

Controlling Transient Flow in Pipeline Systems by Desurging Tank with Automatic Air Control

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Abstract—Desurging tank with automatic air control “DTAAC” is a water hammer protection device, operates either an open or closed surge tank according to the water level inside the surge tank, with the volume of air trapped in the filling phase, this protection device has the advantages of its easy maintenance, and does not need to run any external energy source (air compressor). A computer program has been developed based on the characteristic method to simulate flow transient phenomena in pressurized water pipeline systems, it provides the influence of using the protection devices to control the adverse effects due to excessive and low pressure occurring in this phenomena. The developed model applied to a simple main water pipeline system: pump combined with DTAAC connected to a reservoir. The results obtained provide that the model is an efficient tool for water hammer analysis. Moreover; using the DTAAC reduces the unfavorable effects of the transients.

Keywords—DTAAC, Flow transient, Numerical model, Pipeline system, Protection devices.

I. INTRODUCTION

THE study of fluid transient began with the investigation of sound waves in air, the wave propagation in shallow water and the blood flow in arteries, and increased considerably in recent years [1], [2]. A hydraulic transient is a flow condition where the velocity and pressure change rapidly with time due to a flow control component changes status (for example, a valve closing or pump stopping).

Transient flow is one of the major problems faced the pressurized pipeline systems during the filling phase and/or pump failure or sudden operations of the control devices, the overpressure caused by water hammer can easily exceed the pipeline rating pressure; therefore, the risk of explosion is released. Also, the low pressure is not less dangerous than the overpressure; it can cause pipeline collapse and/or wastes and pesticides intrusion to the pipeline. Pipeline rupture due to the water hammer is not uncommon and the repairing costs are not often trivial. In addition to its material damages, the water hammer is responsible for stopping the waterworks.

To reduce or even to eliminate the dangerous effects of the water hammer; the surge devices have been added to the pipeline systems such as the open surge tank, closed surge tank and, ...etc, most of these protection equipments aim to protect against unfavorable large pressure fluctuations and

tend to maintain the pressure at a nearly constant value at some fixed places, or tend to keep the pressure from exceeding a predetermined value [1], [3], [4]. Several criteria can be adopted to determine which surge devices are to be used such as the effectiveness, dependability, evaluation of cost character and frequency of maintenance requirement over an exceeded period [5].

DTAAC consists of a vertical tank, connected to the network through a tube located at the center of the lower bottom, the top of the tank is actually a chamber limited by a central ventilation tube extends inwardly, this tube has a float control to control the exchanges with the outside atmosphere, DTAAC can absorb both the overpressure and negative pressure, this special tank has mainly two different functions according to the water level inside the surge tank:

1. Closed surge tank when the vertical ventilation tube is partial or full submerged (Fig. 1)
2. Open surge tank whenever the water level is below the vertical ventilation tube level (Figs. 2 and 3).

The use of digital computers for analyze hydraulic transients has been used tenths of years ago [1], [3], [4], [6]-[12], and increased considerably in recent years, also sophisticated numerical methods has been introduced for such analyses [1], [2], [13]. Computer simulation models allow using computer in controlling the pipe system devices [14], [15]. In this article a computer program has been developed in order to simulate and design hydraulic transients in pipeline including desurging tank with automatic air control.

II. MATERIALS AND METHODS

Note: Most of the formulations shown in this document are taken from [16], [17]:

When changes in velocity and consequently pressure are occur rapidly, both the compressibility of the liquid and the elasticity of the pipe must be included in the analysis, this procedure is often called "elastic" or "water-hammer" analysis and involves acoustic pressure waves traveling through the pipe and the solution of partial differential equations, even though the term transient refers to all unsteady flows, it is generally used to identify the "elastic" case specifically [17].

The general expression for the acoustic pressure wave is

$$a = \frac{\sqrt{K/\rho}}{\sqrt{1+c\frac{K}{E}\frac{D}{e}}} \quad (1)$$

where K and ρ are the bulk modulus of elasticity and density of the fluid, D and e are the inner diameter and the thickness of the pipe respectively, E is the Young modulus (modulus of

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elasticity) of the pipe material, and c is a coefficient that accounts for the pipe support conditions:

- $c = 1 - 0.5\mu$, the pipeline is anchored only at the upstream.
- $c = 1 - \mu^2$, the pipeline is anchored against longitudinal movement.
- $c = 1$, the pipeline has expansion joints throughout.

where μ is the Poisson's ratio for the pipe material.

The simplified equations that govern unsteady flow in pipeline system are motion and continuity equations which solved together ((2) and (3)).

$$\frac{\partial H}{\partial x} + \frac{1}{g} \frac{\partial V}{\partial t} + \frac{fV|V|}{2gD} = 0 \quad (2)$$

$$\frac{\partial H}{\partial t} + \frac{a^2}{g} \frac{\partial V}{\partial x} = 0 \quad (3)$$

where: H is the piezometric head, V is the flow velocity, x is the distance along the pipeline, t is the time, g is the acceleration of gravity, f is the pipeline friction factor (assumed constant), D is the pipeline diameter, and a is the celerity of a pressure wave in the pipeline assumed constant).

By multiplying (3) by unknown constant λ , adding it to (2), and taking the total derivative to obtain the compatibility (4) and (6).

$$\frac{g}{a} \frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 \quad C^+ \text{ equation} \quad (4)$$

$$\text{For } \frac{dx}{dt} = +a \quad (5)$$

$$\frac{g}{a} \frac{dH}{dt} - \frac{dV}{dt} - \frac{fV|V|}{2D} = 0 \quad C^- \text{ equation} \quad (6)$$

$$\text{For } \frac{dx}{dt} = -a \quad (7)$$

Solution of (4) and (6) is done by using finite differences solution. Fig. 1 illustrates a simple pump - reservoir system, the pipeline is divided to N equal sections of length Δx , and the calculations were made at node 1.

A transient is generated at time t by a sudden pump failure; solution of the equations governing the transient phenomena consists of finding the values of head and flow at each node as the transient progresses, calculations were made at each Δt time interval, where L is the pipeline length.

$$\Delta t = \frac{L}{aN} \quad (8)$$

In general, to calculate the head and flow at node 1 at time $t_0 + \Delta t$, the head and flow at node 2 at instant time t_0 are assumed to be known before any generated transient.

The unknown head and flow at node 1 at time $t_0 + \Delta t$, which labeled HP_1 and QP_1 can be calculated by integrating (4) and (6), the known head and flow at the previous time step are H_1 and Q_1 , before the integration, both equations multiplied by (adt/g) , V changed to Q , and dt replaced

by $dx = a dt$. For the C^- equation, the integration was made from node 2 to node 1, therefore (10) is obtained.

$$\int_{H_2}^{H_1} dH + B \int_{Q_2}^{Q_1} dQ + R_1 \int_{x_2}^{x_1} Q|Q| dx = 0 \quad (9)$$

$$HP_1 - H_2 - B(QP_1 - Q_2) + R_1 Q_2 |Q_2| (x_1 - x_2) = 0 \quad (10)$$

Let

$$\Delta x = x_1 - x_2$$

$$HP_1 - H_2 - B(QP_1 - Q_2) - RQ_2 |Q_2| = 0 \quad (11.a)$$

where $R = R_1 \Delta x$

By rearranging the above equation

$$HP_1 - BQP_1 = H_2 - BQ_2 + RQ_2 |Q_2| \quad (11.b)$$

Let

$$CM = H_2 - BQ_2 + RQ_2 |Q_2| \quad (12)$$

Therefore, (13) is obtained

$$HP_1 - BQP_1 = CM \quad C^- \text{ equation} \quad (13)$$

where H_2 and Q_2 are the head and flow respectively at node 2 at instant time t_0 .

With

$$B = \frac{a}{gA} \quad \text{and} \quad R = \frac{\lambda \Delta x}{2gDA^2}$$

Desurging tank with automatic air control at the upstream end of the pipe: Instantaneous pump stopping is studied in detail in this article. This special tank has mainly two different functions according to the water level inside the surge tank.

A. Operation as Open Surge Tank

The boundary conditions here as shown in Fig. 1 is DTAAC, when the vertical pipe is out of water, this case is exactly the same as for the open surge tank; since the tank in this case is open to the atmosphere.

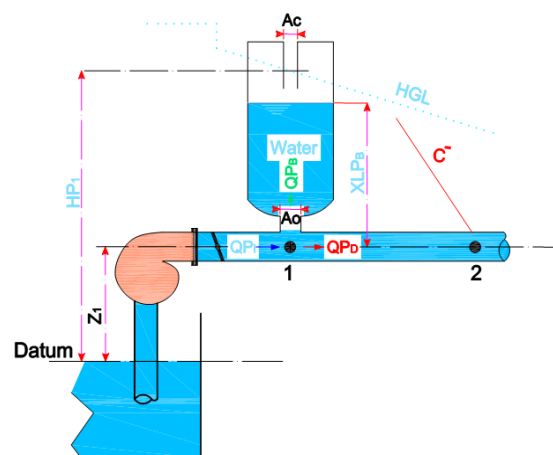


Fig. 1 Desurging tank with automatic air control: Notations for head and flow calculations (Operation as open surge tank)

The equations required to calculate the head and flow at the boundary where the DTAAC is installed at node 1 (Fig. 1), are illustrated through the following system of equations. In addition to C -equation that derived above, the unknown variables in these equations which identified in Fig. 1 are: QP_i , QP_D , QP_C , HP_1 and XLP_C

$$HP_1 = CM + BQP_D$$

$$XLP_C = XL_C + (QP_C + Q_C) \frac{\Delta t}{2A_C} \quad (15)$$

$$HP_1 = XLP_C + Z_1 + KQP_C|QP_C| \quad (16)$$

$$QP_i = QP_C + QP_D \quad (17)$$

$QP_i = 0$ In instantaneous pump stopping

where QP_i is the pump discharge, QP_C is the exchanged discharge between the pipe and the DTAAC, QP_D is the downstream discharge, HP_1 is the piezometric head at node 1 and XLP_C is the water level inside the DTAAC.

These four equations are combined to obtain a single nonlinear equation in QP_C .

$$KQP_C|QP_C| + C_1QP_C + C_2 = 0 \quad (18)$$

where:

$$C_1 = \frac{\Delta t}{2A_C} + B; C_2 = XL_C + Q_C \frac{\Delta t}{2A_C} + Z_1 - CM$$

and

$$K_C = \pm \frac{K_{orifice}}{2gA_{orifice}}$$

B. Operation as Closed Surge Tank

During operation of DTAAC works as a closed surge tank, there are two situations in which the vertical duct is partially or completely filled with water, in the first case the largest volume fraction of water exchange between the pipe and the tank is stored inside the tank and the rest is stored inside the ventilation duct, while in the second case the whole volume of water entered in the tank is stored inside the tank body.

1. Ventilation Duct is Partially Full

In addition to the unknown variables mentioned in the previous case relating to the operation of DTAAC as open surge tank, a three other variables are added such as the volume, pressure of the air at the moment $t + \Delta t$ and the difference in water levels in the tank and the ventilation duct " XP_C " at the same time, this variable is exactly the height of water that represents the air pressure at the instant $t + \Delta t$.

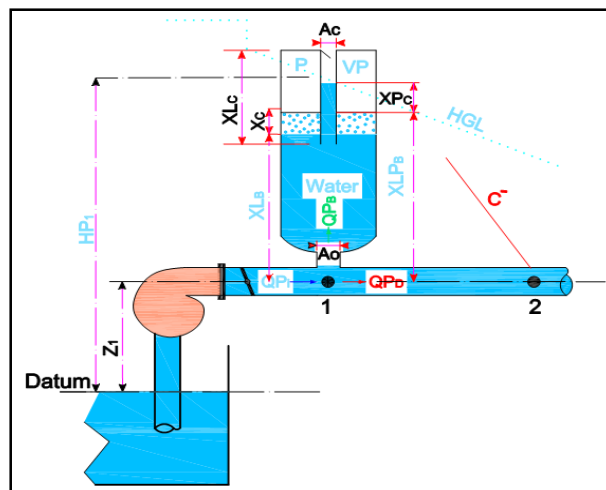


Fig. 2 Desurging tank with automatic air control: Notations for head and flow calculations (Operation as Air chamber - the ventilation duct is partially full).

The equations required to calculate the head and flow at the boundary where the open surge tank is installed at node 1 (Fig. 2), are illustrated through the following system of equations, In addition to (15) and (18) that mentioned above.

$$XLP_C = XL_C + \frac{1}{2} \frac{(QP_C + Q_C)\Delta t - A_C(XP_C - X_C)}{(A_B - A_C)} \quad (19)$$

$$HP_1 = XLP_C + Z_1 + KQP_C|QP_C| + \frac{P}{\rho g} \quad (20)$$

$$\left(\frac{P}{\rho g} + H_b\right) * VP^\gamma = H_b V_0^\gamma = cte \quad (21)$$

$$VP = V + \frac{1}{2} (QP_C + Q_C)\Delta t + A_C(XP_C - X_C) \quad (22)$$

With

$$XP_C = \frac{P}{\rho g} \text{ and } X_C = \frac{P_0}{\rho g}$$

where A_C is the section of the ventilation duct, A_B is the tank cross sectional area, H_b is the atmospheric pressure (m), V is the initial volume of air at time t , XL_C is the length of vent, and X_C is the air pressure in meters head at time t and P_0 is the pressure of the air inside the tank at the instant t .

The initial air volume V_0 at time $t = 0$, is defined by the relationship:

$$V_0 = XL_C(A_B - A_C) \quad (23)$$

2. Ventilation Duct is Completely Full

As soon as the water level in the vent reached to the top of the tank, the DTAAC works just like a closed surge tank, the whole volume of water entered in the tank is stored inside the tank body so we have fewer variables compared to the previous case, and it is precisely the XP_C .

The first five previous equations remain valid, with the exception of (19) and (21) above, which must be replaced by the following relations:

$$XLP_c = XL_c + \frac{1(QP_c + Q_c)\Delta t}{2(A_B - A_C)} \quad (24)$$

$$VP = V + \frac{1}{2}(QP_c + Q_c)\Delta t \quad (25)$$

III. SIMULATION RESULTS

In order to demonstrate the use of the elastic method for transient analysis, a pump feeds a reservoir at upstream end is considered. The foregoing case study illustrates a typical concept to consider when analyzing hydraulic transients.

Case study: A pump feeds a reservoir as shown in Fig. 4 with $Q = 0.05 \text{ m}^3/\text{s}$, where the water level elevation $H_R = 30 \text{ m}$, through a conduit having the following characteristics, $L = 1000 \text{ m}$, $D = 0.30 \text{ m}$, $\lambda = 0.02$, and $a = 1000 \text{ m/s}$. At a given moment the pump is stopped after a power failure.

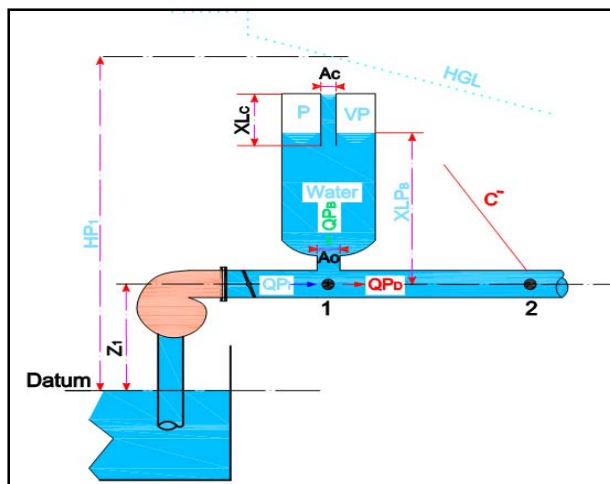


Fig. 3 Desurging tank with automatic air control: Notations for head and flow calculations (Operation as Air chamber - the ventilation duct is completely full)

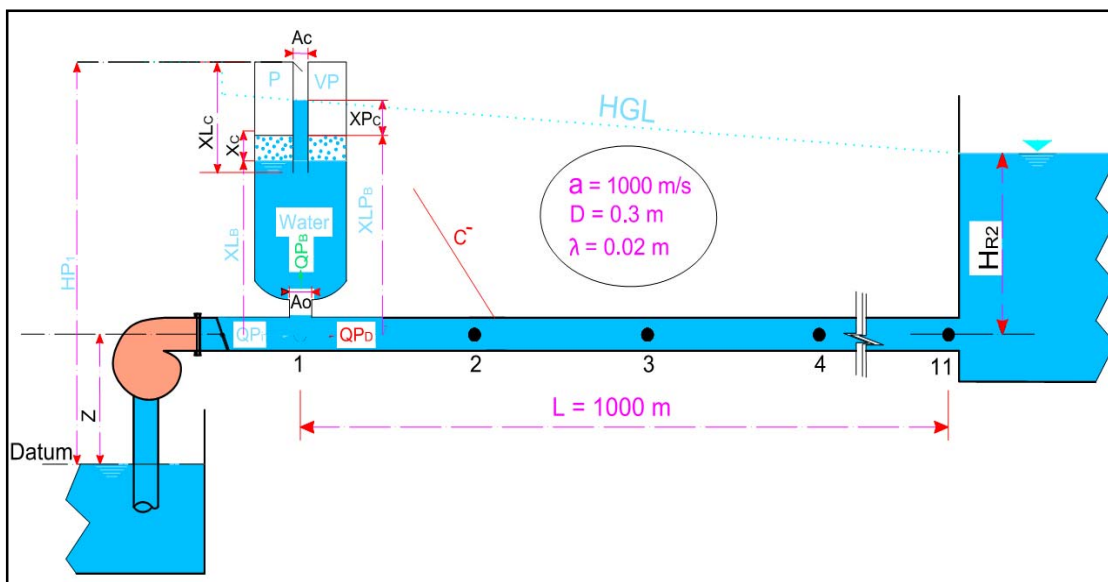


Fig. 4 Simple pump - reservoir system combined with desurging tank with automatic air control

This case study demonstrates the capability of the developed program to simulate the water hammer effect by simulating the sudden pump stopping at the upstream of a long pipe in which water is flowing, the model takes into account the fluid and pipe wall elasticity. For this case study, a simple system is presented in order to best illustrate the water hammer simulation capability of the developed program, the simulation results for the unprotected pipeline are presented in the following figures:

A. Instantaneous Pump Stopping without Including Protective Devices

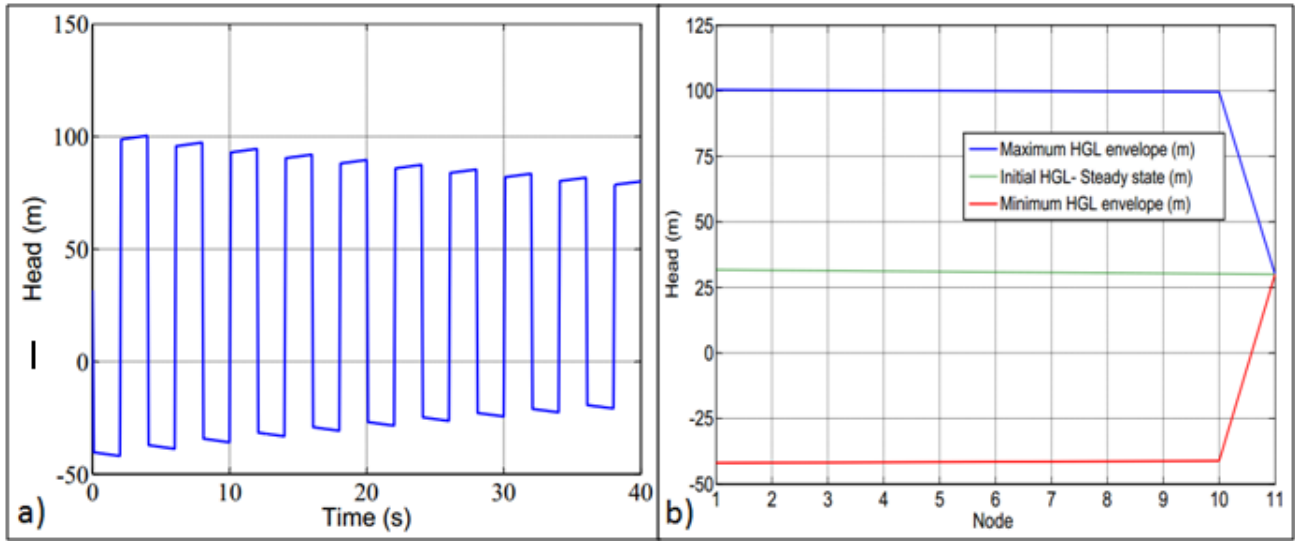


Fig. 5 Transients in a pumping system (a) Head change versus time at the pump (b) Hydraulic grade lines (without including the desurging tank with automatic air)

Fig. 5 shows the variation of head versus time, this simulation conducted within 40 second, the maximum and minimum pressure occurred at the times 3.9 and 1.9 second respectively after generating transient, and this pressure head amplitude becomes weaker from one cycle to another till it is

vanish due to head losses, the maximum and the minimum pressure envelopes for the unprotected pipeline along the entire pipe length "1000 m" are 100.31 m and - 41.94 m respectively, while in the steady state before generating any transient are 45.13 m and 30 m respectively.

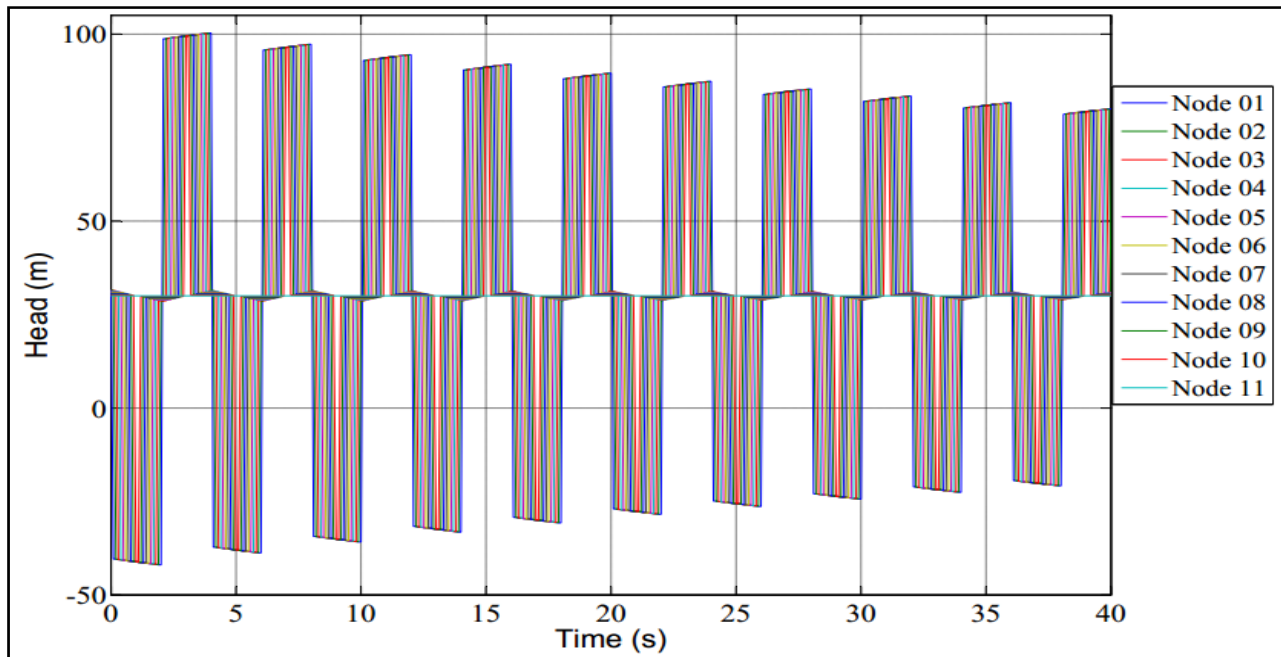


Fig. 6 Variation of head at each node Vs time (without including the desurging tank with automatic air control)

B. Instantaneous Pump Stopping with Closed Surge Tank Included

A Desurging tank with automatic air control installed immediately downstream of the pumping station, the surge tank has 0.75 m² cross-sectional area and the entrance

diameter is 0.15 m, the length of ventilation duct and its cross-sectional area are 2.5 m² and 0.1 m respectively, The simulation results for the protected pipeline are presented in the following figures:

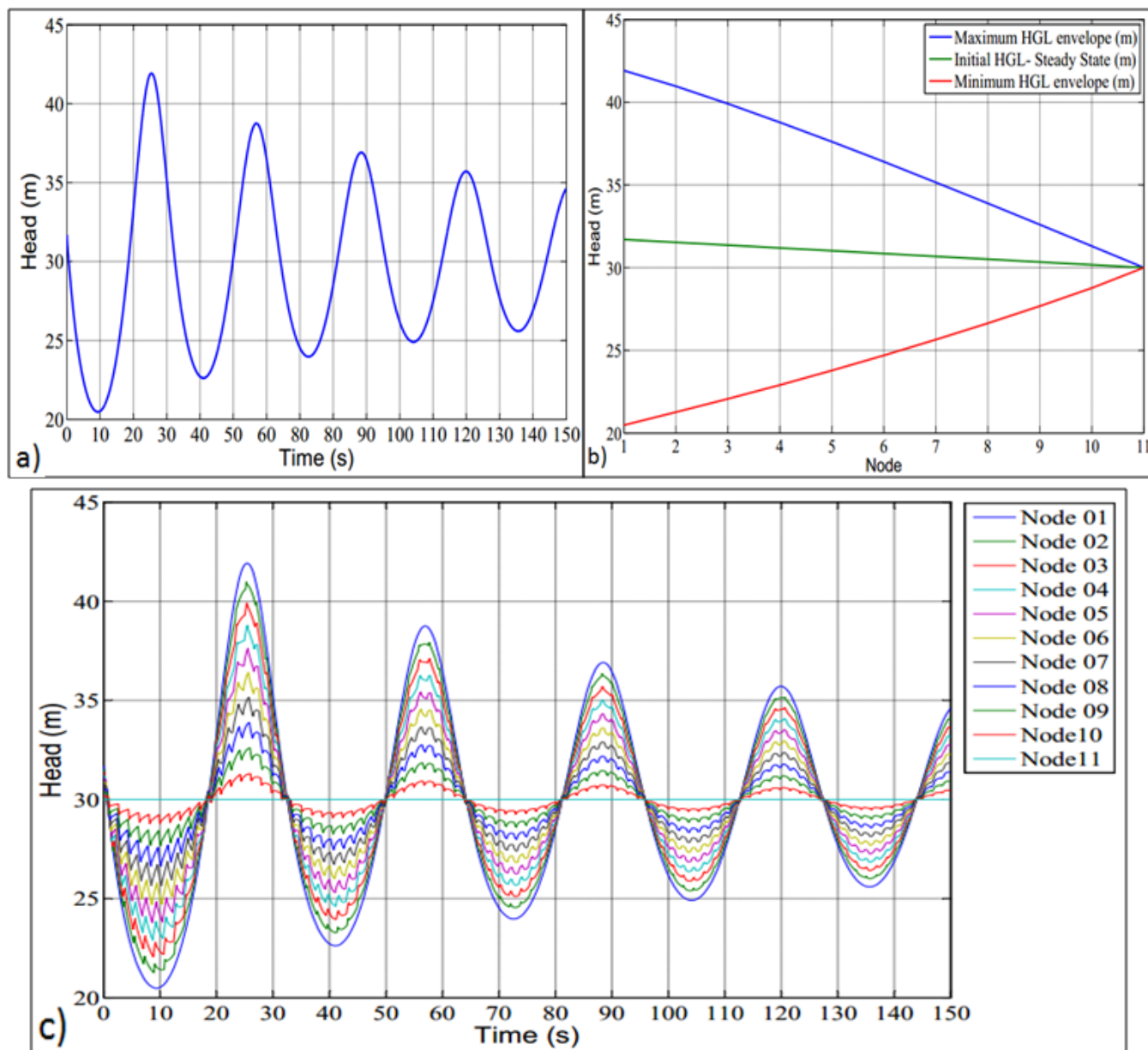


Fig. 7 Transients in a pumping system (a) Head change versus time at the pump (b) Hydraulic grade lines (with including the desurging tank with automatic air control) and (c) Variation of head at each node Vs time (with including the desurging tank

Fig. 7 shows that the maximum pressure and minimum pressure occurred at the times 25.29 and 9.36 second respectively, and the pressure head amplitude become weaker from one cycle to another till it is vanish due to head losses, the maximum and the minimum pressure envelopes for this case are reduced to 41.915 m and 20.476 m respectively, and the pressure head at the nodes further from the source of transient are less in amplitude and become more less whenever it goes further from it. The analysis of the water level variation versus time in front of the desurging tank with automatic air control is presented in Fig 8.

It's clear in this case that the desurging tank with automatic air control worked only as air chamber during the entire simulation period; since the water level never fell below 7.5

m, a level that corresponds to the boundary between functions as open surge tank and as air chamber, the minimum level of the water in the desurging tank with automatic air control is 8.675m, the maximum variation of the water level is only 0.563m.

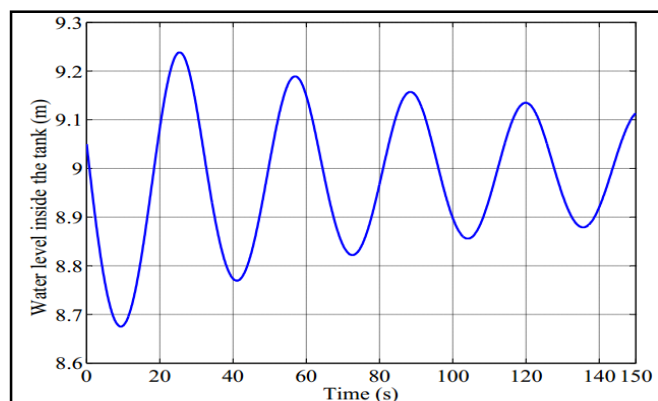


Fig. 8 Water level variation inside the desurging tank with automatic air control versus time

IV. CONCLUSION

The study of water hammer effect phenomena in pipeline systems is very important due to the adverse impact resulting in pump, valve failures and catastrophic pipe ruptures, therefore, its analysis is very important in determining the values of transient pressures that can result from flow control operations and to establish the design criteria for system equipment and devices in order to provide an acceptable level of protection against system failure due to pipe collapse or bursting. Numerical simulation model is a helpful tool for the engineers to decide among different technical and economic solutions regarding water hammer protection.

Desurging tank with automatic air control is an effective means of protecting and reducing water hammer overpressures and negative pressures, moreover, this protection device has the advantages of its easy maintenance, does not need to run any external energy source (air compressor), and is cheaper than other protecting devices.

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