Developing multi-objective optimization model with conflicting goals to improve the surge protection devices design for water hammer

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Abstract

In this study, a Multi-objective Optimization Model (MOM) is developed and solved for the optimum design of surge protection devices (including air chamber and shock damper) with conflicting goals. The shock damper is a new type of surge tank invented by researchers. For the first time, the design parameters of the shock damper as decision variables are raised in a MOM problem, and results are benchmarked with solving the model for the air chamber as well. Method of characteristics (MOC) is chosen for the numerical solution of water hammer PDE's and its system of equations for interior and boundary nodes are used as constraints of the optimization model. The conflicting criteria of the MOM are functions of: safety in the system and installation cost of protection devices. In the following by using the weight coefficients and normalized objective functions obtained by dividing each of the mentioned functions by the maximum potential values of them, the resulting problem is solved by Genetic Algorithm (GA).

The results, while investigated conceptually, show the significant improvement of multi-objective design in the performance and cost-saving in protection devices and the better function of shock damper regarding both criteria.

Keywords: Water hammer, air chamber, shock damper, minimum cost, maximum safety, multi-objective design

1. Introduction

1.1. Water hammer phenomena and simulation

Water hammer (or transient flow) can cause serious damage to pipelines, connections and other components, and can also cause leaks at the system. Several reasons can cause the water hammer effect in the system such as the sudden opening and closing of flow control valves, the operation of one-way valves, bursting pipes, failure of pumps, restarting the pump, etc.[1, 2]. The failure of the pump (due to power failure) in a water transmission system (WTS) is an inevitable phenomenon and its presence can lead to severe water hammer in the system [3, 4]. There are two approaches for simulation of transient flow caused by the sudden failure of the pumps include implicit and explicit that are studies conducted by other researchers [5-7]. In the implicit approach; firstly, the dimensionless parameters of the pump head, discharge, and the rotational speed of the pump are defined, which are extracted from the pump's curves [5]. Then, using the mass, momentum, and energy conservation principle and equations of the MOC, pumps are assumed as a boundary condition and the relevant equations are extracted. The obtained system of equations is nonlinear, which can be solved at each time step by the Newton-Raphson method [4, 8, 9]. For the explicit approach, Larock et al. [7] performed an exemplary and comprehensive study. Their method, despite its simplicity, was more complete than the previous studies.

1.2. Protection and optimization approach

There are two approaches to control transient flow and its effects [10]. First, with no protection devices in the system: changing the diameter and thickness of pipes or appropriate utilization of the WTS in such a way that there are no sudden changes in discharge flow and consequently, water hammer does not occur. [11, 12]. Second, the use of control equipment for water hammer after it occures [13-18]. Optimization techniques can be used in both approaches and the obtained model is nonlinear in most cases. For the first approach: Afshar and Mahjoobi [8] and Afshar and Rohani [11], balanced the effects of water hammer due to pump failure in a simple system by changing the diameter of the pipe. Syed et al. [19] also moderated the effects of transient flow in the pumping system by designing the optimum pipe diameter. In the second approach, evolutionary algorithms for solving optimization design problems of control devices such as air chambers, safety valves and surge tanks, have good capabilities and are more flexible than other methods such as gradient-based algorithms [20, 21]. Jung et al. [17,22] using GA and Particle Swarm Optimization (PSO), solved the optimum problem of surge protection devices in two separate papers. they only considered safety issues in their model as an objective function and concluded the good performance of evolutionary algorithms. Kim et al. [23] used a GA and an impulse response method to study the design of surge tanks for water transmission pipelines to protect against water hammer. Chamani et al. [16] developed the method for designing the differential surge tanks using fuzzy genetic algorithm. Skulovich et al. [13, 24, 25] conducted valuable researches on optimizing the design and layout of control equipment with respect to water hammer in the water distribution networks which also took into account budget constraints.

1.3. Shock damper and optimum design

Bostan et al. [10] introduced a new type of surge tank named shock damper. Despite the ordinary air chambers, this device works hydraulically without the need for a compressor. Its performance was tested and experimental validation of numerical simulation has been done [26]. Thereafter, considering maximum safety as an objective function, an optimization problem was defined for designing it [27]; However, one of the most important parameters in the design of shock damper is the construction cost which was not considered.

1.4. The research gap

Almost all optimization models developed for water hammer protection devices are single-objective models [14-17, 28-31] in which the goal is to minimize transient effects (or maximize safety) or to minimize the cost of installing protective devices. Recently, however, there have been studies that have considered maximum safety as an objective function and budget constraints as a constraint on the optimization model. At the same time, the design variables considered in these studies included the dimension and location of protection devices such as air chambers, safety valves, and surge tanks [13, 18, 25]. Also, some researches have been launched to use multi-objective optimization approaches in controlling the effects of water hammer, mainly in the operation phase of hydropower plants [32-36]. It should also be noted that the shock damper is a new device for damping shock waves in water distribution systems, whose design parameters have been optimized by solving single-objective problems before this research [20-21].

So defining a multi-objective optimization problem for design of typical protection devices such as air chamber and newer such Shock damper is a new area for research that can have parctical applications in water infrastructures. Comparing the shock damper function with a typical (an ordinary) air chamber, considering both cost and performances criteria simultaneously, is another aim of this research.

1.5. This research

In this research, first the water hammer PDE's and numerical solving of them (MOC) are introduced briefly. Then, mathematical equations of the air chamber and Shock damper and their design parameters are presented. By doing so, a MOM is established with objective functions (goals) of minimizing transient effects (or maximizing safety) in the system and the installation cost of protection devices simultaneously. These goals are in conflict with each other and do not have the same dimension, so the weight method and normalization techniques are used. A flowchart is defined and proposed for optimal process solving and design with GA. To test the performance of the desired material a case study has been investigated in which the occurrence of water hammer is due to the failure and restarting of pumps. This problem has previously been studied by other researchers such as Larock et al. [7]. That failure and restarting can cause serious pressure oscillations in the system. The pressure change over time is examined at critical nodes (nodes with maximum and minimum absolute pressure head) in different scenarios with: 1- no protection in the system 2- classical ordinary design with no optimization. 3- multi-objective optimization approaches considering both conflicting goals and 4- considering maximum safety in a system with no cost criteria. Results show the good performance of the shock damper compared to the air chamber while employing a simple mechanism with no energy or operation costs, as well as an optimum design to achieve better performance with lower construction costs for both air chamber and shock damper.

2. Materials and methods

Firstly, in this section, transient hydraulic PDEs and the numerical approach (MOC) for solving them are presented. Secondly, the air chamber and shock damper and their corresponding equations will be introduced as protection devices against the water hammer. the MOC system of equations for the protection devices and other nodes (include interior and boundary conditions) are used as constraints of the optimization model. In the next step, considering the cost and performance as objective functions, a MOM is created for their design. Using some techniques these functions become normalized and dimensionless. Finally, with the exploitation of the GA, two flowcharts are presented for developing and solving of the model.

2.1. Problem definition

To simulate the hydraulic behaviour of a pipeline system in transient condition, applying the principles of mass and momentum conservation in a moving control volume, a pair of partial differential equations (PDE's) as equations (1) and (2), are extracted [1]

$$\frac{\partial V}{\partial t} + g\frac{\partial H}{\partial x} + \frac{fQ|Q|}{2DA^2} = 0 \qquad (1)$$

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

Where H=pressure head and Q=discharge; both are a function of the location (x) and time (t), and the X-axis is coincident with the pipe axis. a=speed of the sound wave propagation in the fluid that is a function of fluid and system properties [7], g= gravity acceleration, D=Diameter of pipe, A=Area of pipe, and f=Darcy-Weisbach coefficient. All units are standard metric units. One of the most common methods of solving the above equations is MOC. Here, the system is divided into nodal points that include interior and boundary nodes [10, 11]. At each node for each time step, the unknown values of discharge and head are obtained from their known values in the previous time step [29].

2.2. Boundary conditions of MOC

Equations associated with boundary nodes (nodes related to the equipment, connections, reservoirs, pumps, and any node other than the interior nodes) are obtainable in the corresponding references [1-3, 5-7]. In the following, the equations for boundary conditions of the air chamber and shock damper are presented.

2.2.1. Boundary condition of the air chamber

The air chamber is one of the conventional pieces of equipment that controls the water hammer as shown in Figure 1. The air chamber that is installed near downstream of the pump station is mostly used for controlling the positive and negative surge of water hammer [30].

Figure 1. Air chamber and its different parts (which has been reproduced by the authors) [7].

Boundary condition equations of the air chamber are as follows [7]:

$$C^{-}: Q_P = A(C_1 + C_2 H_P) \tag{3}$$

$$C_1 = \frac{Q_{P+1}}{A} - \frac{g}{a} H_{p+1} - \frac{f\Delta t}{2DA^2} Q_{p+1}\left|Q_{p+1}\right|, \;\; C_2 = \frac{g}{a} \tag{4}$$

$$Q_C = N_{pa} Q - Q_P \tag{5}$$

$$h_p = F(\frac{Q}{n}, n^2, N_{st}) \tag{6}$$

$$H_T = Z_P - H_{atm} +$$
$$(H_{T_0} - Z_P + H_{atm}) \left(\frac{C_{T_0}}{C_T}\right)^{\eta} \quad (7)$$

$$Q_c = C_0 A_n \sqrt{2g(H_T - (H_S + h_p))} \quad (8)$$

In the above relationships, H_p and Q_p pressure and discharge at the downstream node of air chamber at higher time step respectively, N_{pa} number of parallel pumps, Q discharge of each pump, Q_c inlet discharge of air chamber to the pipeline, H_S head in the suction side , C_0 coefficient of outlet, A_n cross-section of the nozzle, H_T amount of head in the air chamber, n rotational speed of the pump, N_{st} number of pump's stages, h_p is head of pumps that is function of Q, Nst and n (n: variable rotation speed of pumps) [8], η polytropic power, C_{T0} initial volume of closed tank, C_T volume of air chamber at each time step and H_{atm} atmospheric head.

2.3. Shock damper

2.3.1. Introduction to shock damper

The shock damper includes the spring, damper, moving mass and seal packing equipment, main tank and pipe connection (Figure 2). It acts as a vibrating system with a degree of freedom (vertically) to control positive and negative pressure waves resulted from water hammer. If a shock damper is installed in the system, during the water hammer, it can dampen the transient energy in a safe way using a few oscillations; more details about its mechanism can be found in the corresponding papers [10, 26, 27].

Figure 2. Shock damper and its components as a boundary condition in MOC equations (which has been reproduced by the authors) [10].

The parameters shown in Figure 2 are as follows: Q_i^{n+1}, H_i^{n+1} and $Q_{i+1}^{n+1}, H_{i+}^{n+1}$ are discharge and pressure heads at nodes before and after shock damper at time step n+1, L_r, D_r, L_C and D_C are the height and diameter of the main tank and connection pipe, M mass of the moving part, C is the damping coefficient, K_S is spring stiffness; other parameters are defined in the following.

2.3.2. Development of shock damper equations

By using concepts of conservation of mass, energy and momentum, and considering the MOC equations, the equations to simulate the behavior of the shock damper during the occurrence of water hammer will be derived [10].

$$Q_c^{n+1} = (\alpha_2^n Q_c^n + \alpha_3^n) / \alpha_1 \qquad (9)$$

$$H_c^{n+1} = \frac{C_1^n - C_2^n - (Q_c^{n+1} / A)}{2g / a} \qquad (10)$$

In the above equation, Q_c^{n+1}, H_c^{n+1} are discharge and pressure head at the shock damper node in each time step, other parameters are defined as below that you can find more details in related paper.

$$\alpha_1 = \left[\frac{L_c}{gA_c\Delta t} + \frac{a}{2Ag} + \frac{\Delta t}{4A_r} + \frac{M}{2\gamma A_r^2\ \Delta t} + \frac{C}{4\gamma A_r^2} + \frac{K_s\Delta t}{4\gamma A_r^2} \right] \qquad (11)$$

$$\alpha_2^n = \left[\begin{array}{l} \frac{L_c}{gA_c\Delta t} - \frac{\Delta t}{4A_r} + \frac{M}{2\gamma A_r^2\ \Delta t} - \\ \frac{C}{4\gamma A_r^2} - \frac{K_s\Delta t}{4\gamma A_r^2} - \frac{fL_c}{2gA_c^2 D_c} Q_c^n \end{array} \right] \qquad (12)$$

$$\alpha_3^n = \left[\begin{array}{l} \frac{H_i^n}{2} + \frac{(C_1^n - C_2^n)a}{2g} - \\ Z_s^n - \frac{P_0^n}{2\gamma} - \frac{K_s\Delta_0 + Mg}{2\gamma A_r} \end{array} \right] \qquad (13)$$

In these relationships, C_1^n, C_2^n are values as a function of neighbor nodes and previous time steps, A_c, A_r *and* A are the cross-section area of connection pipe, main tank and pipeline, P_0^n is the amount of pressure under the mass in the time step n, γ is the specific gravity of water, H_i^n is the piezometric head in nodes i-th and time n, Z_s^n is the level of mass in the n-th time relative to the axis of the main pipe, Q_i^n the discharge amount of node i-th and time n-th.

In Table 1, the advantages and disadvantages of the air chamber and Shock damper are summarised.

Table 1. Comparison between Air chamber and Shock damper in terms of performance and design parameters

2.4. Definition of the optimization problem

To design the control equipment for water hammer, in water networks, several design variables such as equipment dimensions and parameters should be selected. The final aim is controlling the maximum and minimum pressure head to avoid damage to the system. Thus, a right optimisation problem should be defined and solved. The standard form of any optimisation problem consists of the elements of the objective function, constraints, decision and state variables [37], which are studied in the following.

2.4.1. Objective function and normalization

The optimization problem in this study is a multi-objective problem and the objectives are in contrast; objectives include maximum safety in the system and the construction (or installation) cost of surge protection devices as below:

$$
\begin{aligned}
&\textit{Objective Function}: \\
&Min\ F = w_1 f_1 + w_2 f_2 + Penalty \\
&f_1 = \frac{F_1}{F_1^{\max}}, \quad f_2 = \frac{F_2}{F_2^{\max}} \\
&F_1 = \left|\Delta H_+\right| + \left|\Delta H_-\right|, \quad F_2 = a_{\cos t} \forall + b_{\cos t} \\
&Penalty = \sum_{i=1}^{m} \lambda_i \left|\Delta_i\right|
\end{aligned}
\tag{14}
$$

Where F is the objective function that should be minimized, w_1 *and* w_2 are the weight coefficients, F_1 is the safety function; if it is minimized for critical nodes (nodes with maximum and minimum pressure head) in all time steps, the maximum safety in the system is achieved (with solving the MOC equations the maximum over pressure (ΔH_+) and minimum pressure drop (ΔH_-) during the transient condition are calculated). F_2 is construction cost of surge protection devices such as air chamber or shock damper, so it is assumed [31] that the construction cost is a linear function of the main tank volume ($\forall$) and the coefficients ($a_{\cos t}, b_{\cos t}$) that can be calculated by fitting between updated cost vs. volume. f_1 and f_2 are normalized function of safety and construction cost, respectively. Penalty is a summation of penalty factor to absolute violations ($\lambda_i \left|\Delta_i\right|$) for each constraint, and it is used to observe the constraint equations.

In multi-objective optimization problems, various objective functions should be normalized between 0 and 1 [37], so all objective functions are considered equally in the solution process. Depending on the importance of each objective we can use a bigger weight coefficient for it. To normalize, it is necessary to divide each of the objective functions into their corresponding proportional values. One of the simplest approaches is to optimize each of the objectives individually first. Then divide each objective by those optimum values and then sum up all normalized terms as one objective [32, 33]. Another method is optimizing each of the objectives individually [35] and considering other objectives as a state variable of the optimization model (state variables appear in optimization models and their values change with changing of decision variables) and not considering them as constraints or objective function. At last, the maximum values of the above state variables can be used for normalization. Using the second approach ensures that all objective functions are within the desired range of (0, 1). Here for finding the maximum values for normalizing, first by minimizing the F_1 pressure fluctuations of water hammer should tend to zero so we can calculate the maximum construction cost of protection devices ($F_2^{\max}$) and in a similar way by minimizing the F_2 construction costs tend to zero (no protection in system) and the maximum pressure oscillation between critical node can calculate ($F_1^{\max}$). The summary of this section is shown schematically with some explanations in Figure 3.

2.4.2. Constraints

Problem constraints cover physical and executive constraints. Executive constraints include feasible and acceptable values for the design parameters of protection devices such as the device dimensions, spring stiffness, damping coefficient, etc. To determine the behavior of the system during the optimization process, physical constraints are used, which here include the MOC equations for interior and boundary nodes such as the equations developed to simulate the behavior of the shock damper. It can be written as follows:

For interior nodes, using the MOC technique coupled with PDE's of transient hydraulic can be written below [6,27]:

$$Q_i^{n+1} = \frac{1}{2}\begin{bmatrix} (Q_{i-1}^n + Q_{i+1}^n) + \dfrac{gA}{a}(H_{i-1}^n - H_{i+1}^n) + \\ \dfrac{g}{a}\Delta t \ (Q_{i-1}^n - Q_{i+1}^n)\sin\alpha - \\ \dfrac{f\Delta t}{2DA^2}(Q_{i-1}^n\left|Q_{i-1}^n\right| + Q_{i+1}^n\left|Q_{i+1}^n\right|) \end{bmatrix} \quad (15)$$

$$H_i^{n+1} = \frac{1}{2}\begin{bmatrix} (H_{i-1}^n + H_{i+1}^n) + \dfrac{a}{gA}(Q_{i-1}^n - Q_{i+1}^n) + \\ \dfrac{\Delta t}{A} \ (Q_{i-1}^n + Q_{i+1}^n)\sin\alpha - \\ \dfrac{a}{g}\dfrac{f\Delta t}{2DA^2}(Q_{i-1}^n\left|Q_{i-1}^n\right| + Q_{i+1}^n\left|Q_{i+1}^n\right|) \end{bmatrix}$$

For Boundary Nodes:

$$H_i^n, Q_i^n \in \textit{Boundary Condition Equations} \quad (16)$$

$$L_c, A_c, A_r, M, C, K_s, L_r \ \textit{and Airchamber Volume} \in \{\textit{Availabe Values}\} \quad (17)$$

In the above relationships, Eq. (15) calculates the discharge and pressure values for interior nodes (non-boundary). For pressure and discharge values at boundary nodes, including the air chamber, shock damper, reservoir, valves, and other network equipment, the related equations are employed to set the boundary conditions in Eq. (16) in a general form. Eq. (17) is related to the possible values of design parameters which include the volume of the main tank for the air chamber and the dimension of the shock damper and its quantities: stiffness of spring, moving mass, and damping coefficient. The purpose of solving the above problem is to find the amounts of surge protection device (air chamber or shock damper) design parameters, as the objective function is minimized.

Figure 3. An outline of multi-objective optimization and process for designing of protection devices against water hammer.

2.4.3. Solution of the optimization problem

The transient analysis of a WTS is a relatively complex task, with high computational cost. For the optimum design of control equipment of transient flow, in any simulation in the optimization process, the system must perform a transient analysis that greatly increases the computational cost. As mentioned above, in this study, GA has been considered as a solution to the optimization problem. Here, a flowchart of problem-solving by GA is presented (Figure 4). At first, an initial population is chosen randomly for design parameters, and to analyze the system in a transient state it is required to know the initial conditions. Hence, in the next step, the system in the steady-state is analyzed using classical hydraulic equations, and the initial conditions, including the known values of discharge and head in all nodes, are obtained. In the next step, transient analysis was performed by MOC equations, and constraint violations and the objective function were calculated. By using the concept of the GA, among the first population, a new generation of decision variables is produced and the design process is repeated. The stop condition of the algorithm is used to reach a certain number of generations. In the end, all responses related to different generations are compared and the best values are selected. Below values are considered for running GA model in this paper: population size= 100, max generations=22, penalty factor=100000, crossover fraction= 0.8 mutation=0.01, function tolerance= 0.1, initial penalty=100 and migration fraction=0.2.

Figure 4. Flowchart of genetic algorithm problem-solving.

3. Results and discussions

3.1. Case stuty

To investigate the efficiency of the proposed model, the problem shown in Figure 5 is used. The WTS, as shown, consists of two reservoirs having information about the water levels in reservoirs, pipe characteristics such as length, diameter and Darcy-Weisbach coefficients. In addition, the wave propagation speed in all pipes is equal to 1006 m/s. To transfer water with the discharge rate of 757 l/s from a reservoir at the level of 120 m to another at the level of 256.6 m, four parallel pumps are used in each of the five stages. In order to investigate the effects of water hammer in the system, it is assumed that in the worst condition, all the pumps fail together. Twenty seconds after the failure of the pumps, the system restarts within 40 s, and the pump with the rotational speed of 300 rpm will reach a steady state value of 1770 rpm. Failure and restarting the pumps cause severe water hammer in the system.

Figure 5. Schematics and specifications of the case study (which has been reproduced by the authors) [8].

In the cost objective function, a linear function between surge volume and construction cost was considered, to determine the coefficient of the cost function by fitting the linear function to the data of Table 2 [31], 4940 $/m^3 and 3232 $ are obtained for a_{cost} and b_{cost}, respectively.

Table 2. Cost of air chamber construction per volume [31].

For this study, the above coefficients have acceptable accuracy in the volume range required by the air chamber for protection (less than 12 cubic meters). It is also assumed that the cost of construction of the air chamber and shock damper is the same, meaning that for both constructions, the cost is a linear function of their volume. But it should be noted that the shock damper has no maintenance costs. For non-violations of the constraints, a large number is considered for the penalty function coefficient $\lambda_i = 10^5$. The desired multi-objective model for air chamber design and shock damper is solved separately with four different combinations of weight coefficients; combination 1: $w_1/w_2=0$, given these values, there is virtually no optimization design. According to the literature, the appropriate values proposed by Larock et al. [7] for the air chamber are also used in the shock damper. Combination 2: $w_1/w_2<<1$ means the weight of f_2 is so bigger than f_1, so the weighted protection cost tends to be infinite and optimization algorithm seeks for solutions that f_2 tends to be zero. In other words, it seeks for no protection. Given the results for this combination we can find the maximum values of F_1 (or $F_1^{\max}$). Meanwhile, with no protection the model can be validated by the presented results at the critical nodes in Ref [7]. Combination 3: $w_1/w_2>>1$ that means the weighted values of safety in system tends to be infinite and GA wills to offer solutions with maximum cost ($F_2^{\max}$). Using the mentioned parameters and running GA algorithm for combinations 2 and 3 for the current case study, corresponding quantities are calculated as: $F_1^{\max} = 228.37\ m\ water\ \ pressure-head$, $F_2^{\max} = 60000\ \$$.

Combination 4: $w_1/w_2=1$, with these values the GA seeks for optimum solutions considering both critrias of objective functions.

To control the effects of water hammer in the system, Larock et al. [7] applied an air chamber and two one-way surges. An air chamber was located at the downstream of the pumps, with a total volume of 4.5 m^3. The specifications of the one-way surges are: the first surge at the end of the second pipe with the height of 3 m, tank with diameter of 1.8 m; while the height of second surge in the middle of the third pipe is 5 m with tank diameter of 1.8 m. In this study for comparing the performance and cost of our chamber and shock damper simultaneously under equal condition, for the shock damper, we also use one-way surges with the same specifications .

3.1.1. Design of Air chamber

In this stage, the optimization model is solved for the mentioned four combinations of weight coefficients, then for air chamber, values of f_1 and f_2, pressure heads at critical nodes and quantities of main objective function F are presented in Table 3.

As shown in Table 3, in the second row with no protection, water hammer creates a surplus pressure of approximately 182 m in the pump node compared to the steady-state, and the pressure head in the mentioned node has reached about 334.97 m, which is very significant and can cause the bursting of pipes and connections in this area. In the middle of the third pipe, the effects of water hammer cause the pressure head in the area to reach negative values (-10 m), which can create the water column separation phenomenon in the system, and harmful effects will subsequently happen. With classical design (no optimization process and based on previous experiences) Larock et al. [7] suggested an air chamber with a volume of 4.5 m^3, so the maximum and minimum pressure heads are limited to 230.12 and 0.09 m. The objective function for this design is equal to 0.9852. Using optimization process, objective function's value is reduced to 0.8478 (13% reduction) with better performance to damping the water hammer but with more construction cost. In combination 3, with no limitation for construction cost, the objective function tends to be 1 with air chamber volume near to 12 m^3, however, some pressure oscillations remain in the system.

Table 3. the solution of the multi-objective model for the air chamber with different combinations of weight coefficients and the corresponding value of objective functions, design and state variables.

3.1.2. Design of Shock damper

Similar to previous stage, the desired model is solved in various combinations of weights for shock damper design. The results summarized in Table 4.

In Table 4, no protection scenario is similar to the previous stage (the second row). As mentioned before, the shock damper is investigated by the authors, so regarding their experiences some suitable values are considered for combination 1, with these values the critical pressure heads due to the water hammer, are restricted to 179.02 and 0.24 m, with a total value of 0.9112 for the objective function. After optimization, the objective function reaches 0.6438 with a reduction of 30%. It causes a better performance to damp over/lower pressures to 167 and 14.37 m, respectively. Compared to the air chamber, the shock damper has a greater number of design variables summarized in the last column of Table 3. But similar to the air chamber, the main design parameter is the volume of the main tank and almost a part of the construction cost depends on it. Changing other parameters of shock damper does not have significant effects on cost but they have serious effects on its performance. So the optimum design of a shock damper is a more complex process than a similar air chamber with more computational cost efforts but with more flexibility. In Figure 6 values of the objective function with evaluations are presented for shock damper and air chamber. As shown in this figure, GA reaches optimum values after near 600 and 1500 evaluations for them ,respectively.

Table 4. the solution of the multi-objective model for the shock damper with different combinations of weight coefficients and corresponding values of objective functions, design, and state variables.

Figure 6. GA efforts for solving multi-objective design problem for air chamber and shock damper.

3.2. Discussion

For deeper investigations among results, hydraulic performance (f_1) and construction cost (f_2) for the designed protection devices are presented; also due to the fact that the damper has more design variables, it has been discussed more. As mentioned before, critical nodes are nodes with maximum and minimum pressure heads during transient condition. in this study, the pump node has a maximum head of about 335 m and the node in the middle point of the third pipe has a minimum head of about -10 m, if pressure heads at the critical nodes are limited to safe values, no damage will occur at the system. In Figures 7 and 8, pressure oscillations with time at the critical nodes are shown for various combinations of weight coefficients for the air chamber and shock damper.

Figure 7. Pressure oscillations with time at the pump node (node with maximum head) for various combinations of weight coefficients for air chamber and shock damper: a)

no protection, b) classical deign, c) multi-objective optimum design and d) with maximum construction cost.

In Figures 7a and 8a, with no protection devices in the system, serious pressure oscillations occur, the results in this section can also be used for verification of developed models in this study, because they are presented by Larock et al. [7] previously and there is an excellent harmony between these results and theirs. Using typical design for the air chamber and shock damper (Figure 7b and Figure 8b) the water hammer effects are damped to the safer bounds at both critical nodes, but there are significant pressure oscillations in the system. Considering maximum construction cost (or in other word maximum safety) reduces the transient effects to zero, however, this approach does not make sense due to the limited budget per project (Figure 7d and Figure 8d). For optimal design of the problem by considering both cost and safety criteria simultaneously, using equal weight functions for the normalized objective function, pressure changes with time are significantly reduced with the minimum costs of protection devices. (Figure 7c and Figure 8c). By comparing the function of the air chamber and shock damper in Figures 7 and 8, it seems they are similar in performance to protect against water hammer in all conditions, although shock damper has a little bit better efficiency with more flexible design parameters.

Figure 8. Pressure oscillations with time at the middle point of the last pipe node (node with minimum head) for various combinations of weight coefficients for air chamber and shock damper: a) no protection, b) classical deign, c) multi-objective optimum design and d) with maximum construction cost.

Shock damper has other decision variables besides the volume of the main tank which has little effect on the cost function. The main effective parameters of the shock damper are: reservoir’s volume, spring’s stiffness and damping coefficient [11, 24]. In Figure 9 effects of this parameters on objective functions f_1 and f_2 are presented, also air chamber has only one design parameter include its volume, so effect of it is shown in this figure as well.

Figure 9. Effects of design variables of protection devices on the normalized objective function of performance (f_1) and construction objective function (f_2) for the: a) damping coefficient of shock damper, b) spring stiffness of shock damper, c) main tank volume of shock damper and d) main tank volume of air chamber.

As it is shown in Figures 9a and 9b, there is an optimum range for the quantity of damping coefficient and spring stiffness, the optimum values are approximately equal to $C=2\times10^8$ *N. Sec/m* and $K=1.5\times10^7$ *N. m* for these design variables. Considering the optimum value for the volume of shock damper about 5 m^3 with these parameters it has the best performance (f_1=0.1595) and minimum cost (f_2=0.4839). Changing K and C have little effects on f_2 and significant effects on f_1, so they make shock damper more flexible for design. The effects of volume design parameter on shock damper and air chamber are presented in Figures 9c and 9d. For both, although increasing volume raises construction cost almost linearly, the rate of reduction of transient effects after specific values of volume reduces to zero. In other words, increasing the volume too much has no effects on damping process anymore. The optimum values of them are calculated and presented in previous sections.

4. Conclusion

In this paper, for the first time, a multi-objective model with conflicting goals for optimum design of surge protection devices include shock damper and air chamber, is developed and solved. At first, the water hammer PDE's and numerical solution of it for simulating the transient conditions in water pipelines were introduced. Boundary condition equations for air chamber and shock damper (as a new surge tank innovated by the researchers) were discussed in detail. Then, an optimization model was developed for designing the surge protection device as a multi-objective problem. The objective function contains conflicting goals including the minimum surge protection construction cost while achieving the maximum safety in the system against water hammer. This problem was converted to a single objective problem considering the weight functions and normalizing of objective functions. The GA method is chosen for solving, and a flowchart is presented for a deeper understanding of the optimum design process. To evaluate the performance of the proposed model, a pumping system was considered. For the water hammer, the scenario of failure and restarting the pumps were used. The maximum and minimum heads of water hammer, for four different cases, were studied. These cases include different combinations of weight coefficients that everyone has conceptual meaning: a) $w_1/w_2<<1$ means no protection in the system, b) $w_1=w_2=0$ means no optimization process has been done and the system is equipped with a classical design based on previous experiences, c) $w_1/w_2=1$, means the optimum design of system considering conflicting goals of safety and cost, and d) $w_1/w_2>>1$ means designing protection devices with maximum safety and no cost limitation. By solving the desired model with GA, the algorithm increases to 1 for cases a and d. For case c, optimum values of the main objective function reach 0.8478 and 0.6438 for air chamber and shock damper respectively that indicating 14% and 30% improvement compared to the ordinary design (case b). Further performance upgrade of shock damper after optimization, refers back to flexibility of its design parameters; air chamber has only one design parameter (volume of the main tank) but shock damper has three design parameters include: coefficient of damping, spring stiffness and main tank volume. So, its design is a more complex task than an air chamber with more GA evolutions (more than 1500 and about 600 evaluations for the optimum design of the shock damper and the air chamber, respectively) for solving the optimization problem. But damping coefficient (*C*) and spring stiffness (*K*) have minimum effects on construction cost, so by seeking through the available range of them, GA can find better solutions more flexible. The optimum values are approximately equal to $C=2*10^8$ *N. Sec/m* and $K=1.5*10^7$ *N. m.* For these design variables, considering about 5 m^3 for the main tank, the best performance (f_1=0.1595) and minimum cost (f_2=0.4839) are achieved. Changing *K* and *C* have little effects on f_2 and significant impact on f_1, so they make shock damper more flexible for design. Pressure changes over time in critical nodes, values of design parameters, and objective functions were investigated in detail and several tables and diagrams were presented. According to the results, the developed multi-objective model can be used for practical applications for design of water transmission protection devices such as air chamber as a conventional and shock damper as a new type. Also shock damper, like the air chamber, has good performance in damping water hammer effects, but an optimized design is needed to achieve the maximum function and minimum cost for both of them.

Ethical Approval

This manuscript has not been submitted to another journal for simultaneous consideration. The submitted work is original and not have been published elsewhere in any form or language (partially or in full).

Authors Contributions

Conceptualization, M.B.; Methodology, M.B., C.A.; Software, M.B. and C.A.; Validation, M.B.; Formal Analysis, C.A., M.B.; Investigation, M.B.; Resources, M.B., Data Curation, C.A., Writing-Original Draft Preparation, M.B.; Writing-Review &

Editing, C.A.; Visualization, C.A., M.B.; Supervision, M.B.; Project Administration, M.B., Funding Acquisition, C.A., M.B.,

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Conflicts of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and materials

The raw /processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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The captions of figures

Figure 1. Air chamber and its different parts (which has been reproduced by the authors) [7].

Figure 2. Shock damper and its components as a boundary condition in MOC equations (which has been reproduced by the authors) [10].

Figure 3. An outline of multi-objective optimization and process for designing of protection devices against water hammer.

Figure 4. Flowchart of genetic algorithm problem-solving.

Figure 5. Schematics and specifications of the case study (which has been reproduced by the authors) [8].

Figure 6. GA efforts for solving multi-objective design problem for air chamber and shock damper.

Figure 7. Pressure oscillations with time at the pump node (node with maximum head) for various combinations of weight coefficients for air chamber and shock damper: a) no protection, b) classical deign, c) multi-objective optimum design and d) with maximum construction cost.

Figure 8. Pressure oscillations with time at the middle point of the last pipe node (node with minimum head) for various combinations of weight coefficients for air chamber and shock damper: a) no protection, b) classical deign, c) multi-objective optimum design and d) with maximum construction cost.

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The captions of tables

Table 1 Comparison between Air chamber and Shock damper in terms of performance and design parameters.

Table 2. Cost of air chamber construction per volume [31].

Table 3. the solution of the multi-objective model for the air chamber with different combinations of weight coefficients and the corresponding value of objective functions, design and state variables.

Table 4. the solution of the multi-objective model for the shock damper with different combinations of weight coefficients and corresponding values of objective functions, design, and sate variables.

Figures

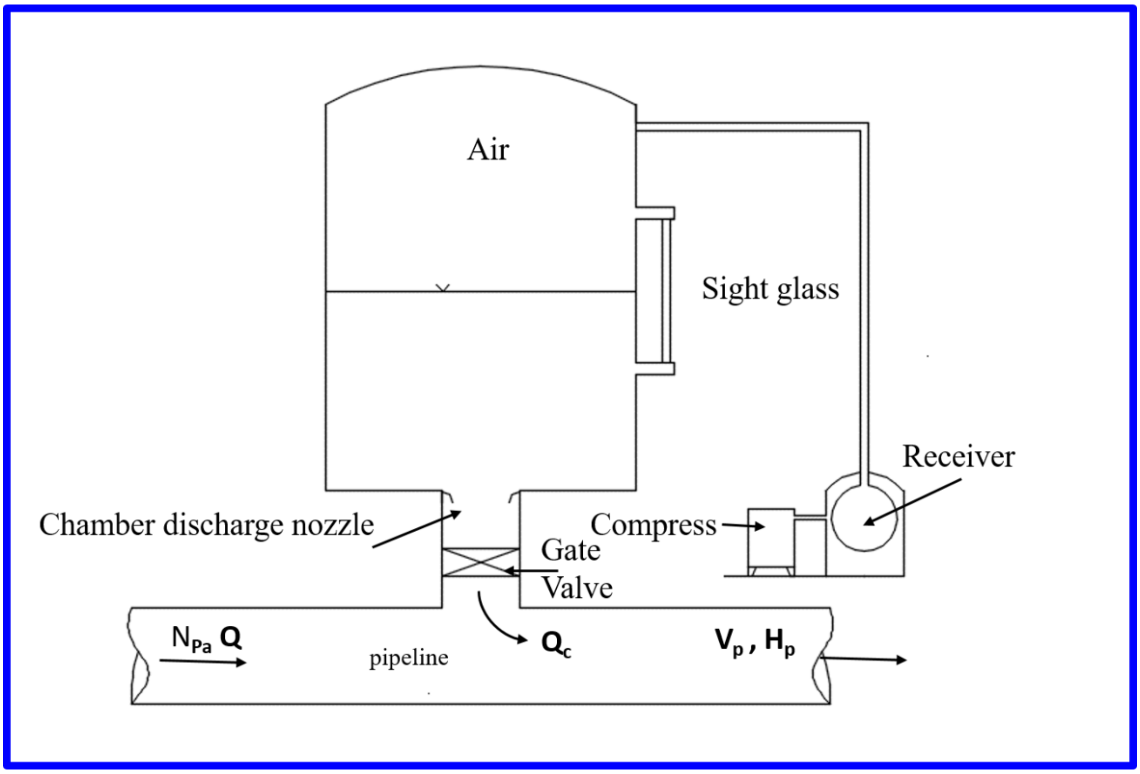


Figure 1.

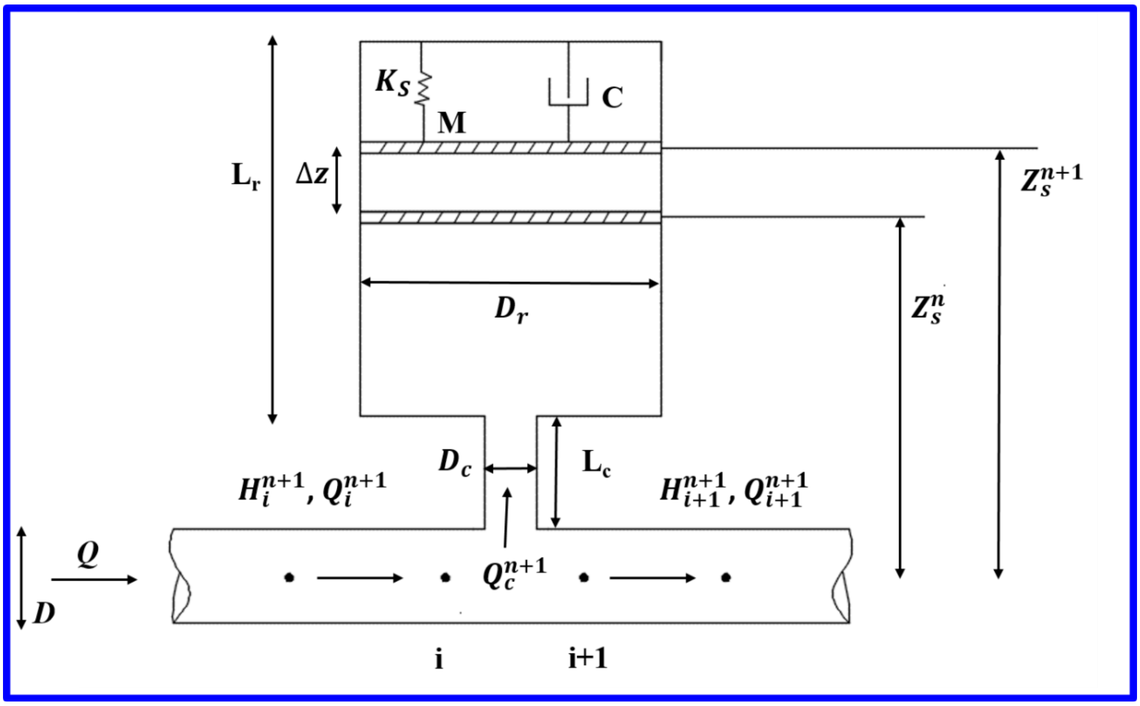


Figure 2.

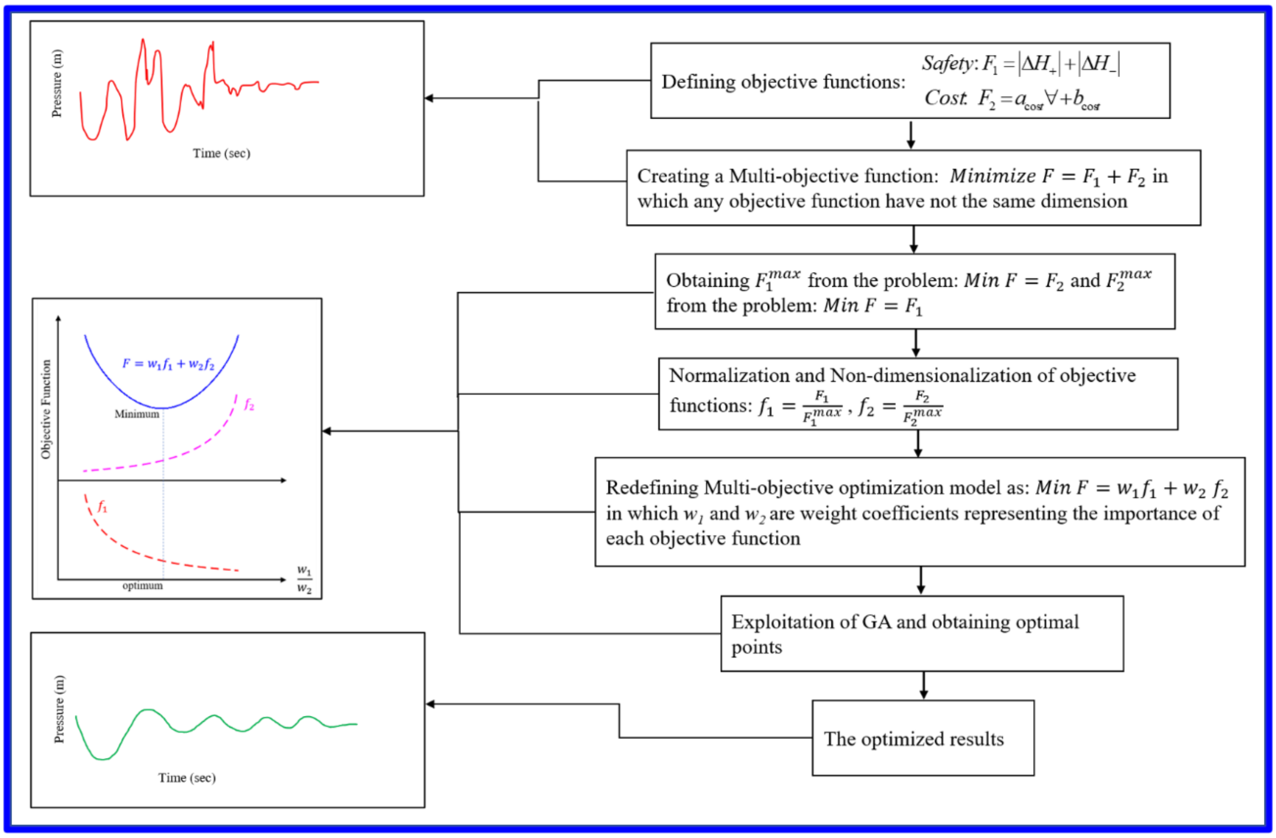


Figure 3.

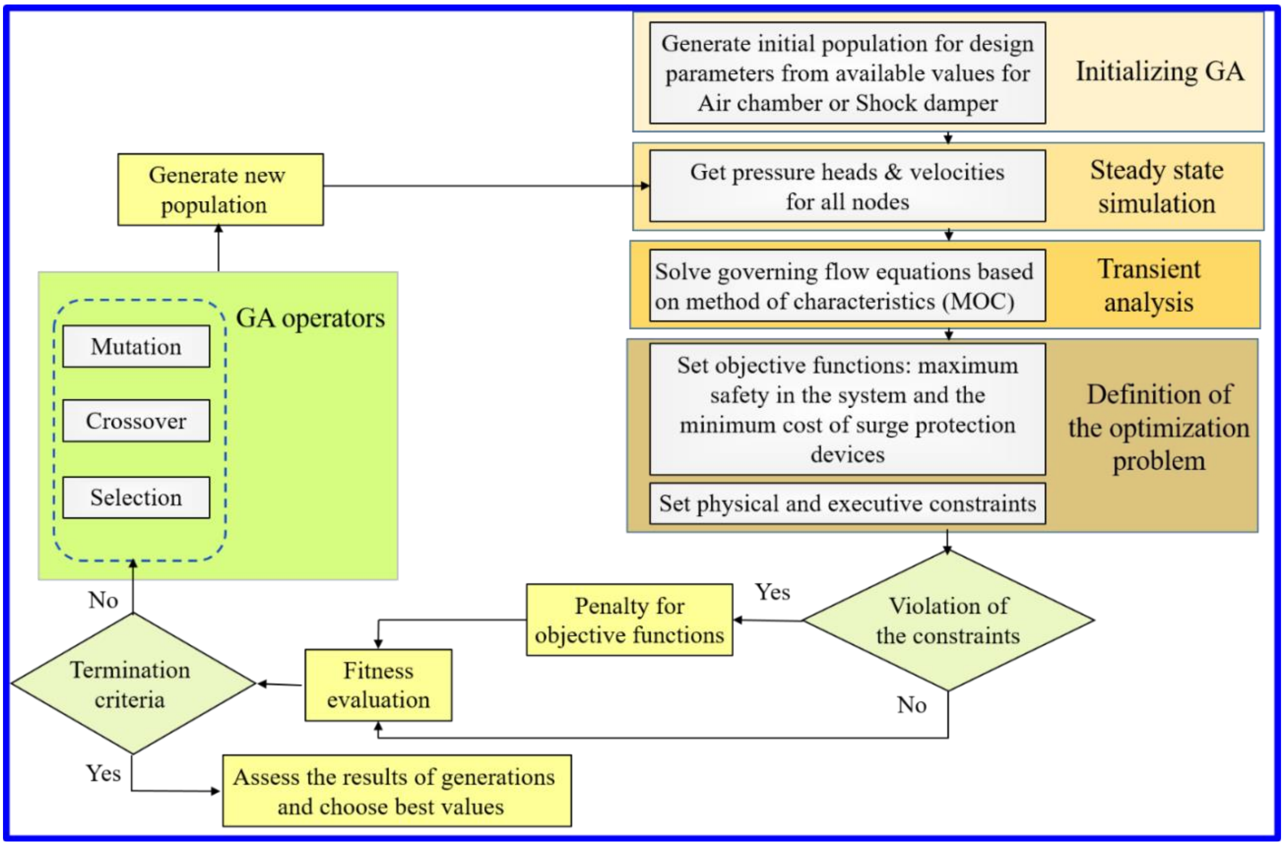


Figure 4.

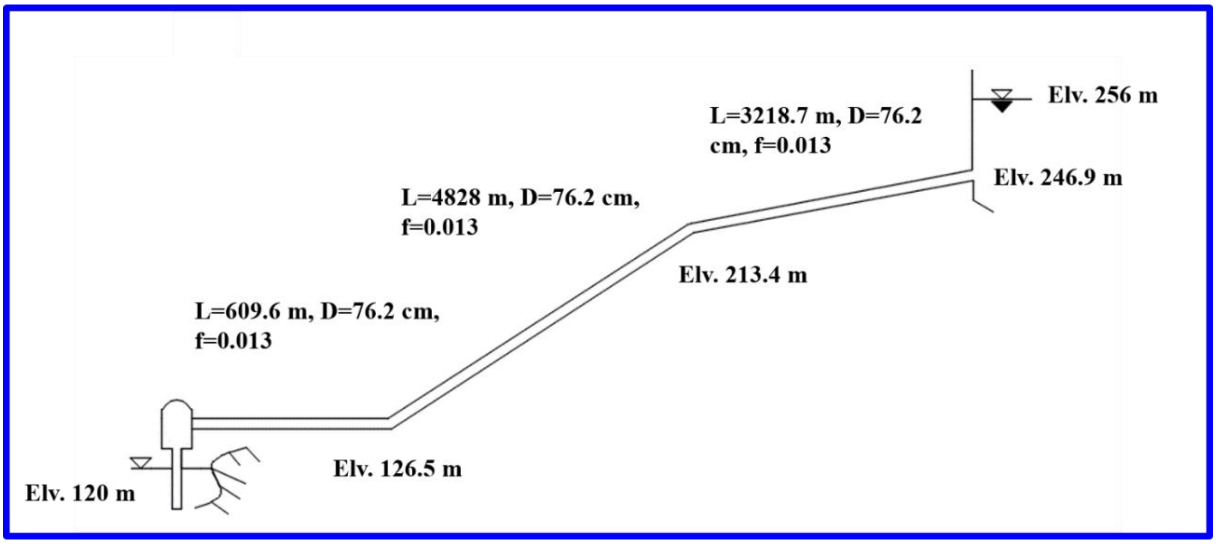
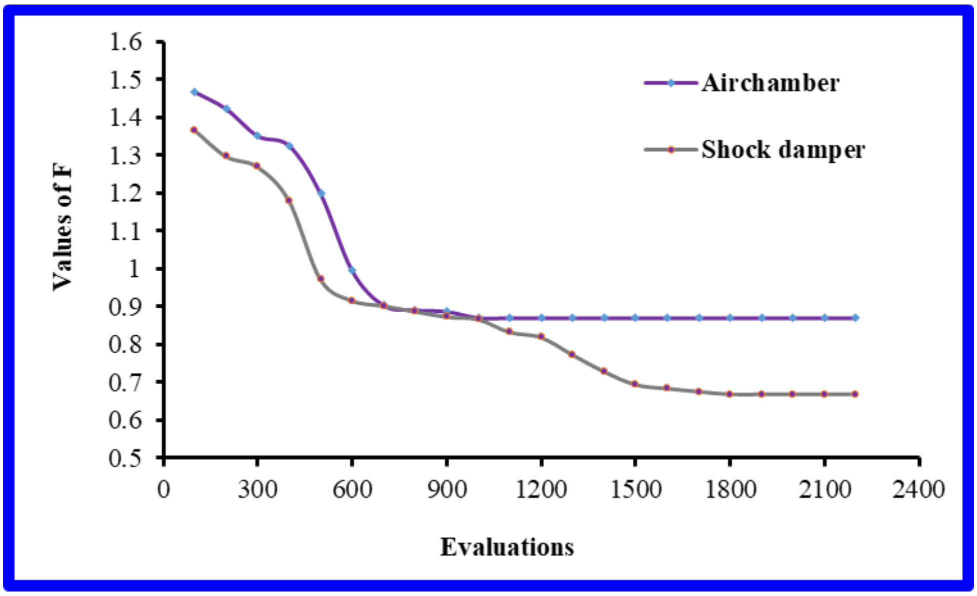


Figure 5.



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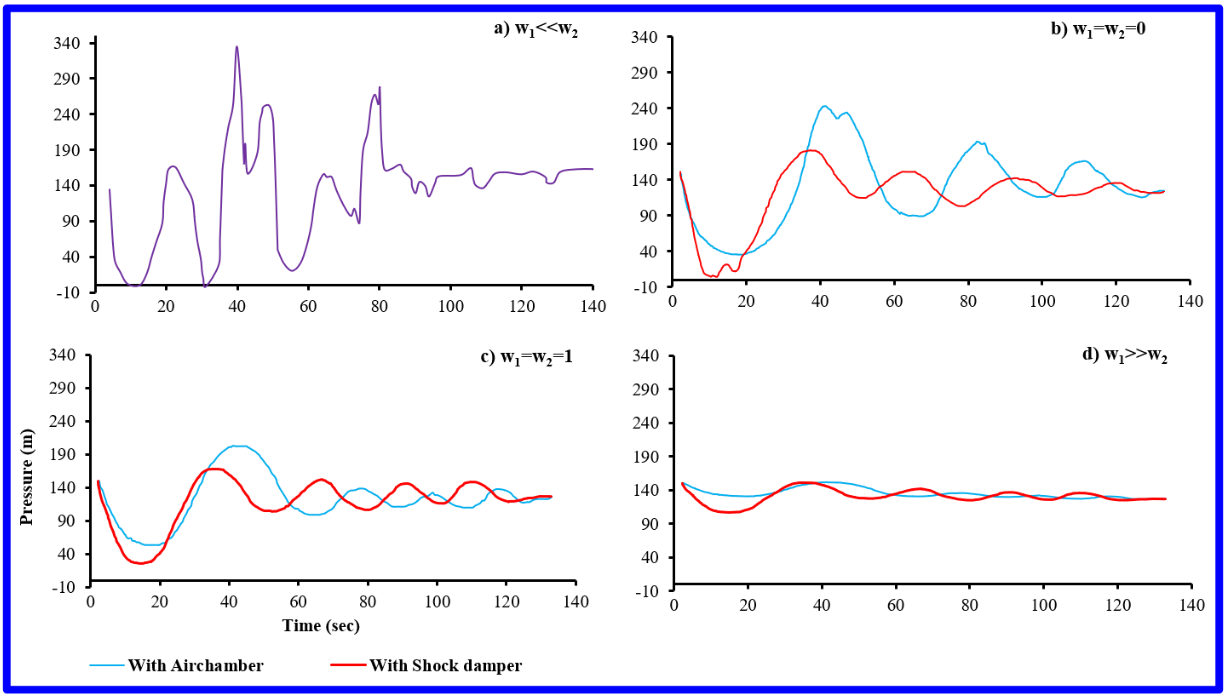

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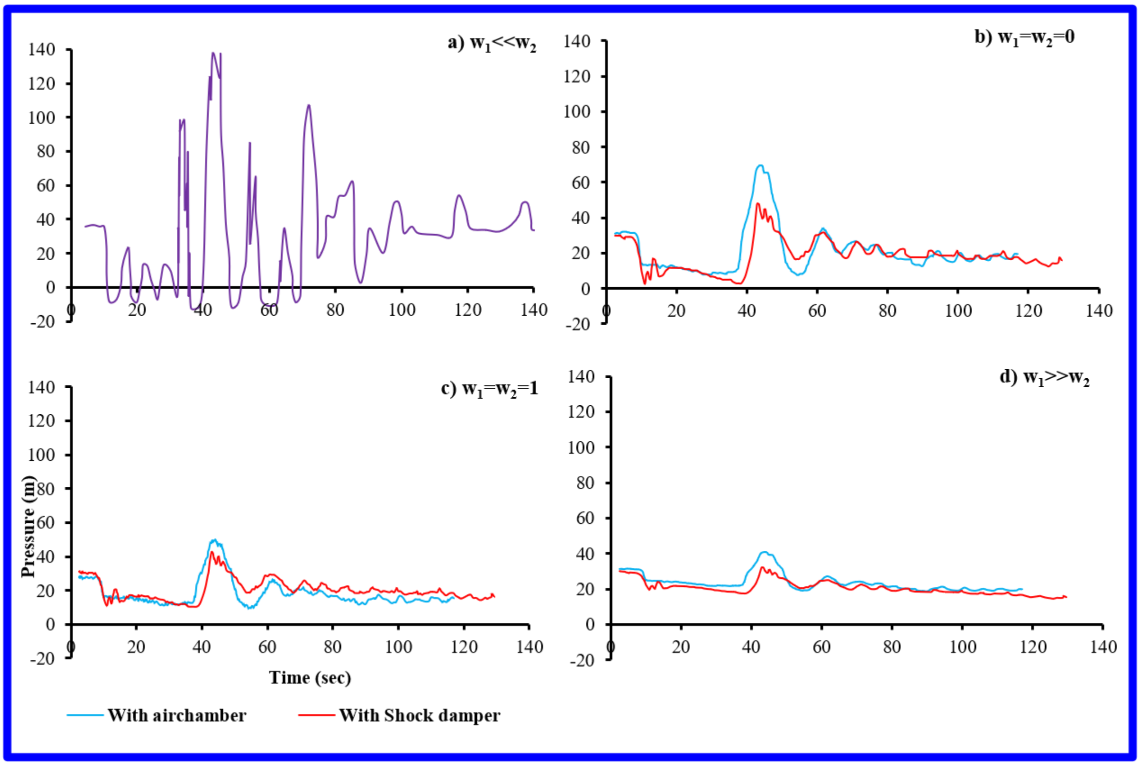


Figure 8.

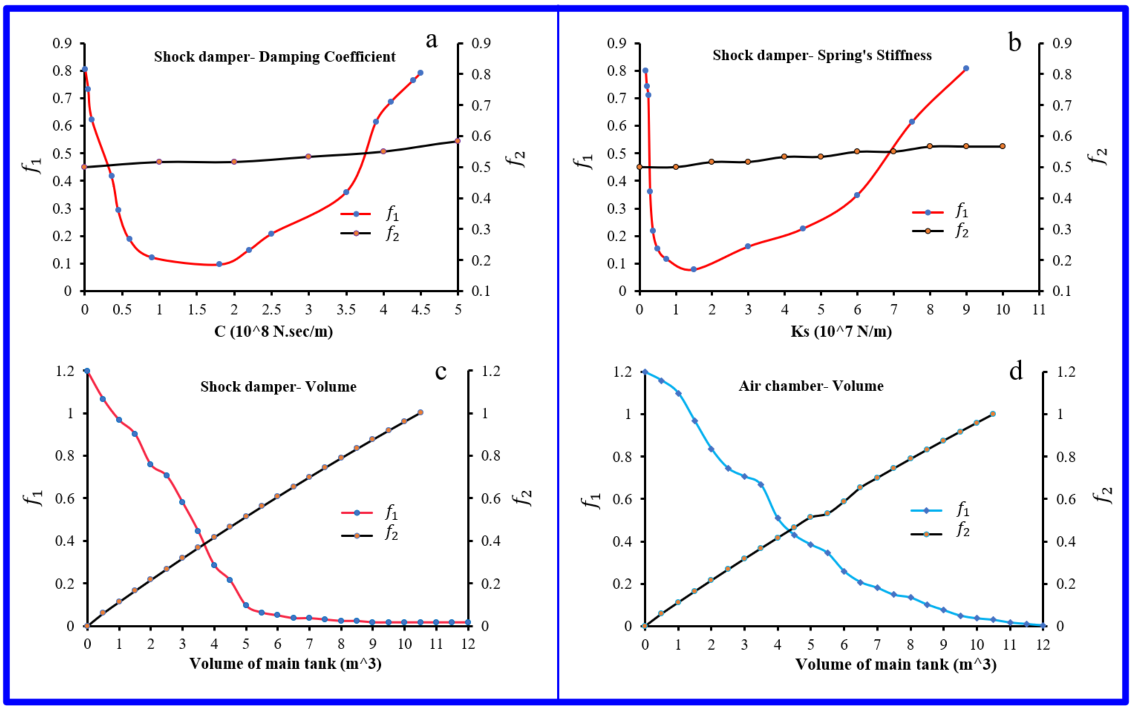
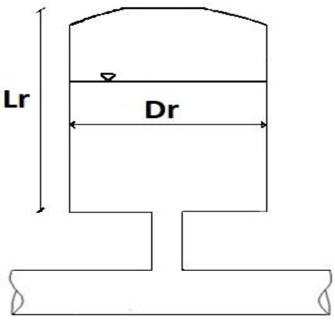


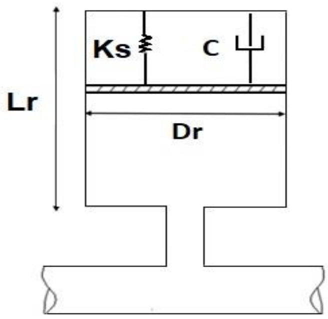
Figure 9.

Tables

Table 1.



Air chamber



Shock damper

Design Parameters	***D_r, L_r***	***D_r, L_r, K_s and C***
Advantages	- Smooth behaviour in the damping of pressure oscillations and water hammer - More efficient to recover negative pressure at the distant points	- More parameters and flexibility for design, damping coefficient and spring stiffness influence the performance of it without increasing the cost function - Hydraulic operation without the need for compressor and operating costs
Disadvantages	- Fewer parameters and less flexibility for design with a direct impact on cost function - Having operating cost and the need for a compressor	- Less smooth behaviour in the damping of pressure oscillations - Less efficient to recover negative pressure at the distant points

Table 2.

Volume (m^3)	Price ($)
0	0
8	50000
10	55000
20	100000
25	250000
30	300000
35	340000
40	367000

Table 3.

Combination	Method	Volume (m^3)	H_{min} (m)	H_{max} (m)	f_1	f_2	F
1	$w_1=w_2=0$ Classical design [7]	4.52	0.09	230.12	0.4427	0.4965	**0.9852**
2	$w_1/w_2 \ll 1$ No protection	0.00	-10.00	334.30	1.0000	0.0000	**1.0000**
3	$w_1/w_2 \gg 1$ Maximum protection	12.00	18.12	158.84	0.1161	1.0000	**1.1161**
4	$w_1/w_2 = 1$ Optimum design	5.7	15.16	201.52	0.3063	0.5415	**0.8478**

Table 4.

Combination	Method	Volume (m^3)	H_{min} (m)	H_{max} (m)	f_1	f_2	F	Other design parameters
1	$w_1=w_2=0$ Classical design [7]	7.00	0.24	179.02	0.6485	0.2732	**0.9212**	$D_r = 2.5m, L_r = 1.5m$ $K_S = 5.00x10^7 N/m,$ $C = 9.00x10^9 N.sec/m$
2	$w_1/w_2 << 1$ No protection	0.00	-10.00	334.30	1.0000	0.000	**1.0000**	________________
3	$w_1/w_2 >> 1$ Maximum protection	12.00	18.33	153.11	0.0306	1.000	**1.0306**	$D_r = 4.16m, Lr = 0.88m$ $K_S = 1.22x10^7 N/m,$ $C = 1.93x10^8 N.sec/m$
4	$w_1/w_2 = 1$ Optimum design	5.00	14.39	167.21	0.1595	0.4839	**0.6438**	$D_r = 2.46m, Lr = 1.05m$ $K_S = 1.54x10^7 N/m$ $C = 2.01x10^8 N.sec/m$

Biographies

Cyrus Amini received BSc in mechanical engineering from Isfahan University of Technology (IR) and PhD in applied mechanics from University of Tabriz (IR). His interest areas are Friction Stir Welding, Low Plastic Burnishing, Material Characteristics and Optimization. Currently, he is collaborating with DEFAM group at Barcelonatech (Spain) in the field of numerical simulations.

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