) + msl for a length of 30.00 m. It then branches to two pipelines each of 1200 mm diameter sloping upward for a length of 1600 m to elevation (111.41 m) + msl, as shown in Figure 1.

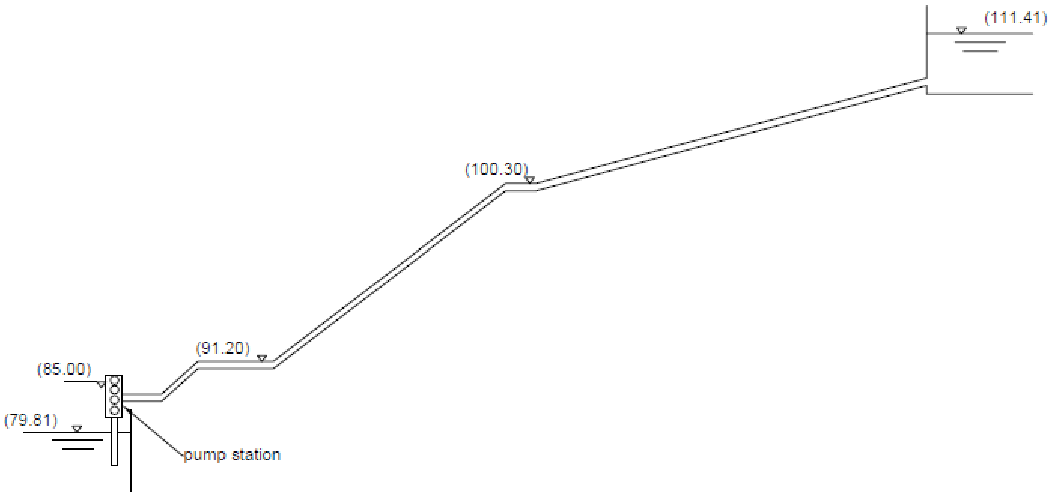

Fig. 1. Schematic diagram of the pipeline system; source: own elaboration

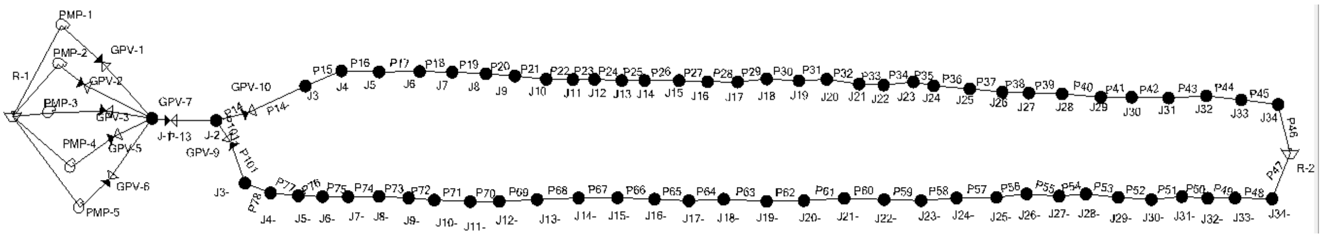

Fig. 2. The pipeline hydraulic system; *GPV* = an indication for check valve *J* = indication for the junction, and it is an item to represent the pipeline profile as shown in Figure 3, *P* = an indication for the pipes in the system; source: own elaboration

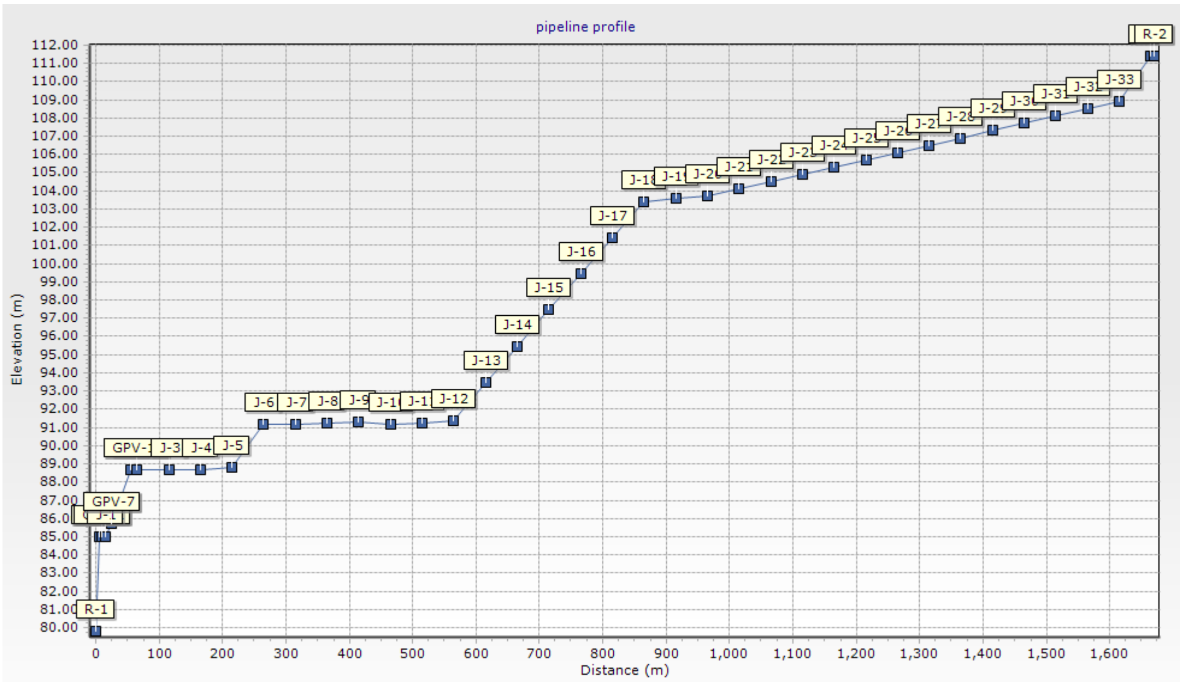

Fig. 3. The pipeline system profile; source: own elaboration

Bentley HAMMER model is used to perform the simulation and analysis of hydraulic transients in the pipeline system due to power failure of the pump. The employed software is Bentley HAMMER V8i (SELECTseries4). The pipeline system is represented via Bentley HAMMER Software, as illustrated in Figures 2 and 3.

From previous it can be clearly seen that, transient performance of a piping system may be improved, in general, by changing the geometrical design (the system boundaries). This design modification may be particularly effective in suction lines, since it greatly decreases the possibility of cavitation. Thus various scenarios will be studied such as the effect of inlet-pipe diameter of air Vessel (using only air vessel) where different values of inlet pipe diameter of air vessel are studied with various air vessel volumes to find the optimum case that provides economical protection against water hammer. Three cases are tested for air vessel volumes, which are case 1 of an air vessel of 400 m^3volume, case 2 of an air vessel of 375 m^3volume, and case 3 of an air vessel of 350 m^3volume for 300–1800 mm inlet pipe diameters. As well as studying the effect of inlet-pipe diameter of air vessel (using air Vessel + two Surge Tanks) while different values of inlet pipe diameter of air vessel are studied with various areas of surge tanks to find the optimum case that provides economical protection against water hammer. Four areas of surge tanks are investigated, which are 10, 12, 14, and 16 m^2 for 700–1200 mm inlet pipe diameters. While the studied air vessel in this scenario is 200 m^3volume. An important scenario such as testing the effect of changing pipe diameter will be presented as different pipeline diameters have been studied for three different volumes of air vessel to investigate the optimum and economical case of protection against water hammer. The total volumes of air vessel are 400 m^3 as case 1, 375 m^3 as case 2, and 350 m^3 as case 3 while changing the pipeline diameters from 800 mm to 1800 mm. Finally, the effect of changing pipe material will be tested. Various pipeline materials have been studied for three different volumes of air vessel to investigate the optimum and economical case of protection against water hammer. The total volumes of air vessel are 400 m^3 for case 1, 375 m^3 for case 2, and 350 m^3 for case 3. The studied pipeline materials are glass reinforced plastics (GRP), steel, cast iron and concrete. The inlet pipe diameter and pipeline diameter are 1500 mm and 1200 mm, respectively.

The previous scenarios will be tested to reach the optimum case with the best protection and most economical scenario.

RESULTS AND DISCUSSION

ANALYSES OF DATA

The pipeline system is simulated under different circumstances for non-protected and protected conditions. For non-protected pipeline, when a power failure occurs suddenly, the check valves close upon that failure. Meanwhile, the flow velocity rapidly reaches zero and then reverses, negative pressure waves are prevailed downstream from the pump, and positive pressure waves are prevailed upstream through the suction pipe. Also, vapour pressure and column separation may occur in the discharge pipelines.

The maximum positive and the minimum negative pressures in the pipeline system after the power failure are presented in Figure 4. The maximum pressure is 952.5kPa at start of the pipeline and the negative pressure reached 100 kPa. These values of pressures are more than the allowable working pressures.

As shown in Figure 5, the maximum head and minimum head in each pipeline reached to 185.97 and 78.43 m at begin of the pipeline, respectively. Cavitation occurred at the location 825 m of the pipeline, and the initial head under steady state conditions is illustrated. It is obvious that the minimum head is lower than the pipeline elevation as a result of the negative pressure along the pipeline.

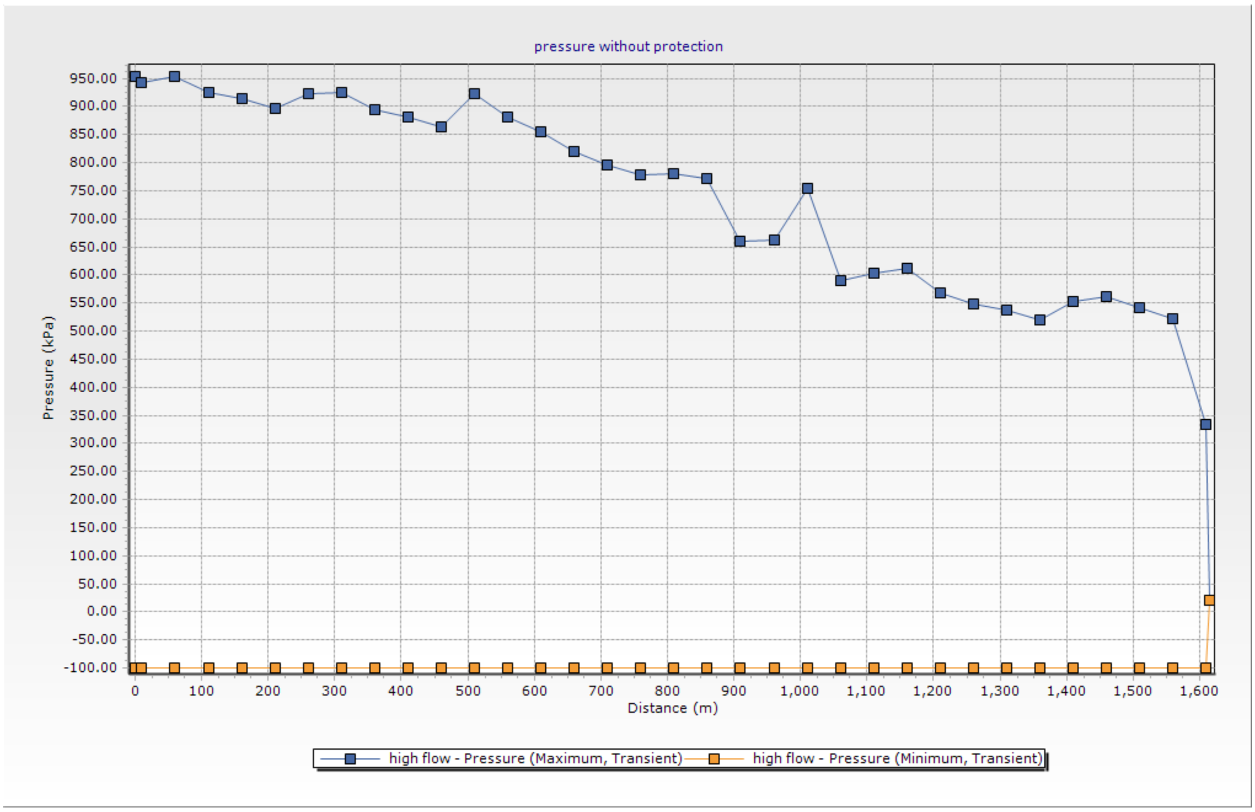

Fig. 4. Pressure (max and min.) along the pipeline system; source: own study

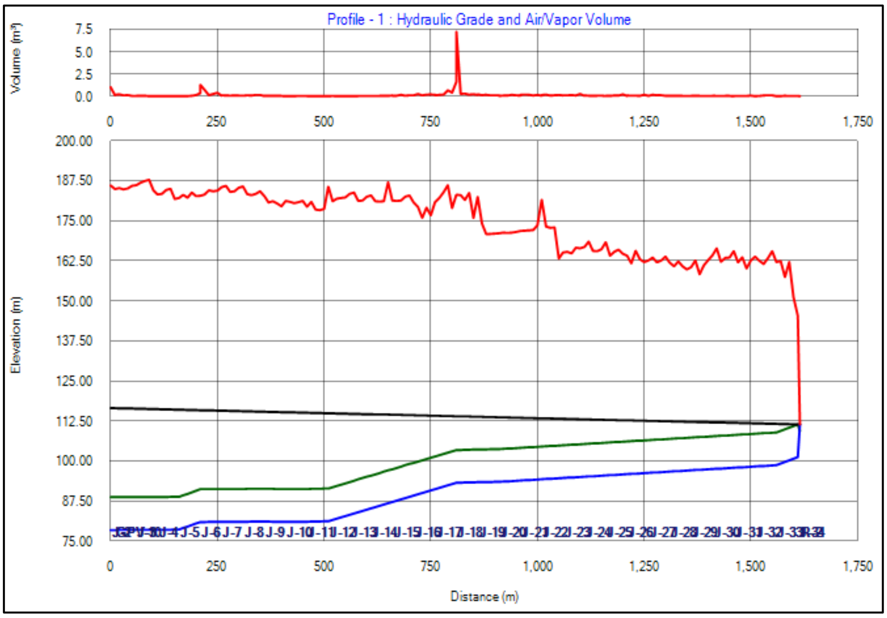

Fig. 5. Hydraulic grade (max, min. and initial), elevation and vapour volume along the pipeline system; *J* with numbers, it is an indication for the junction's number along the pipeline; source own study

PROTECTION CASE (1) VIA AN AIR VESSEL

An air vessel is installed as a common solution to protect the pipeline system, as shown in Figures 6 and 7. The purpose of this device is to limit the pressure drop and to avoid the possible occurrence of column separation or air bubbles formation due to vapour pressure in the pump. The total volume and the liquid volume of the air vessel are 400 and 200 m^3, respectively.

As shown in Figure 8, the maximum pressure in each pipeline changed and reached 401 kPa, which is less than the working pressure (600 kPa), and the minimum negative pressure in pipeline reached 7.3 kPa, which is less than the allowable pressure (–10 kPa). These values are safe for the pipeline system. The maximum and minimum heads in each pipeline changed and reached to 129.43 m and 96.58 m at beginning of the pipeline, which provide safety against collapsing, as presented in Figure 9. Also, the vapour volume is 0.00 at all locations which confirm the safety of the pipeline system.

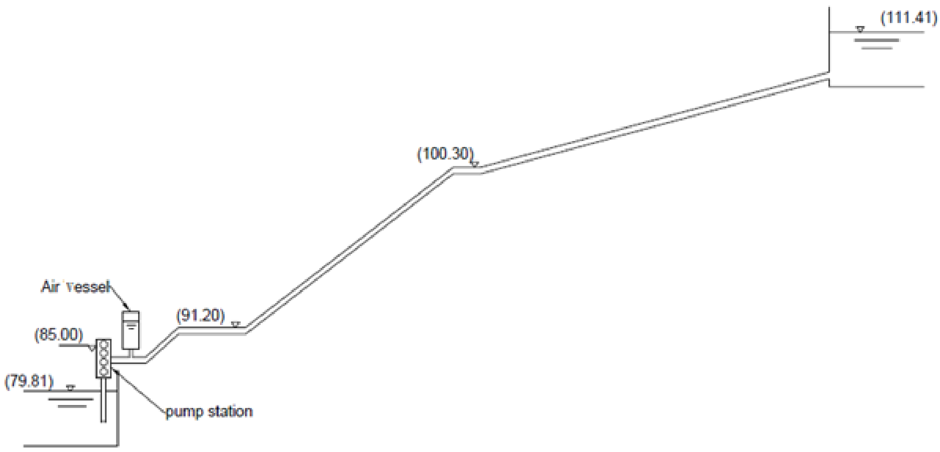

Fig. 6. Schematic diagram of pipeline system with protection via an air vessel; source: own study

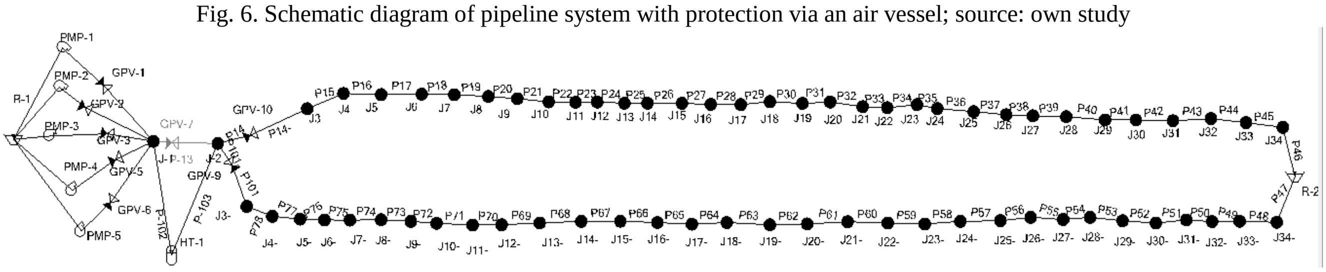

Fig. 7. The pipeline hydraulic system with protection via an air vessel; source: own study

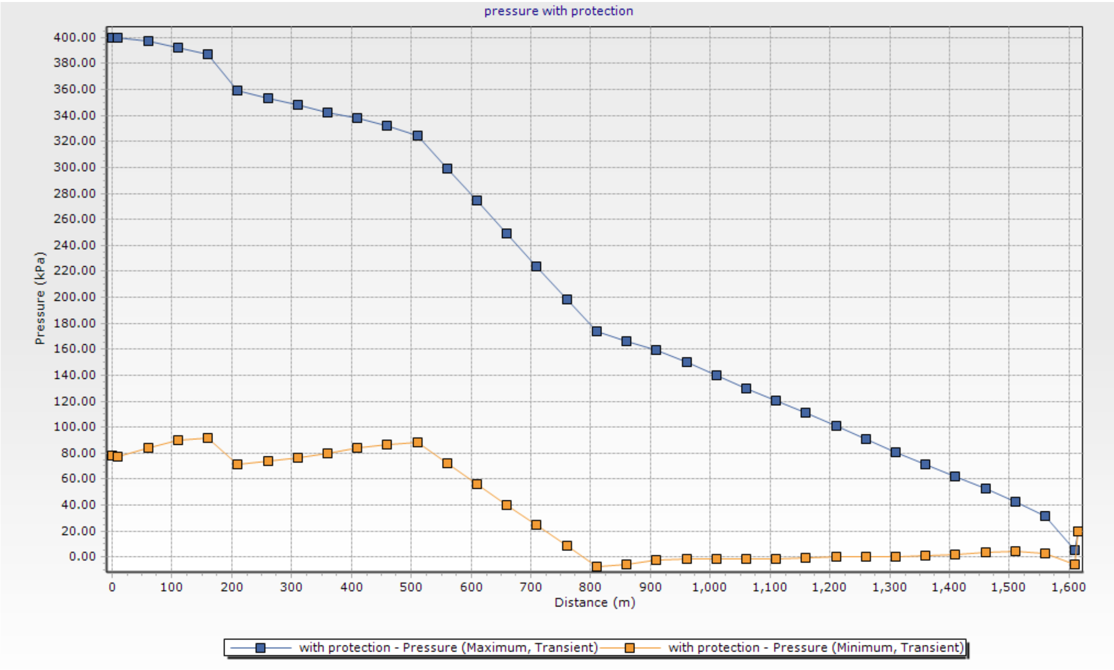

Fig. 8. Pressure (max and min.) along the pipeline system with protection via an air vessel; source won study

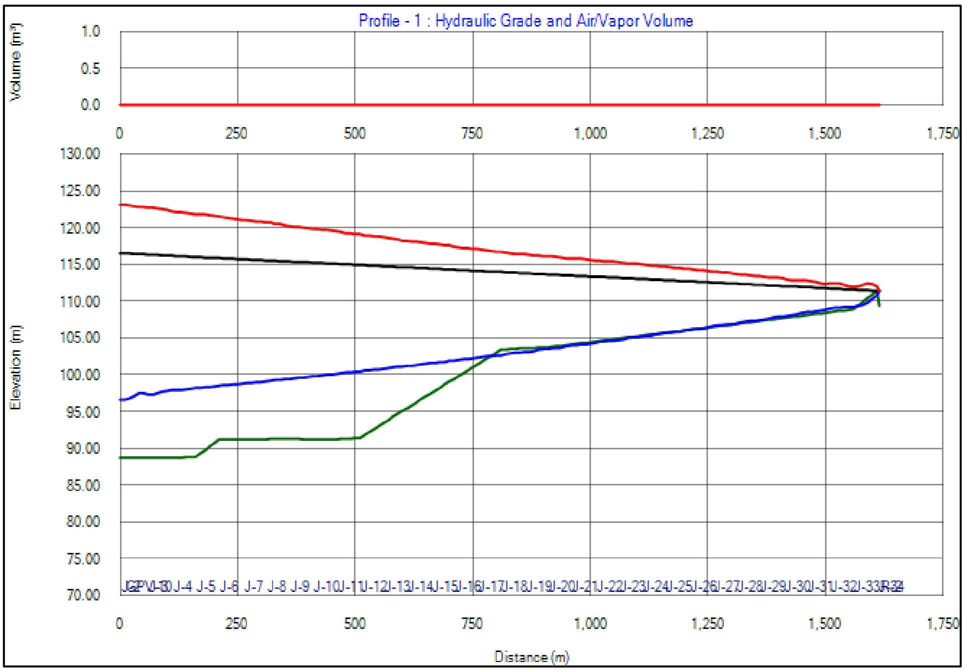

Fig. 9. Hydraulic grade (max, min. and initial), elevation and vapour volume along the pipeline system with protection via an air vessel; *J* with numbers, it is an indication for the junction's number along the pipeline; source: own study

PROTECTION CASE (2) VIA AN AIR VESSEL AND TWO SURGE TANKS

Another protection system against the transient events is employed, which is composed of an air vessel on the main header, and two surge tanks at the middle of the GRE pipes. The purpose of the surge tank is to mitigate pressure variations due to rapid changes in velocity in the pipeline system. When the load on the system decreases, the fluid direction is reversed and gets stored in the surge tank. On the other hand, when the load on the system increases, additional amount of fluid will be supplied by the surge tank. The total volume of the air vessel is 200 m^3, and the area of each surge tank is 16.00 m^2 with variable initial height of water surface, as shown in Figures 10 and 11.

From the obtained results, as shown in Figure 12, the maximum pressure in each pipeline changed and reached 382.66 kPa ,which is less than the working pressure (600 kPa), and the negative pressures through the pipeline system is 6.2 kPa near the end of the pipeline, which is less than the allowable pressure (–10 kPa). These values are safe for the pipeline system.

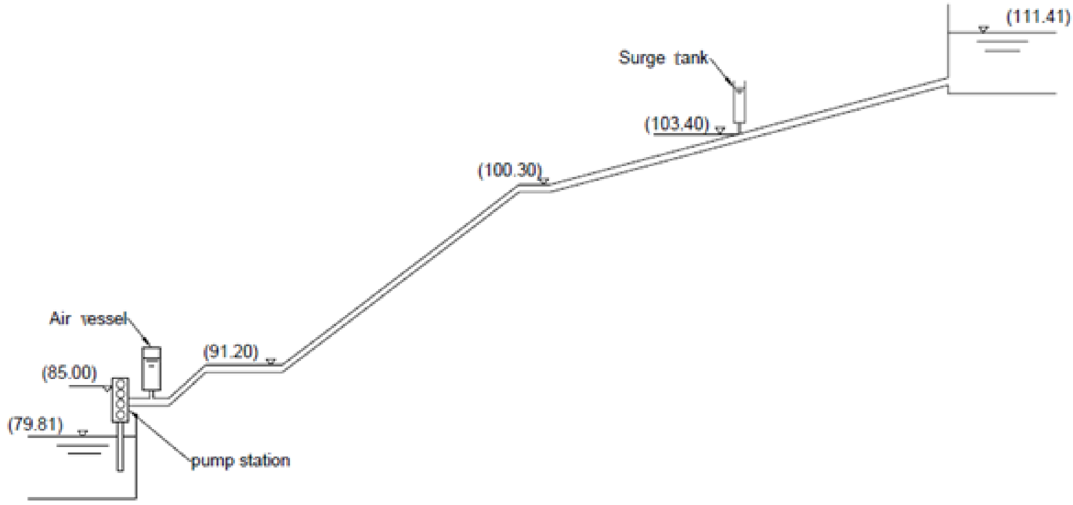

Fig. 10. Schematic diagram of pipeline system with protection via an air vessel and two surge tanks; source: own study

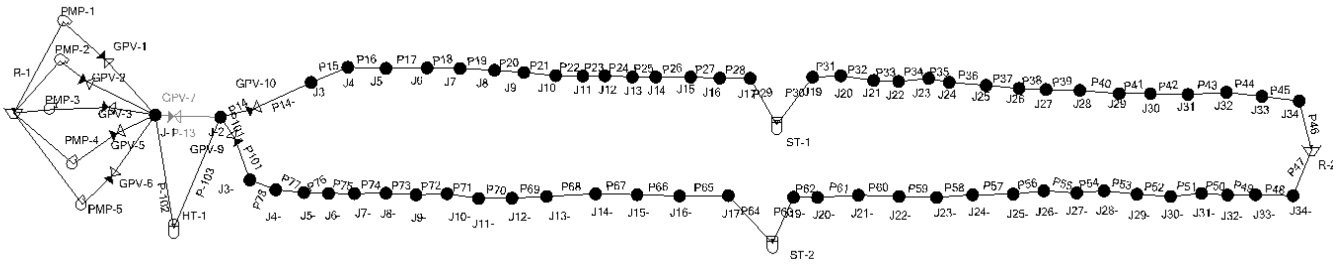

Fig. 11. The pipeline hydraulic system with protection via an air vessel and two surge tanks; source: own study

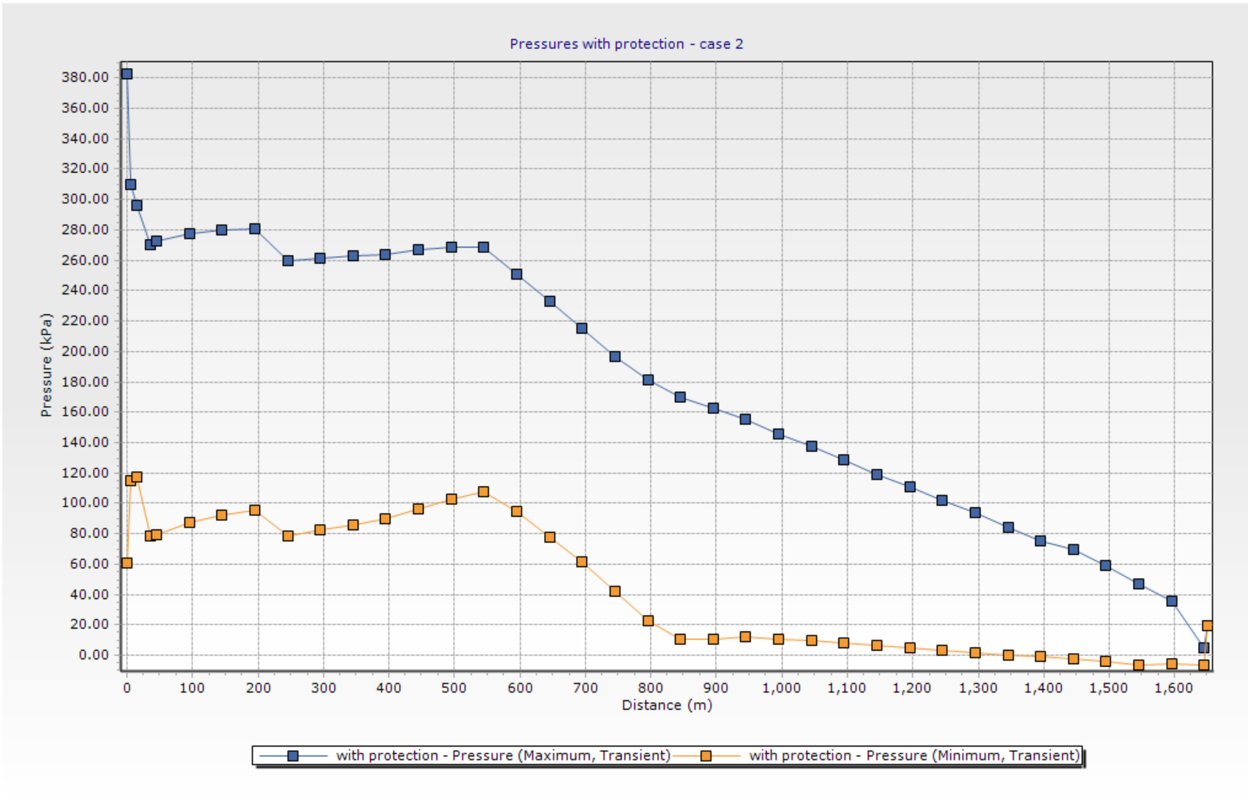

Fig. 12. Pressure (max and min.) along the pipeline system with protection via an air vessel and two surge tanks; source: own study

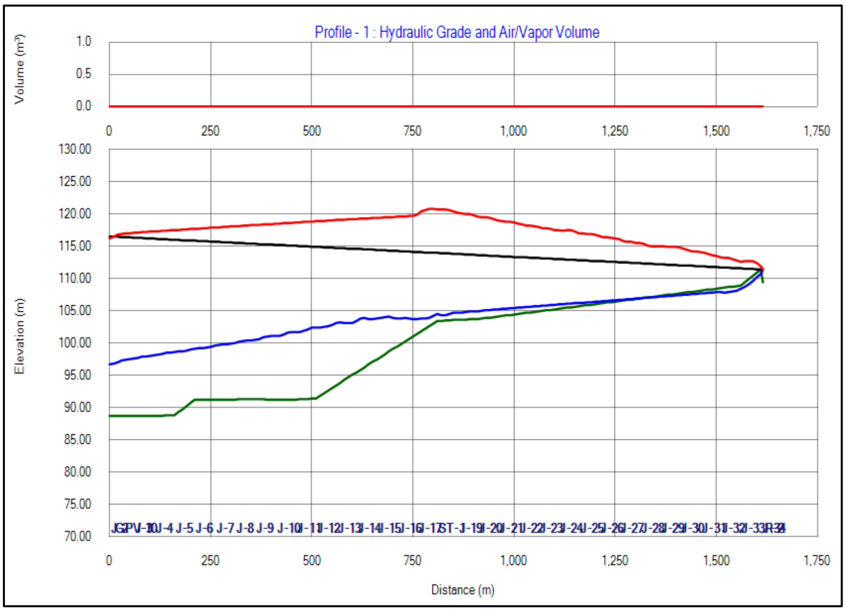

Fig. 13. Hydraulic grade (max, min. and initial), elevation and vapour volume along the pipeline system with protection via an air vessel and two surge tanks; source: own study

The maximum and minimum heads in each pipeline changed and reached to 124.10 m and 91.17 m at beginning of the pipeline, which provide safety against collapsing, as presented in Figure 13. Also, the vapour volume is 0.00 at all locations that confirms the safety of the pipeline system.

PROTECTION CASE (3) VIA FIVE AIR VESSELS AND VACUUM BREAKER VALVE

To avoid a large air vessel size, five smaller air vessels are used for protection, which reduces the required area of land. The total volume of each air vessel is 40 m^3. To prevent serious negative pressure damage due to power failure of the pumps, a vacuum breaker valve is usually installed at the highest point of pipeline system, as shown in Figures 14 and 15.

From the obtained results, as shown in Figure 16, the maximum pressure in each pipeline changed and reached 558.2 kPa, which is less than the working pressure (600 kPa), and the negative pressures through the pipeline system is 7.98 kPa at a distance 845 m of the pipeline, which is less than the allowable pressure (–10 kPa). These values are safe for the pipeline system.

As illustrated in Figure 17, the air sucked into the vacuum breaker valve, which prevents the pipeline from column separation, is 1 m^3 at the valve location that assures safety of the system.

The figure also represents the initial head under steady state conditions, and the maximum and minimum heads due to unsteady state case, which proved to be safe under the system protection as the minimum head is higher than the pipeline elevation.

From the obtained results, as shown in Table 1, it can be concluded that using one air vessel and two surge tanks provide the best protection against the pump power failure. On the other hand, using five air vessels and vacuum breaker valve will provide easier executing for the protection devices in the site, where this case of protection reduces the land area required for construction.

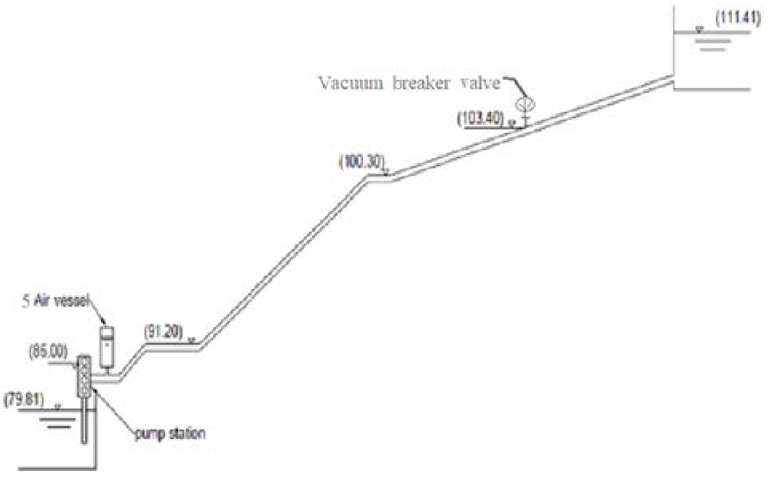

Fig. 14. Schematic diagram of pipeline system with protection via five air vessels and vacuum breaker valve; source: own study

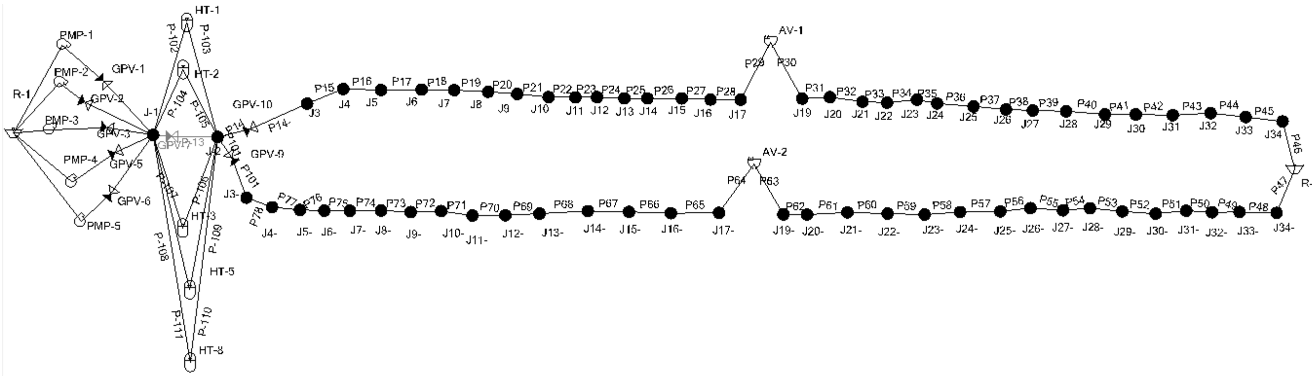

Fig. 15. The pipeline hydraulic system with protection via five air vessels and vacuum breaker valve; source: own study

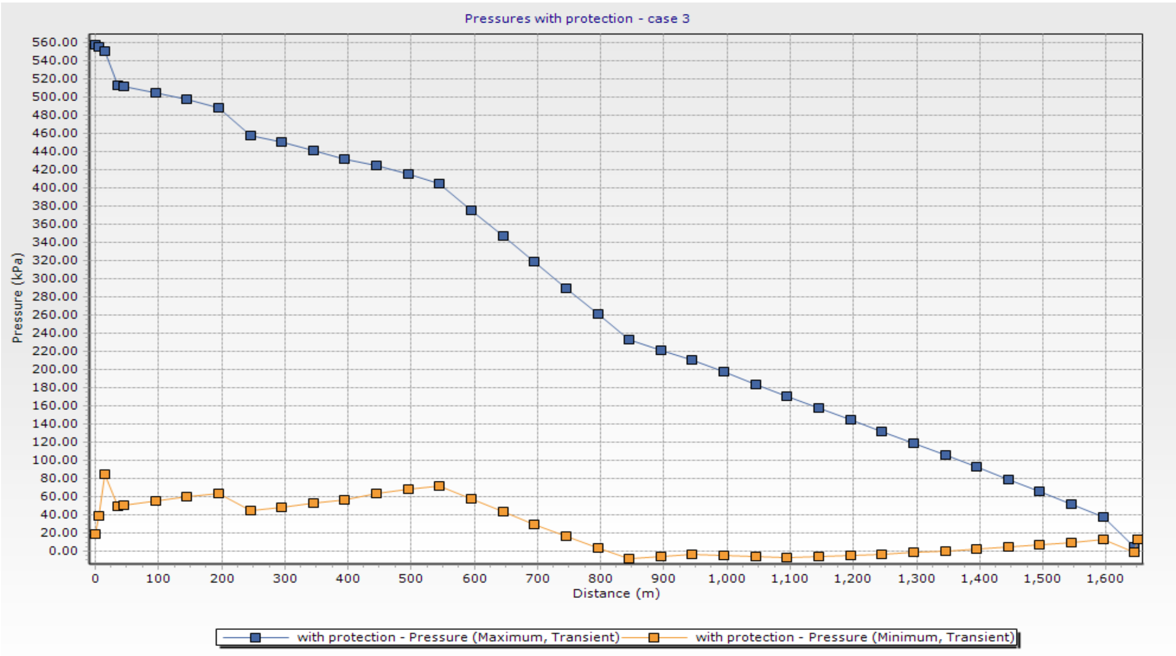

Fig. 16. Pressure (max and min.) along the pipeline system with protection via five air vessels and vacuum breaker valve; source: own study

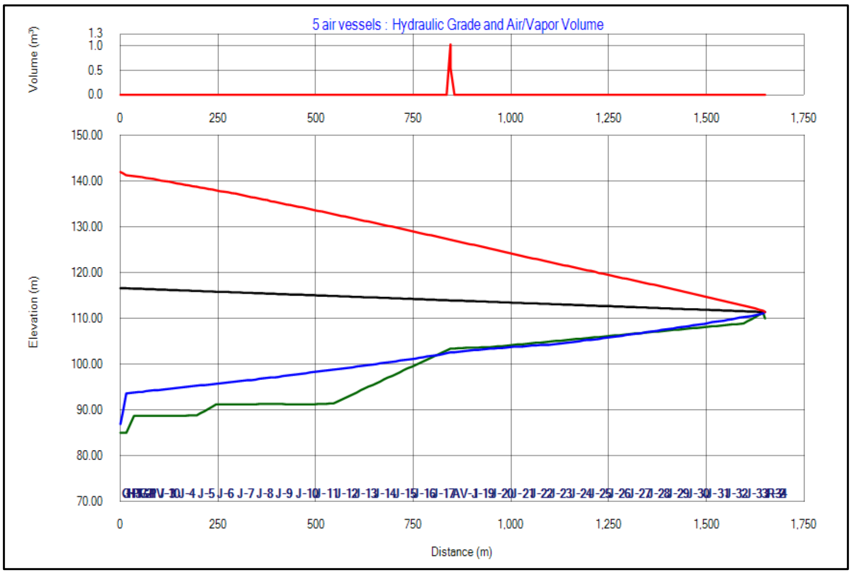

Fig. 17. Hydraulic grade (max, min. and initial), elevation and vapour volume along the pipeline system with protection via five air vessels and vacuum breaker valve; source: own study

Table 1. Obtained results of the pipeline system

Studied cases		Case of steady state	Case of transient with no protection	Cases of protection with		
				an air vessel (400 m^3)	an air vessel (200 m^3) and two surge tanks (2×16 m^2)	five air vessels (5×50 m^3) and vacuum breaker valve
Pressure (kPa)	max	272.7	952.5	401	382.66	558.2
	min.	0.1	–100	–7.3	–6.2	–7.98
Vapour volume (m^3)		0.000	0.730	0.000	0.000	0.000

Source: own study.

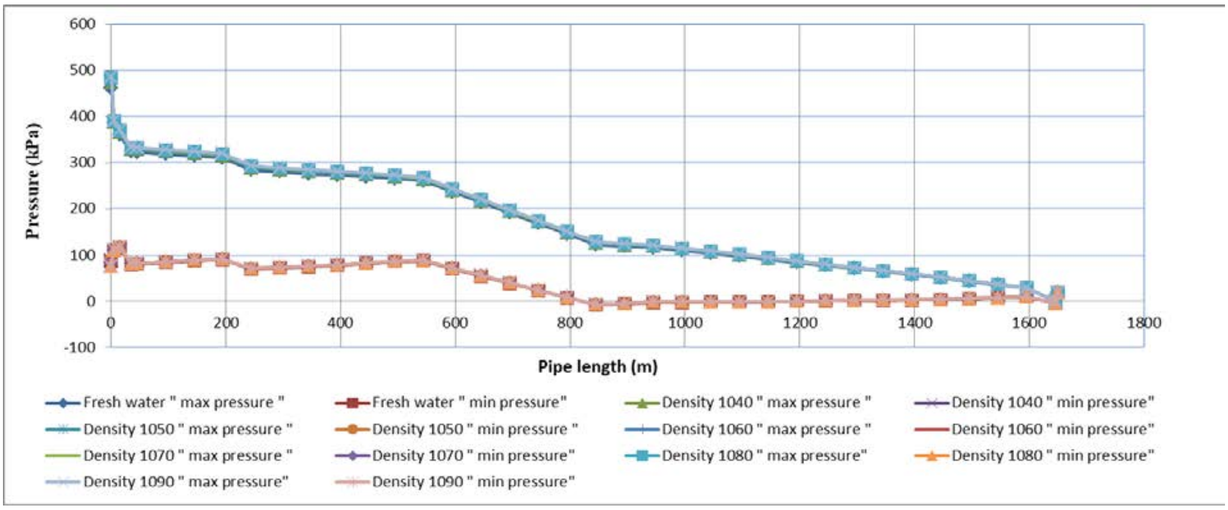

Fig. 18. Maximum and minimum pressures for different values of water density; source: own study

EFFECT OF WATER DENSITY ON THE PIPELINE SYSTEM

The surge pressure increases as the density increases according to Joukowsky equation. The effect of mixed water passing through the pipeline system, such as the case of using reused or treated water, is studied to make sure that the protection system provides the required safety for the pipeline system. The protection case 1 (using an air vessel only) will be used to study the effect of water density and to check the efficiency of the protection system against water hammer.

The values 1000–1090 kg·m^{-3} are investigated for the water density. The resulted maximum and minimum pressures that affect the pipeline system are shown in Figure 18. It is obvious that changing the flow density does not have a significant impact on the pressures, where the values of surge pressures are so close for the studied range of water densities.

EFFECT OF INLET PIPE DIAMETER OF AIR VESSEL ON THE PIPELINE SYSTEM (USING AN AIR VESSEL)

The obtained results of maximum and minimum pressures for 300–1800 mm inlet pipe diameters of air vessel are presented in Table 2.

For all three different volumes of air vessel, it is obvious that the 700 mm inlet pipe diameter of air vessel is a critical value. The pressures decrease as the diameter increases till the value 700 mm (40% of the original diameter), and then the pressures increase as the diameter increases.

It is concluded that case 3 is not safe against the minimum pressures for all studied inlet pipe diameters, while both case 1 and case 2 are safe against minimum pressure when using 1200 mm or more as inlet pipe diameter. Thus, it is recommended to use an air vessel of 375 m^3 volume in case of using only one air vessel as a protection against the pump power failure.

A regression analysis is performed, and equations are obtained to predict the maximum and minimum pressures according to the inlet pipe diameter for case 1 of an air vessel of 400 m^3 volume, as shown in Figure 19.

Table 2. Maximum and minimum pressures for different inlet pipe diameters and air vessel volumes

Inlet pipe diameter (mm)	Case 1, air vessel of 400 m^3 total volume		Case 2, air vessel of 375 m^3 total volume		Case 3, air vessel of 350 m^3 total volume	
	pressure (kPa)					
	max	min.	max	min.	max	min.
300	724	–100	724	–100	723	–100
400	662	–100	660	–100	640	–100
500	551	–100	510	–100	501	–100
600	460	–100	461	–100	498	–100
700	323	–100	325	–100	335	–100
800	333	–100	337	–100	351	–100
900	346	–66	353	–66	373	–67
1000	357	–37	366	–37	393	–38
1100	364	–20	375	–20	408	–20
1200	376	–8	381	–9	420	–14
1300	387	–8	387	–9	429	–14
1400	395	–7	395	–9	436	–14
1500	401	–7	401	–9	441	–14
1600	405	–7	405	–9	445	–14
1700	408	–7	408	–9	448	–14
1800	410	–7	410	–8	450	–14

Source: own study.

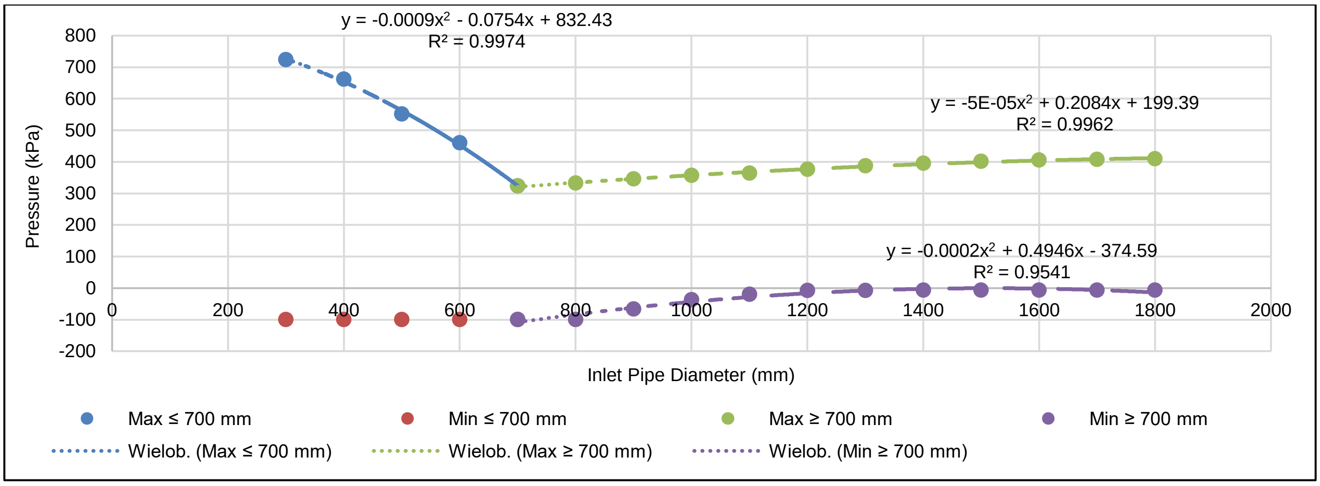

Fig. 19. Minimum and maximum pressure for different inlet pipe diameters (using an air vessel); source: own study

EFFECT OF INLET PIPE DIAMETER OF AIR VESSEL ON THE PIPELINE SYSTEM (USING AIR VESSEL AND TWO SURGE TANKS)

The obtained results of maximum and minimum pressures for 700–1200 mm inlet pipe diameter of air vessel are presented in Table 3.

For all four different areas of surge tanks, it is obvious that the maximum pressures increase as the diameters increase, and the minimum pressures decrease as the inlet pipe diameters increase. Increasing the area of the surge tank provides more safety against the system failure as it provides the system with a reasonable amount of water to prevent column separation to occur at the highest point of the system.

It is concluded that using an air vessel with 800 mm inlet pipe diameter and two surge tanks with area of 14 m^2 for each tank will be the most economical solution.

A regression analysis is performed, and equations are obtained to predict the maximum and minimum pressures according to the area of surge tank, as shown in Figure 20.

Table 3. Maximum and minimum pressures for different inlet pipe diameters and surge tank areas

Pressure (kPa)	Area of surge tank (m^2)	Inlet pipe diameter (mm)					
		700	800	900	1000	1100	1200
Max	10	313	486	520	679	639	863
	12	303	306	337	494	522	753
	14	295	294	337	383	408	428
	16	288	283	337	383	408	428
Min	10	–48	–100	–100	–100	–100	–100
	12	–48	–9	–9	–100	–100	–100
	14	–48	–9	–9	–7	–6	–6
	16	–48	–9	–9	–6	–6	–6

Source: own study.

THE EFFECT OF PIPELINE DIAMETER

The results of maximum and minimum pressures for 800–1800 mm pipeline diameters are illustrated in Table 4. The inlet pipe diameter is 1500 mm. The maximum and minimum pressures for different pipe diameters are presented in Figure 21 for case 1 only because the values of pressure for the three cases are close to each other. In the figure, the pressures associated with diameter 800 through 1200 mm are called case 1a, while the pressures associated with diameter 1200 through 1800 mm are called case 1b.

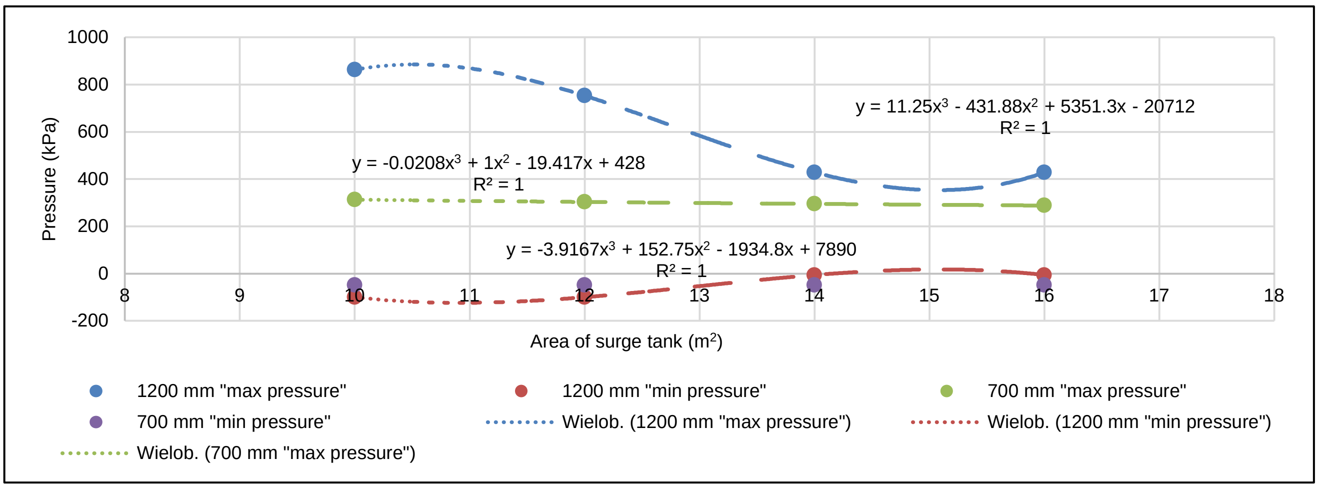

Fig. 20. Maximum and minimum pressure for different inlet pipe diameters and different areas of surge tank; source: own study

Table 4. Maximum and minimum pressure for different pipe diameters and air vessels

Pipe diameter (mm)	Case 1, air vessel of 400 m^3 total volume		Case 2, air vessel of 375 m^3 total volume		Case 3, air vessel of 350 m^3 total volume	
	pressure (kPa)					
	max	min	max	min	max	min
800	588	–3	588	–3	587	–3
900	497	–3	497	–3	495	–3
1000	480	–3	480	–3	479	–3
1100	435	–6	434	–8	431	–13
1200	401	–7	401	–9	441	–14
1300	454	–7	463	–9	481	–13
1400	453	–4	458	–6	474	–11
1500	444	–4	450	–4	465	–9
1600	434	–4	438	–4	453	–5
1700	428	–3	432	–3	445	–3
1800	432	–3	437	–3	450	–7

Source: own study.

Increasing the diameter of the pipeline reduces the surge pressures till the value of 1200 mm that represent 2/3 of original diameter (1800 mm), after which a sudden increase occurs in pressure followed by both increase of minimum pressure and varied changes of maximum pressure.

Regression analyses are employed, and equations are obtained on the figure to predict the pressure at any pipe diameter.

However, it is found that using the 1200 mm pipe diameter is optimum for both cases 1 and 2 of air vessel, where the allowable maximum and minimum pressures are achieved.

THE EFFECT OF CHANGING PIPELINE MATERIAL

The maximum and minimum pressures for different pipe materials are graphically presented in Figures 22 and 23, respectively.

It is found that the great values of maximum pressure occurred for concrete pipes for the three studied cases. Also, the smaller values of maximum pressure were associated with GRP pipes except for case 3.

The obtained results show that the small values of minimum pressure occurred for concrete pipes for the three studied cases. Also, the greater values of minimum pressure were associated with GRP pipes except for case 1.

However, cast iron pipes proved to be the best pipe material for all studied cases for both maximum and minimum pressures.

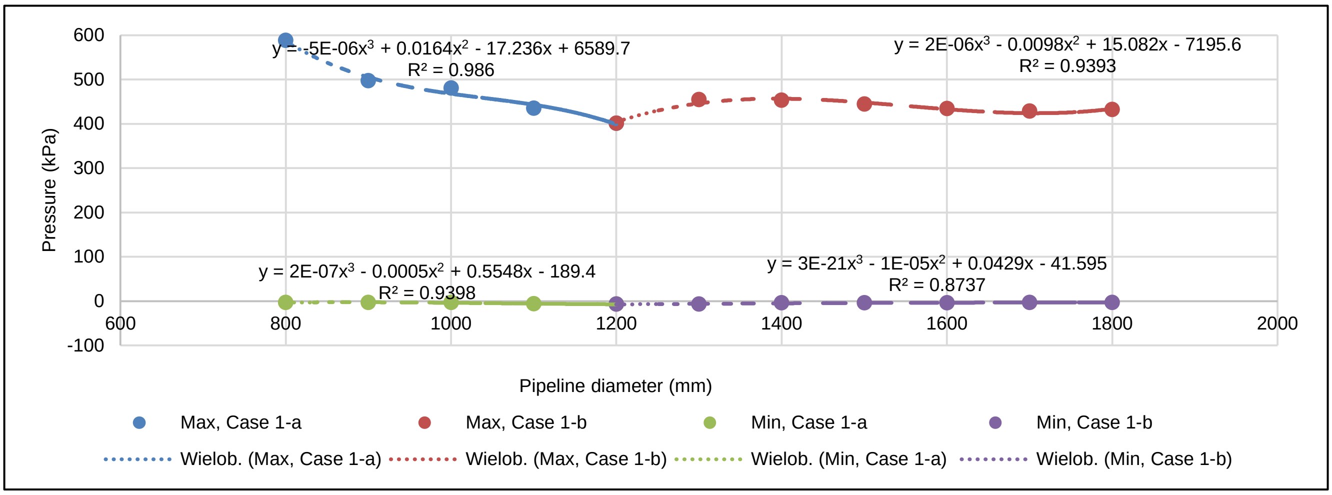

Fig. 21. Pressure for different pipe diameters for case 1 (air vessel of 400 m^3 volume); source: own study

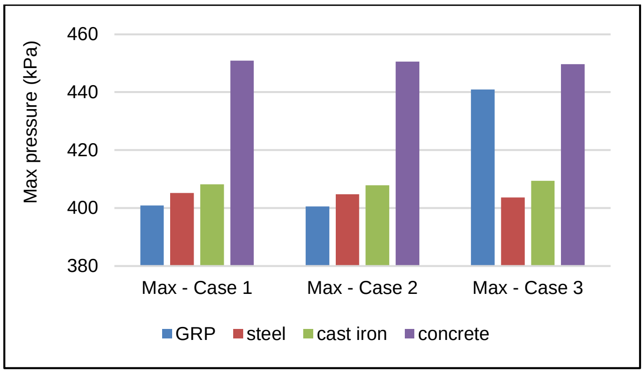

Fig. 22. Maximum pressure for different pipe materials and different total volumes of air vessels: case 1 = 400 m^3, case 2 = 375 m^3, case 3 = 350 m^3; GRP = glass reinforced plastics; source: own study

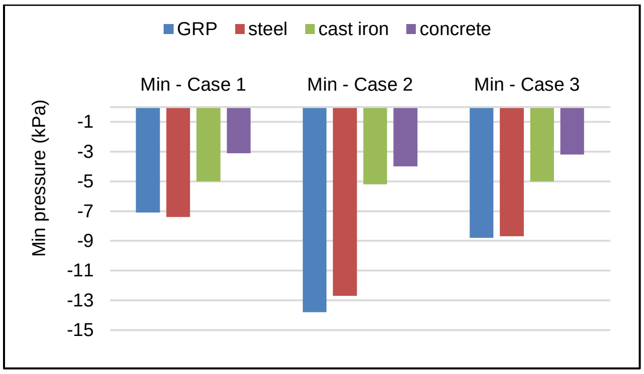

Fig. 23. Minimum pressure for different pipe materials and different total volumes of air vessels: cases 1, 2 and 3; GRP = glass reinforced plastics; source: own study

CONCLUSIONS

From the obtained results, it is concluded that using one air vessel (200 m^3) and two surge tanks (each of 16 m^2) provide the best protection against the pump power failure. On the other hand, using five air vessels (each of 40 m^3) and vacuum breaker valve will be easier and economical.

It is found that changing the flow density does not have a significant impact on the pressures, where the values of surge pressures are so close for the studied range of water densities.

It is concluded that the value 700 mm for inlet pipe diameter (40 % of the original diameter) of air vessel is a critical value. The pressures decrease as the diameter increases till this value, and then the pressures increase as the diameter increases.

To assure safety against the minimum pressures for all studied inlet pipe diameters, it is recommended to use an air vessel of 375 m^3 volume in case of using only one air vessel as a protection against the pump power failure.

A regression analysis is performed, and equations are obtained to predict the maximum and minimum pressures according to the inlet pipe diameter for using only one air vessel of 400 m^3 volume.

In case of using an air vessel and two surge tanks for protection against the pump power failure, it is found that the maximum pressures increase, and the minimum pressures decrease as the inlet pipe diameters increase.

It is concluded that using an air vessel 200 m^3 volume with 800 mm inlet pipe diameter and two surge tanks with area of 14 m^2 for each tank will be the most economical solution for using an air vessel and two surge tanks.

A regression analysis is performed, and equations are obtained to predict the maximum and minimum pressures according to the area of surge tank.

Increasing the diameter of the pipeline reduces the surge pressures till the value of 2/3 of original diameter, after which a sudden increase occurs in pressure followed by both increase of minimum pressure and varied changes of maximum pressure.

It is found that using the 1200 mm pipe diameter (2/3 of original diameter) is optimum for both 400 and 375 m^3 volumes of air vessel, when using only one air vessel for protection.

Regression analyses are employed, and equations are obtained to predict the pressure according to the pipe diameter.

When using only one air vessel for protection, it is found that the great values of maximum pressure and the least values of minimum pressure occurred for concrete pipes for three different volumes of air vessel.

Cast iron pipes proved to be the best pipe material for all studied cases for both maximum and minimum pressures.

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