Study on Status and Development of Hydraulic System Protection: Pump Combined With Air Chamber

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Abstract—Fluid transient analysis is one of the more challenging and complicated flow problems in the design and the operation of water pipeline systems (wps). When transient conditions "water hammer" exists, the life expectancy of the wps can be adversely impacted, resulting in pump and valve failures and catastrophic pipe ruptures. Transient control has become an essential requirement for ensuring safe operation of wps. An accurate analysis and suitable protection devices should be used to protect wps. This paper presents the problem of modeling and simulation of transient phenomena in wps based on the characteristics method. Also, it provides the influence of using the protection devices to control the adverse effects due to excessive and low pressure occur in the transient. The developed model applied for main wps: pump combined with closed surge tank connected to a reservoir. The results obtained provide that the model is an efficient tool for water hammer analysis. Moreover; using the closed surge tank reduces the unfavorable effects of transients.

Keywords—Flow Transient, Water hammer, Pipeline System, Closed Surge Tank, Simulation Model, Protection Devices, Characteristics Method.

I. INTRODUCTION

IN a wps, the flow control is an integrated part of the operation, for instance, opening and closing the valves, starting and stopping the pumps. When these operations very quickly performed, they shall cause the hydraulic transient phenomena.

Transients can introduce large pressure forces and rapid fluid accelerations into a wps. These disturbances may result in pump and device failures…etc.

Several methods have been introduced and used to analyze water hammer problem like the energy [1], arithmetic [2], graphical, characteristics, algebraic, implicit and linear analyzing [3]-[5], Euler and Lagrangian based method [6], and decoupled hybrid methods [7]. Karney used the characteristics with some modification to obtain more efficient calculations of transient in simple pipe system [8], while Tezkan used this method to analyze the transient in complex pipe systems [9]. Kodura and Weinerowska, Karney and Mclnnis, Sirvole and

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Jung compared between the results obtained for both simple and complex pipe systems by using the method of characteristics, and the results are more accurate in the simple systems [1], [10]-[12].

The characteristics method has been used to study the oil pipe systems [13] and cooling networks in nuclear plants [3], [14].

Recently Nabi used this method to analyze real pipe systems in Pakistan; also they studied the effect of installing the protection devices on the pipeline systems [15].

To reduce the dangerous effects of water hammer; the surge devices have been added to the pipeline systems. Most of these protection equipments aim to protect against unfavorable large pressure fluctuations 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 [3], [16], [17]. 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].

Air chamber is a relatively small pressurized reservoir that contains water and air. Generally, it is connected to the main pipe just at the discharge point of the pumps. Its primary purpose is to prevent the negative pressures and the column separation downstream the pumps [18], [19]. After the energy failure, the liquid drains from the air chamber to the pipe and the air volume inside the chamber expands causing a pressure drop.

The magnitude of such pressure drop is dependant of the initial air volume as well as the air thermodynamic process [19], [20]. When the pump power fails, the flow begins to advance in reverse and the retention valve instantly closes to protect the pump. After that, the liquid come into the air chamber [3]. The system oscillates and ultimately comes to rest. The period of the oscillation and the associated head fluctuation depends on the size of both the air chamber and the system. It is important that the tank be large enough that it never empties and allows the air to flow into the pipe [20].

The air chamber has many advantages of use [3]:
- Air volume necessary to keep the maximum and minimum pressures is relatively small.
- Air chamber can be installed to level ground. This fact reduces the foundation costs and it brings a greater resistance against wind forces and earthquakes.
- Air chamber can be installed very close to the pump.

- To prevent the freezing, is cheaper to heat the liquid inside the chamber due to its minor size and proximity to the pump.

The use of digital computers for analyze hydraulic transients has been used tenths of years ago [17] and increased considerably in recent years, also sophisticated numerical methods has been introduced for such analyses [3], [4].

The computer simulation allow using computer in controlling the pipe system devices [21].The proper simulation and design for the pipe systems aims to achieve two main goals: the first goal is to reduce the total cost of the system; for example one can compromise between the price and the useful life of the conduit. The other goal is to protect the pipe systems from damaging due to the gain pressure in the unsteady state which also reduce the cost of maintenance [3], [20].

In this article computer software had been developed in order to simulate and design hydraulic transients in pipeline systems.

II. Materials and Methods

Note: Most of the formulations shown in this document are taken from [20], [22]:

The simplified equations that govern unsteady flow in pipelines are motion and continuity equations which solved together ((1) and (2)), since the two equations provide two unknowns H and V. The method of characteristics used to transform the partial differential equations into total differential equations.

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

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

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

By multiplying (2) by unknown constant λ, adding it to (1), and by rearranging and taking the total derivative to obtain the compatibility ((3) and (5)):

$$\frac{g}{a}\frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 \qquad C^+\text{equation} \qquad (3)$$

$$\text{For } \frac{dx}{dt} = +a \qquad (4)$$

$$\frac{g}{a}\frac{dH}{dt} - \frac{dV}{dt} - \frac{fV|V|}{2D} = 0 \qquad C^-\text{equation} \qquad (5)$$

$$\text{For } \frac{dx}{dt} = -a \qquad (6)$$

Solution of (3) and (5) 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. The calculations were made at node i.

Fig. 1 Pump at upstream end

A transient is generated at time t by 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 which calculated by (7). The nodes are equally spaced at a distance Δx and the wave speed is assumed to be constant.

$$\Delta t = \frac{L}{aN} \qquad (7)$$

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

The unknown head and flow at the nodes i at time $t_0 + \Delta t$ are labeled HP_i, and QP_i can be calculated by integrating (3) and (5), the known head and flow at the previous time step are H_i and Q_i, before the integration, both equations multiplied by adt/g, V changed to Q, and dt replaced by $dx = adt$. For the C^+ equation, the integration was made from node $(i-1)$ to node (i); therefore (8) is obtained:

$$\int_{H_{i-1}}^{H_i} dH + B\int_{Q_{i-1}}^{Q_i} dQ + R_1\int_{x_{i-1}}^{x_i} Q|Q|dx = 0 \qquad (8)$$

$$HP_i + BQP_i = CP \qquad C^+\text{equation} \qquad (9)$$

The same procedure was made for the C^- compatibility equation, by integrating from node $(i+1)$ to node (i); (10) is obtained:

$$HP_i - BQP_i = CM \qquad C^-\text{equation} \qquad (10)$$

In which

$$CP = H_{i-1} + BQ_{i-1} - RQ_{i-1}|Q_{i-1}| \qquad (11)$$

$$CM = H_{i+1} - BQ_{i+1} + RQ_{i+1}|Q_{i+1}| \qquad (12)$$

where H_{i-1}, Q_{i-1}, H_{i+1} and Q_{i+1}, are the heads and flows respectively at the nodes $i-1$ and $i+1$ at instant time t_0.

With $B = \dfrac{a}{gA}$ and $R = \dfrac{\lambda \Delta x}{2gDA^2}$

The solutions are (13) and (14):

$$HP_i = \frac{1}{2}(CP + CM) \qquad (13)$$

$$QP_i = \frac{(CP - HP_i)}{B} \qquad (14)$$

In the above section the equations used for calculating head and flow at intermediate nodes were derived, while the equations needed to calculate head and flow at the boundaries are derived in the following section.

A. Closed Surge Tank at Pump Downstream

1. Instantaneous Pump Stopping

The unknown variables in the flowing equations are QP_B, QP_D, HP_1, VP, XLP_B and P.

$$HP_1 = CM + BQP_D \qquad (15)$$

$$XLP_B = XL_B + (QP_B + Q_B)\frac{\Delta t}{2A_B} \qquad (16)$$

$$HP_1 = XLP_B + K_B QP_B|QP_B| + P + Y_1 \qquad (17)$$

$$VP = V - \frac{1}{2}(QP_B + Q_B)\Delta t \qquad (18)$$

$$P * VP^\gamma = cte \qquad (19)$$

$$QP_D = -QP_B \qquad (20)$$

with $Y_1 = Z_1 - H_b$

Where QP_B is the exchanged discharge between the pipe and the air chamber, QP_D is the downstream discharge, HP_1 is the piezometric head at node 1, VP is the air volume inside the air chamber, XLP_B is the water level inside the air chamber, γ is the exponent of the polytropic equation and P is the gas pressure. These six equations combined to obtain a single nonlinear equation in QP_B.

$$\left(C_1 - (QP_B + Q_B)\frac{\Delta t}{2A_B} - BQP_B - K_B QP_B|QP_B|\right)U = cte \qquad (21)$$

with

$$U = \left(V - \frac{1}{2}(QP_B + Q_B)\Delta t\right)^\gamma \text{ and } C_1 = CM - XL_B - Y_1$$

2. Slow Pump Shutdown

The flow delivered by the pump does not vanish instantly, so the first five equations previously established remain valid with the exception of the continuity equation to be written as:
$QP_i = QP_D + QP_B$

Moreover, the equations that define the flow and head as a function of the pump rotational speed must be used.

$$HP_1 = H_{mnt} + Z_1 - K_{Chk}QP_i|QP_i| \qquad (22)$$

$$H_{mnt} = a_2 QP_1^2 + a_1 np QP_1 + a_0 np^2 \qquad (23)$$

$$np = np_i - c\left(\frac{p}{np} + \frac{p_i}{np_i}\right) \qquad (24)$$

$$p = np\, b_2 QP_1^2 + b_1 np QP_1 + b_0 np^2 \qquad (25)$$

$$QP_i = QP_C + QP_D \qquad (26)$$

With $np = \dfrac{N}{N_0}$ and $C = \dfrac{900\, \rho\, g}{\pi^2 I_0}$

where H_{mnt} is the pump head, K_{Chk} is the check valve singular loss coefficient, N is the rotational speed, p is the power consumption, a_0 to a_2 and b_0 to b_2 are the coefficients of the pump characteristics.

III. SIMULATION RESULTS

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

Case study: A pump feeds a reservoir as shown in Fig. 3, where the water level elevation $H_R = 60$m, through a conduit having the following characteristics, L = 1000m, D = 0.15m, $\lambda = 0.024$, and a = 1000 m/s. At a given moment the pump is stopped after a power failure In order to simulate transients for this case, three different pump stopping options had been chosen. Instantaneous stopping and stopping with 2 and 8 kg.m^2 moment of inertia. The pump characteristics are shown in Fig. 2.

A closed surge tank installed immediately downstream of the pumping station, the surge tank has 0.5 m^2 cross-sectional area and 0.1 m entrance diameter. The simulation results are presented through the following figures for each case:
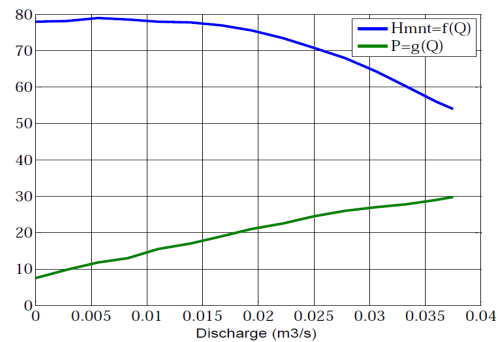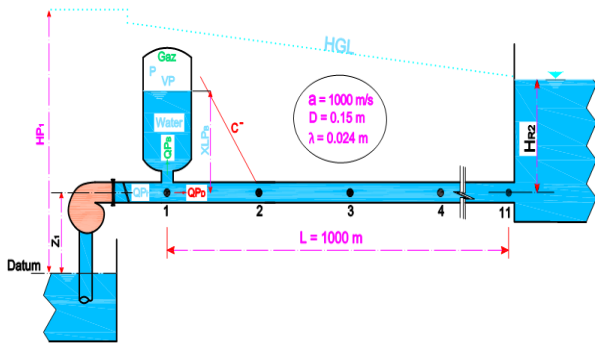

Fig. 2 Pump characteristics

Fig. 3 Simple pump - reservoir system

A. Instantaneous Pump Stopping

Fig. 4 shows that the maximum and the minimum pressure envelopes for the unprotected pipeline along the entire pipe length are 177m and -66.44m respectively, and the pressure head amplitude become weaker from one cycle to another till it is vanish due to head losses.
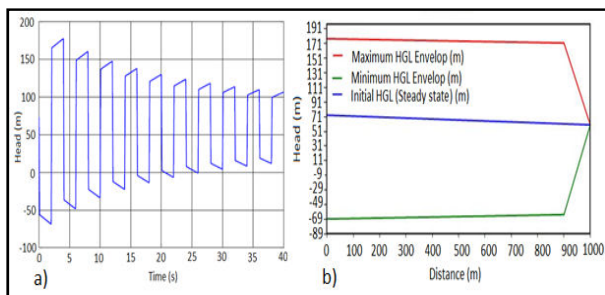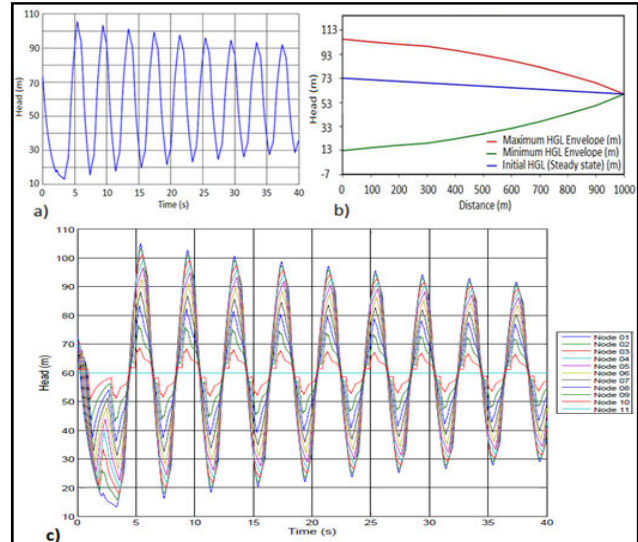

Fig. 4 Transients in a pumping system (a) Head change versus time at the pomp and (b) Hydraulic grade lines (without Protection)

B. Pump Stopping with 2 kg.m² Moment of Inertia

A pump's motor exerts a torque on a shaft that delivers energy to the pump's impeller, forcing it to rotate and add energy to the fluid as it passes from the suction to the discharge side of the pump volute. Whenever power fails, the pump slows or stops and a sudden drop in pressure propagates downstream (a rise in pressure also propagates upstream in the suction system). Pump inertia is the resistance of the pump to acceleration or deceleration. Pump inertia is constant for a particular pump and motor combination. The higher the inertia of a pump is, the longer it takes for the pump to stop spinning following its shutoff and vice versa. Larger pumps have more inertia because they have more rotating mass. Pumps with higher inertias can help to control transients because they continue to move water through the pump for a longer time as they slowly decelerate.

The simulation results for this case are represented in Fig. 5, it's obvious that the maximum and the minimum pressure envelopes are reduced to104.98m and 13.21m respectively when the moment of inertia is equal to 2kg.m².

Fig. 5 Transients in a pumping system (a) Head change versus time at the pomp and (b) Hydraulic grade lines (with 2 kg.m² moment of inertia) (c) Head variation of at each node Vs time (with 2 kg.m² moment of inertia)

C. Pump Stopping with 8 kg.m² Moment of Inertia

The simulation results for this case are represented through Fig. 6, it is obvious that the maximum and the minimum pressure envelopes are reduced to 87.73m and 30.67m respectively when the moment of inertia is equal to 8kg.m², and It is clear that the pressure envelope when the moment of inertia is equal 8kg.m² is less than the pressure envelope when the moment of inertia is equal 2kg. m².
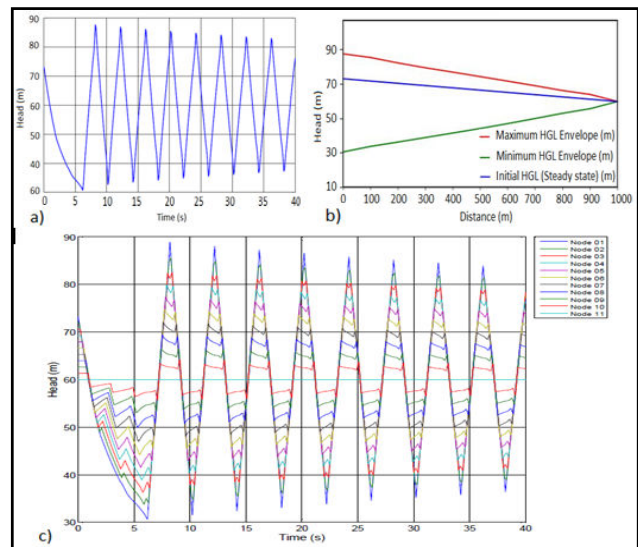
Fig. 6 Transients in a pumping system (a) Head change versus time at the pomp and (b) Hydraulic grade lines (with 8 kg.m² moment of inertia) (c) Head variation of at each node Vs time (with 8 kg.m² moment of inertia)

D. Pump Stopping with a Closed Surge Tank Included
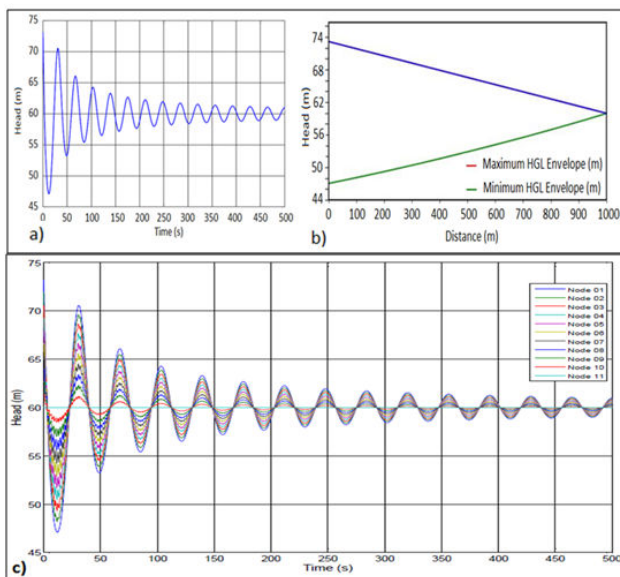

Fig. 7 Transients in a pumping system (a) Head change versus time at the pomp and (b) Hydraulic grade lines (with   including the closed surge tank) (c) Variation of head at each node Vs time (with including the closed surge tank)

The simulation results for this case are represented in Fig. 7 show that the maximum and the minimum pressure envelopes are reduced to73.22m and 47.10m respectively when the air chamber is used, and the pressure head amplitude become weaker from one cycle to another till it is vanish due energy dissipation.

IV. Conclusions

Transients can introduce large pressure forces and rapid fluid accelerations into a piping system. These disturbances may result in pump and device failures…etc. The ability to model transient water column separation is therefore essential to ensure proper system protection and performance.

Due to the devastating effects that a hydraulic transient can cause, 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 so as to provide an acceptable level of protection against system failure due to pipe collapse or bursting.

Clearly, flow control actions can be extremely important and these actions have implications not only for the design of the hydraulic system, but also for other aspects of system operation and protection.

Surge analysis is essential to good design and operation of piping systems. Surge modeling provides the most effective and viable means of predicting potentially negative impacts of hydraulic transients under a number of worst-case scenarios, identifying weak spots, and evaluating how they may possibly be avoided and controlled.

By a simple increase in the pump moment of inertia, overpressure and low pressure can be reduced; also using the closed surge tank ensures adequate protection for the pipeline system against overpressure and low pressure.

Numerical simulation model is a helpful tool for the engineers in charge to decide among different technical and economic solutions regarding water hammer protection.

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