Journal of Applied Sciences Research, 7(12): 2127-2139, 2011
ISSN 1819-544X
This is a refereed journal and all articles are professionally screened and reviewed

ORIGINAL ARTICLES

Improved Design For Irrigation Pipeline Networks

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ABSTRACT

The purpose of this study is to investigate the problems resulting from unsteady flow, in irrigation pipelines networks; due to pump power failure and provides the necessary control devices, to analyze transient flow under all possible operational conditions. The present investigation emphasized on the unsteady flow cases on the problem of pump power failure. In this case, protecting the irrigation pipelines networks against water hammer is of great importance. A hydraulic model is developed to study the transient flow problems. It is prepared considering several boundary conditions to define the irrigation pipelines networks. Therefore, this study aims to investigate the effect of using a protection device; an air vessel; on the network. Otherwise Comparison of protected case using an air vessel *and* using an air vessel with two surge towers as protection devices. Subjects to evaluate and optimize a hydraulic design are economy, safety and control principles to make an effective and efficient system. Through this work, a parametric study is applied using Water Hammer Software Wanda V3.03. Irrigation pipelines networks can be simulated with this water hammer model. The method of characteristics-based solver can be interrupted and resumed during a simulation.This program developed and has validated against many experimental measurements (WL/Delft Hydraulics (2006). The program is available at the Hydraulics Research Institute (HRI), National Water Research Center, Egypt. The results of the study, graphically presented for the various operating conditions. The results include the relationships of discharge, cavitation volume; head and pressure verses locations for the different cases. Also include the relationships of discharge, pump speed verses time histories. In this study, the results show that using the proposedan air vessel as a protection device proved to be effective for prevent column separation , using of air vessel with two surge towers are becoming more effective *and* decrease the size of the initial air vessel. The results show that increasing of diameter of pipes decreases the magnitude of the maximum pressure heads in the resulting water hammer pressure but does not prevent column separation. Otherwise, change of pipe material type from GRP to steel decreases the maximum pressure but does not prevent column separation. Finally, it was found that increasing the polar moment of inertia of the pump does not decrease the maximum pressure or the initial air vessel volume.

Key words: water hammer, hydraulic transients, surge tower, unsteady flow, Wanda and pressure vessels.

Introduction

Water hammer following the tripping of pumps can lead to overpressures, which require some form of water hammer protection. The most effective way of preventing negative pressures and also for reducing overpressures is the use of compressed air vessels.

The unsteady flow can be defined as a state in which the flow parameters are time-dependent. The complexity encountered in the analysis of the unsteady flow is referred to the additional independent variable (time) involved in the process besides the space variables. Furthermore, the process is basically governed by two partial differential equations, continuity equation and momentum equation, the solution of which requires much more complicated procedures. The primary variables in unsteady flow are the discharge (Q) and the pressure head (H).

Mathematical Model:

This research studies the unsteady flow solution using mathematical method of the finite difference. In water hammer theory, both the equations of momentum and continuity are applied on the mean flow. The flow is considered as one-dimensional flow (Wanda User Manual, 2000). Equations (1) and (2) constitute the two basic equations which describe the compressible flow in a pipe (in terms of Q and H):
Momentum Equation:

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$$\frac{1}{A_f}\frac{\partial Q}{\partial t} + g\frac{\partial H}{\partial s} + \frac{f\,Q|Q|}{2DA_f^2} = 0 \qquad (1)$$

- ContinuityEquation:

$$\frac{1}{c_f^2}\frac{\partial H}{\partial t} + \frac{1}{gA_f}\frac{\partial Q}{\partial S} = 0 \qquad (2)$$

Where:

$$c_f^2 = \frac{K_f}{\rho_f}\left(1 + \frac{DK_f}{Ee}\right)^{-1} \qquad (3)$$

In which c_f = Wave propagation speed m/s, K_f = Fluid compressibility N/m^2, ρ_f = Fluid density kg/m^3, D = Internal pipe diameterm, E = Young's' modulus (pipe elasticity) N/m^2, e = Pipe wall thickness m, g = gravitational acceleration m/s^2, H = headm, t = time sec.

It should be mentioned that complete details about numerical solution of the model governing equations, the boundary conditions and the working flow chart is presented in Eman Fawzi (2011).

The assumptions used in the hydrodynamic model are:

Fluid Specifications:

- The density is assumed to be constant (incompressible fluid).
- Flow conditions are constant (discharge = 6.00 m^3/s).
- The kinematic viscosity = 0.1000E^{-05} m^2/s.
- The bulk modulus = 0.2100E^{+10} N/m^2.
- The vapor pressure = 0.1000E^{-05} m^2/s.

Time Parameter:

- The time step = 0.3000E^{-01} sec.
- The simulation end time = 200.0 sec.

Physical Constants:

- The gravitational acceleration = 9.810 m/s^2.
- The atmospheric pressure = 0.1014E^{+06} N/m^2.

Runs Procedures, Results and Analysis:

A number of runs were simulated using the mathematical model; one of which represented the unsteady flow without any protection. This run was used as a reference to allocate the hydraulic performance of previous studies of transient-state caused by pump power failure. These runs were carried out at the Hydraulics Recourses Institute (HRI) Ministry of Water Resources and Irrigation, Egypt at Delta Barrage during the period 1/7/2010 to 1/7/2011. Transient conditions in pipes computed using program Wanda V3.03. In order to avoid surge pressure damage to pipelines, various parameters conditions were considered such as pipe material (steel, plastics), diameter of pipeline, wall thickness of pipes and polar moment of inertia of the pump, to reduce average velocity. The system simulated for non - protected and protected cases. Pump trip in an unprotected pipeline results in a rapid drop in pressure and an elastic wave traveling up and down the pipeline in the case of a protected pipeline, such as with an air vessel, the decelerations and accelerations are slower.

System Configuration:

Pumping station at elevation (85.00 m) + msl consist of six parallel pumps (five pumps are in operation simultaneously and one is considered as a standby pump of similar type) are to be used to pump approximately 6.00 m^3/sec from elevation (79.81m)+ msl at suction level to elevation (111.41m)+ msl at delivery side before the open channel. The pumping station followed by a 1800 mm main header diameter branched to two pipeline 1200 mm diameter delivery water to open channel at the end of pipeline.

The pump discharge lines are check-valve and manifold into a single welded-steel pipeline 1800 mm in diameter. The main header extends from the pump station at elevation (85.00 m) + msl for a distance of 30.00 m at elevation (88.65 m) + msl. It then branched to two pipeline 1200mm diameter slopes upward for a distance of 1600 m to elevation (111.41m) + msl delivery water to open channel at the end of pipeline (see Figures 1 and 2).

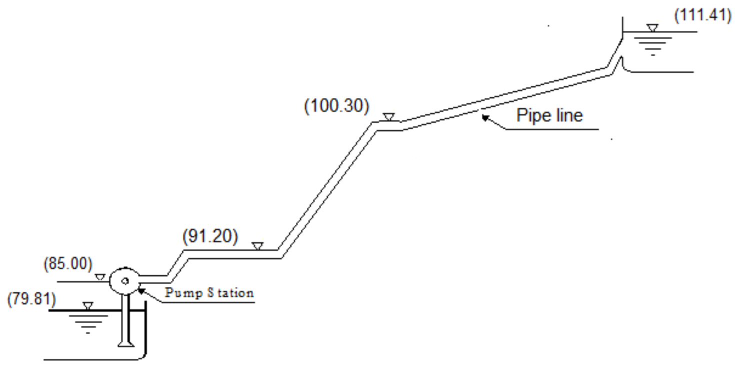

Fig. 1: System Configuration of the Pumped Line.

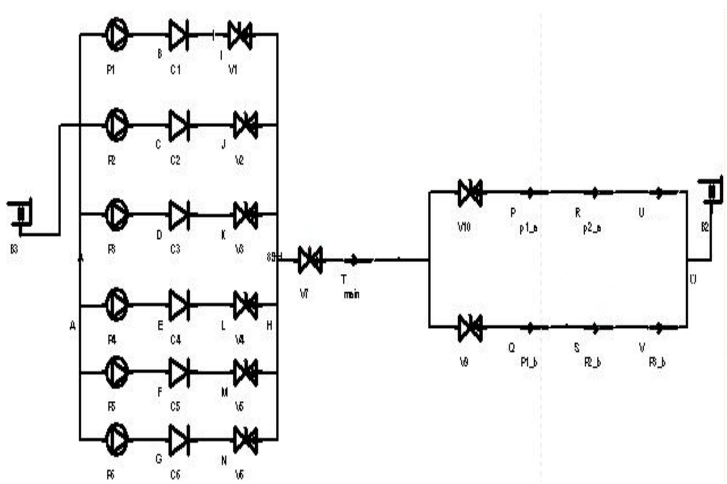

Fig. 2: Schematic Illustration of the Hydraulic System.

Effect of Pump Power Failure:

In this study, a hydraulic model is developed to study the transient flow problems occurring in a pumped pipeline. The pump power failure or pump shutdown is the major design analysis for the pipeline.

System Without Protection:

Five pumps are working together and fail suddenly, Check valve closes upon power failure. The following events take place: the flow rapidly dimensioned to zero and then reverses; negative pressure waves are propagated downstream from the pump and positive pressure waves are propagated upstream through the suction pipe. The pump rapidly loses its forward rotation and reverses shortly after reversal of flow. As the pump increases in speed in the reverse direction, it causes greater resistance to flow which high pressure in the discharge line. When the load on the pumping system is primarily due to fluid fraction, as in the case of long discharge line, vapor pressure and column separation may occurs in the discharge line due to negative pressures. Column separation often occurs after pump failure at the high point of pipeline.

The drop in pressure can also cause air to effervesce or emerge from solution and collect on the soffit or crown of the pipe. Bubbles may subsequently travel up the pipe and cause shock waves, especially on compression, when the water columns oscillate on each side of the air pocket, or when it escapes from air valves or joints (Stephenson 1997).

Figures 3 through 8 shows that column separation and failure of pipeline started the maximum and minimum pressure envelope along the pipeline is 9.622 bars at begin of the pipeline and -0.9969 bars at the all pipeline. The maximum cavitation volume is 0.6852 at the location 825 m. The previous values are unsafe and excess than the allowable (The working pressure of pipeline in the study case is 6 bars), so pipe system can be damaged by water hammer phenomena, the protection is a must.

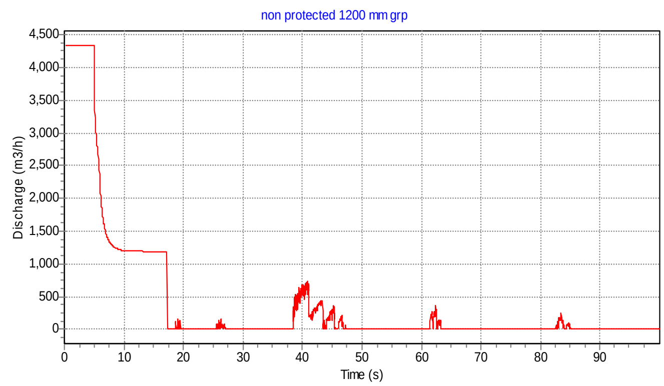

Fig. 3: Discharge-Time History.

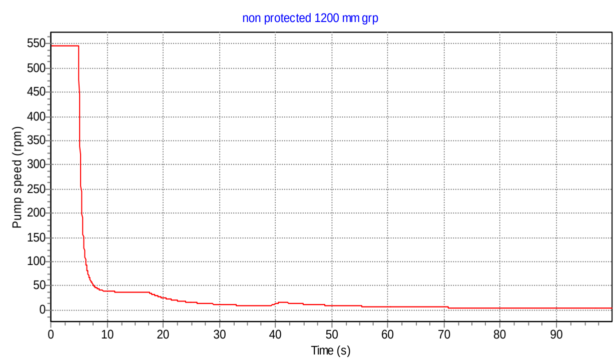

Fig. 4: Pump Speed-Time History.

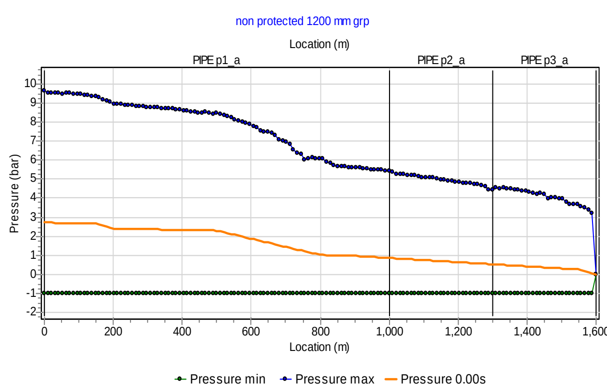

Fig. 5: Pressure envelope and pressure profiles at various time along the pipelines.

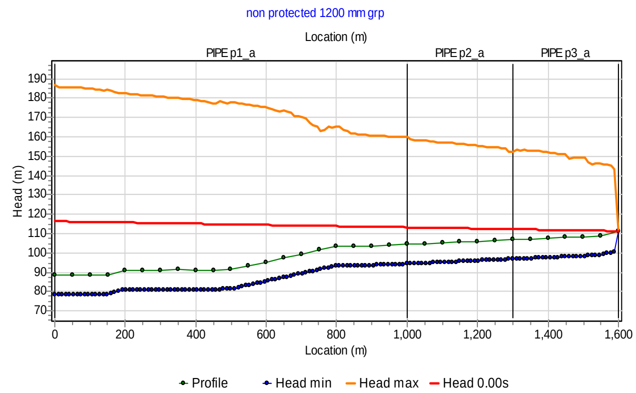

Fig. 6: Head envelope and head profiles at various time along the pipelines.

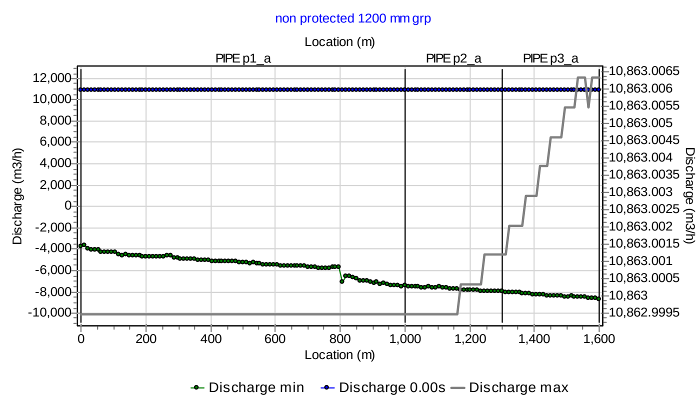

Fig. 7: Discharge envelope and discharge profiles at various times along the pipelines.

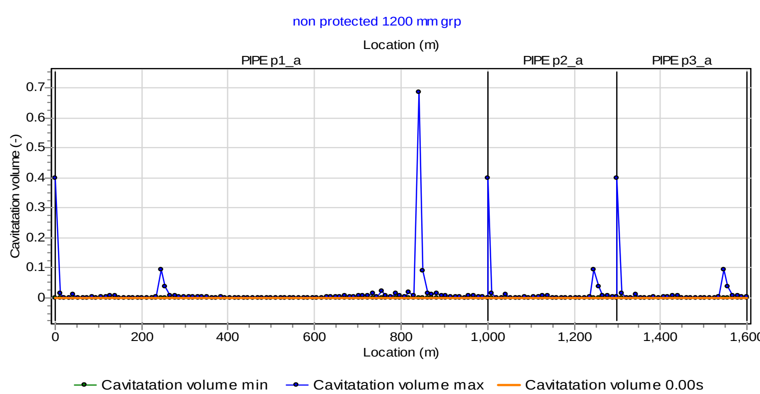

Fig. 8: Cavitation volume-Location.

System With Protection:
Protected case (1) using an air vessel:

Air vessels offer an effective means of reducing water hammer overpressures and negative pressures due to pump trip in pipelines. A solution to this negative surge situation is to install an air vessel on the main header to protect the system see Figures 9, 10 and 11. The purpose of this device is to limit the pressure drop and to avoid the possible occurrence of column separation in the pump during running condition and provide uniform flow of discharge during operation. In this case, we make the computations using the present hydraulic model to obtain the results when using air vessel with different capacities in order to search for an optimum solution to reduce the water hammer pressures and to prevent column separation. Figure 9 shows the schematic of air vessel (Watters 1984). Air vessel is supplied with air compressor to supply the air vessel with required compressed air.

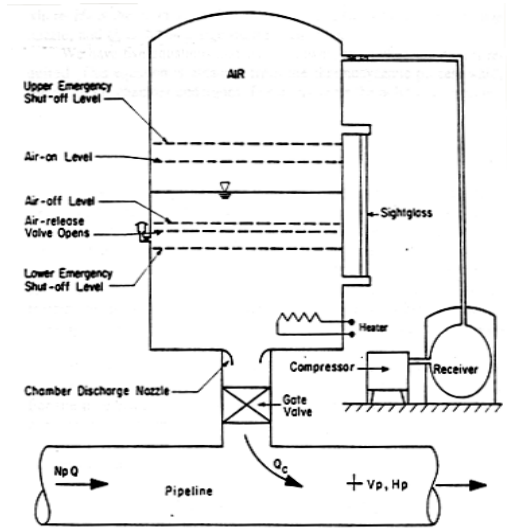

Fig. 9: Schematic Diagram of an Air vessel and Its Appurtenances (Watters 1984).

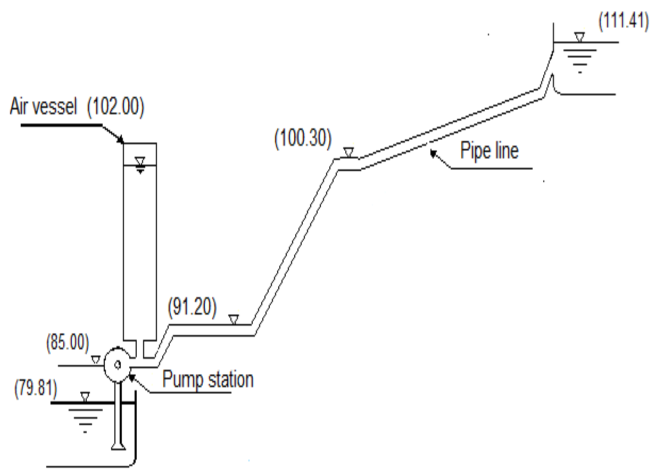

Fig. 10: System Configuration of the Pumped Line Installs an Air Vessel on Main Pipeline.

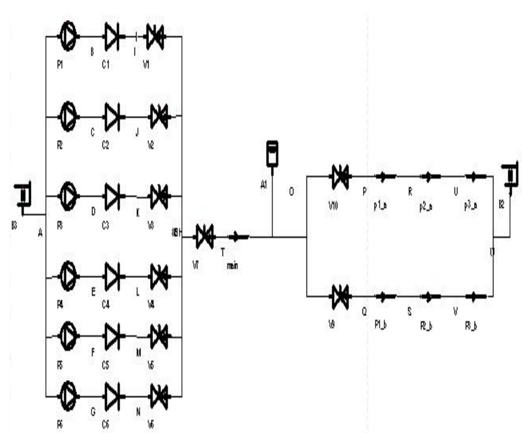

Fig. 11: Schematic Illustrates the Installation of an Air Vessel to Protect Water Pumping.

Using the proposed air vessel as a protection device proved to be effective. Figures 12 through 17 show the curves for the protected system, the maximum pressure in each pipeline changed and reached to 4.33 bars less than the working pressure 6 bars, the negative pressures in pipeline are reached - 0.052 bars at the location 800 m which less than the allowable (-0.1 bars) .The cavitation volume equal zero at all pipeline location.

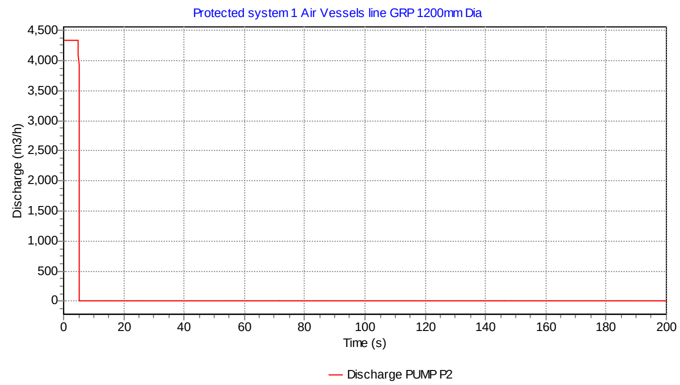

Fig. 12: Discharge-Time History.

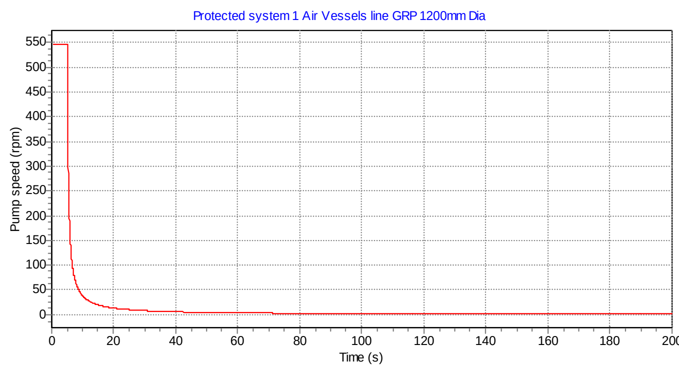

Fig. 13: Pump Speed-ime History.

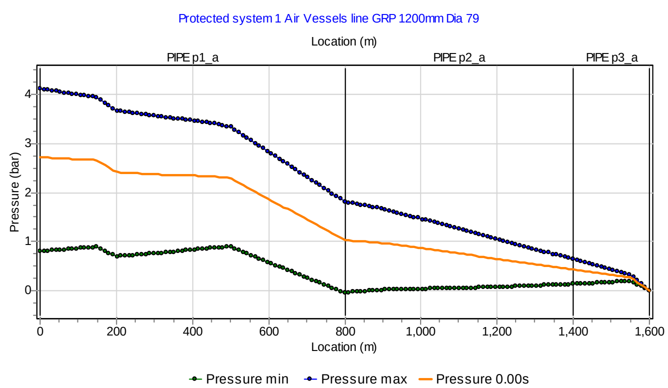

Fig. 14: Pressure Profiles At Various Times Along Pipelines.

Protected case (2) using an air vessel and two surge towers:

Surge tower is commonly used with air vessel to protect pipeline systems against column separation problems. The purpose of the surge tower is to mitigate pressure variations due to rapid changes in velocity of water.

When the load decreases, the water moves backwards and gets stored in it. When the load increases, additional supply of water will be provided by it. In this case we well use two surge towers with constant area equal 16.00 m^2 and variable initial height of water surface (see Figures 18, 19 and 20).

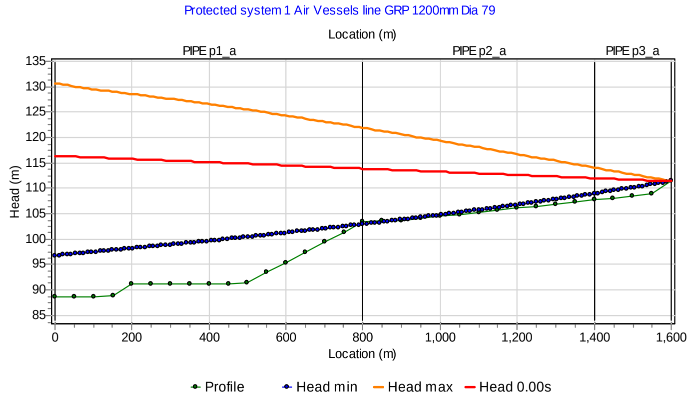

Fig. 15: Head Profiles at Various Times along Pipelines:

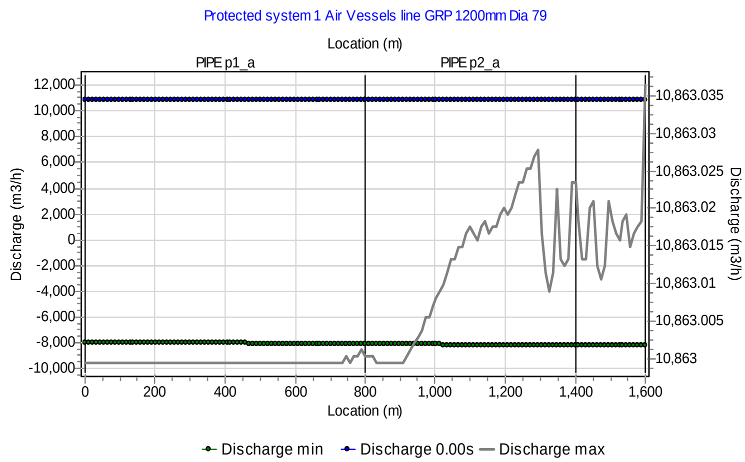

Fig. 16: Discharge Profiles At Various Times Along Pipelines.

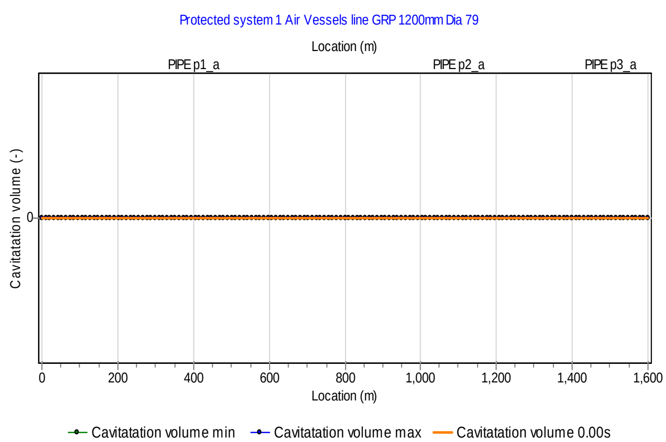

Fig. 17: Cavitation Volume–Location.

Using the proposed an air Vessel and two surge towers as protection devices proved to be effective. Comparison of results for non-protected case *and* for protected cases is presented in Table 1.

From such analysis, an air vessel with surge towers may be used to protect the pipeline against column separation and decrease the initial an air vessel volume, gives economical solution.

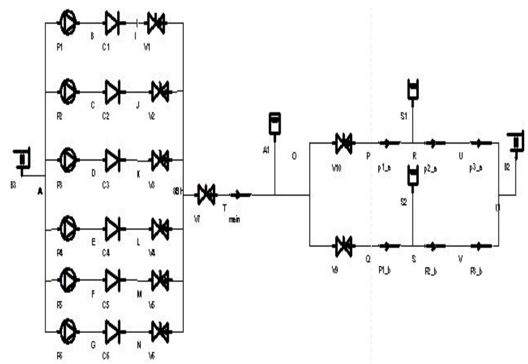

Fig. 18: Schematic Illustrates the Installation of an Air Vessel and Two Surge Towers to Protect Water Pumping.

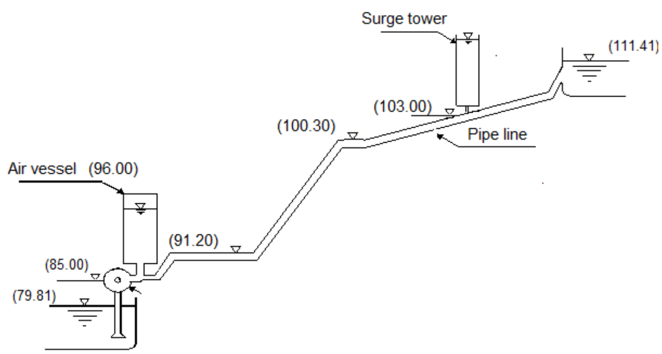

Fig. 19: System Configuration of the Pumped Line Installs an Air Vessel and Two Surge Towers.

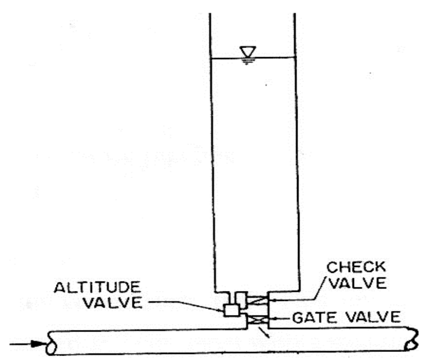

Fig. 20: Schematic of Surge Tower Designs (Douglas 1974).

Table 1: Comparison of Results of the Cases Steady.

Cases steady		Steady state	Non - protected case	Protected case (1)	Protected case (2)
Pressure bar	Minimum	0.00	- 0.996	-0.052	-0.001
	Maximum	2.723	9.479	4.11	4.29
Discharge m^3/h	Minimum	0.00	-7477	- 8158	-7200
	Maximum	10860	10860	10860	10860
Head m	Minimum	111.4	78.48	96.66	96.02
	Maximum	116.4	185.27	130.63	132.46
Cavitation volume		0.00	0.6853	0.00	0.00

Comparison of the data of the air vessels are presented in table 2.

Table 2: Comparison of the Data of the Air Vessels.

Case steady	Protected case (1)	Protected case (2)
Top level m	102.0	96.0
Bottom level m	90.0	90.0
Initial fluid level m	96.0	93.0
Chamber area m^2	33.70	33.70

This technique is useful in determining the final sizing of the air vessel. Select the air vessel by selecting diameter and length gives economical solution or conforms to available materials or building constraints. Note that by using two surge towers, it is possible to reduce the air vessel length from 12.0 m to 6.0 m.This means that a reduction in air vessel volume substantially, by about 50% is obtained.

System Geometrical Design Changes:

The transient performance of a piping system may be improved, in general, by changing the geometrical design. This design change may be particularly effective in suction lines, since it greatly decreases the possibility of cavitation.

Effect of Pipe Diameter:

In this case, the pervious hydraulic model is used, to study the effect of pipe diameter, to protect the pipe line against column separation problem. Two values of pipe diameter were used in this investigation, these values equalto 1400 mm and 1600 mm.

Increases the diameter of the pipeline reduce the surge pressures. This occurs as the velocity is reduced. The downside is the increased cost of the pipe. The pipe diameter equals 1400 mm and 1600 mm have effect in reducing the initial air vessel volume, give economical solution.

Comparison of the results for non-protected cases are presented in Table 3, while for protected cases results using an air vessel are presented in Table 4.

Table 3: Comparison of results of non-protected cases.

Pipe material		GRP		
Wall thickness mm		**18**		
pipe diameter mm		1200	1400	1600
Pressure bar	Minimum	-0.996	-0.996	-0.996
	Maximum	9.479	9.74	8.662
Discharge m^3/h	Minimum	-7477	-12710	-16300
	Maximum	10860	10860	10860
Velocity m^2/s		2.668	2.241	2.03
Cavitation volume		0.6853	0.6514	0.5359

Table 4: Comparison of results of protected cases.

Pipe material		GRP		
Wall thickness mm		**18**		
pipe diameter mm		1200	1400	1600
Pressure bar	Minimum	-0.052	-0.09	-0.09
	Maximum	4.11	4.479	4.469
Discharge m^3/h	Minimum	- 8158	-9608	-10300
	Maximum	10860	10860	10860
Cavitation volume		0.00	0.00	0.00
Chamber area m^2		33.7	33.7	33.7

Comparison of the data of the air vessels are presented in table 5. From such analysis, the pipe diameter equals 1400 mm and 1600 mm have effect in reducing the initial air vessel volume.

Table 5: Comparison of the Data of the Air Vessels.

pipe diameter mm	1200	1400	1600
Top level m	102	100	99
Bottom level m	90	90	90
Initial fluid level m	96	95	94.5
Chamber area m^2	33.7	33.7	33.7

Increase the diameter of the pipeline, the immediate effect is to reduce the surge pressures. Since head change is directly proportional to velocity change, this occurs as the velocity is reduced. When the fluid is brought to rest, change in momentum is reduced in direct proportion to the maximum velocity. The downside is that the increased pipeline size reduces the friction. So the damping of any pressure fluctuations is reduced and the transient may also considerably longer. This adds to the fatigue loading of components in the system. The other consideration is the increased cost of the pipe versus the reduced energy costs over the life of the asset.

Effect of Pipe Wall Thickness:

Over pressures may require excessive pipe wall thickness. In this case, the pervious hydraulic model is used, to study the effect of pipe wall thickness to protect the pipe line against column separation problem. The computation is made for another two values when the pipe wall thickness equals 22 mm and 25 mm for GRP.

Comparison of the results for non-protected cases results are presented in Table 6. While for protected cases results using air vessel are presented in Table 7.

Table 6: Comparison of Results of Non-Protected Cases.

Pipe material		GRP		
pipe diameter mm		1200		
Wall thickness mm		18	22	25
Pressure bar	Minimum	-0.996	-0.996	-0.996
	Maximum	9.479	10.44	11.03
Discharge m^3/h	Minimum	-7477	-8968	-9860
	Maximum	10860	10860	10806
Cavitation volume		0.6853	0.5270	0.9192

Table 7: Comparison of Results of Protected Cases.

Pipe material		GRP		
pipe diameter mm		1200		
Wall thickness mm		18	22	25
Pressure bar	Minimum	-0.052	-0.04	-0.04
	Maximum	4.11	4.12	4.13
Discharge m^3/h	Minimum	- 8158	-8226	-8143
	Maximum	10860	10860	10860
Cavitation volume		0.00	0.00	0.00
Chamber area m^2		33.7	33.7	33.7

Increasing the wall thickness of the pipe (this reduces the internal diameter); the celerity will increase and create even higher surge pressures. Although a more costly method of mitigating transient pressures, once installed higher class pipe work does not require further maintenance and testing as other mitigation devices require.

Effect of Pipe Material:

In this case, the pervious hydraulic model is used, to study the effect of pipe material type from GRP to steel to protect the pipe line against column separation problem.

Comparisons of the results for non-protected cases are presented in Table 8. While for protected cases using an air vessel are presented in Table 9.

Table 8: Comparison of output results of non-protected cases.

pipe diameter mm		1200	
Wall thickness mm		18	
Pipe material		GRP	Steel
Pressure bar	Minimum	-0.996	-0.997
	Maximum	9.479	19.53
Discharge m^3/h	Minimum	-7477	-6462
	Maximum	10860	10860
Cavitation volume		0.6853	0.6853

Table 9: Comparison of results of protected cases.

pipe diameter mm		1200	
Wall thickness mm		18	
Pipe material		GRP	Steel
Pressure bar	Minimum	-0.052	-0.0009
	Maximum	4.11	4.031
Discharge m^3/h	Minimum	- 8158	-7848
	Maximum	10860	10860
Cavitation volume		0.00	0.00
Chamber area m^2		33.7	33.7

Change of pipe material to one with lower modulus, for a particular pipeline it may be possible to use a steal material rather than a GRP material. This applies to low head pipelines found in the mining, water industry where high temperatures do not occur. The reduced modulus results in a reduced celerity (wave speed). The extract below demonstrates that modulus is the prime variable in establishing the celerity. The reduced friction in a plastic material reduces the damping effect of a surge wave and the number of oscillations may actually increase.

The reduced celerity means that the time for a pressure wave to travel to the end of the pipeline and return is increased proportionally. Thus the critical time for closing of valves has to be increased, so that they don't act as rapid close valves and create surge phenomenon on themselves.

Effect of Polar Moment of Inertia of The Pump:

In this case, the pervious hydraulic model is used, to study the effect of polar moment of inertia of the pump to protect the pipe line against column separation problem.
The computation are made for the cases when the moment of inertia equals 20, 50, 100 and 150 kg.m^2.This situations does not improve as the negative pressure remains in the line with the change of polar moment of inertia, does not prevent the occurring of column separation *and* does not have any effect in reducing the initial air vessel volume.

Conclusions:

This study concerns the determination of the problems resulting from the transient flow in pipeline systems caused by the failure of pumps. These studies take into consideration the effects of percentage of dissolved air (air content), the effects of friction factor, pipe material, diameter and thickness of the pipe.

From such analysis it was found that Column separation often occurs after pump failure at the high point of pipeline.

The using of an air vessel effectively protects the pipeline against column separation. It is possible to decrease the initial an air vessel volume by studying the variation of the transient flow using the pervious hydraulic model.

Air vessel with surge towers may be used to protect the pipeline against column separation and decrease the initial air vessel volume.

Increases the diameter of the pipeline reduces the surge pressures *and* decreases the initial air vessel volume. This occurs as the velocity is reduced. The downside is the increased cost of the pipe. The variables have a lesser effect on the answers and do not protect the pipeline against column separation.

The negative pressure remains in the line with the change of polar moment of inertia of the pump, with change of pipe material, from GRP to steel, with change of pipe wall thickness *and* doesnot decrease the initial air vessel volume.

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