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Optimal parameters of protection devices for controlling hydraulic transient using genetic algorithms

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ABSTRACT

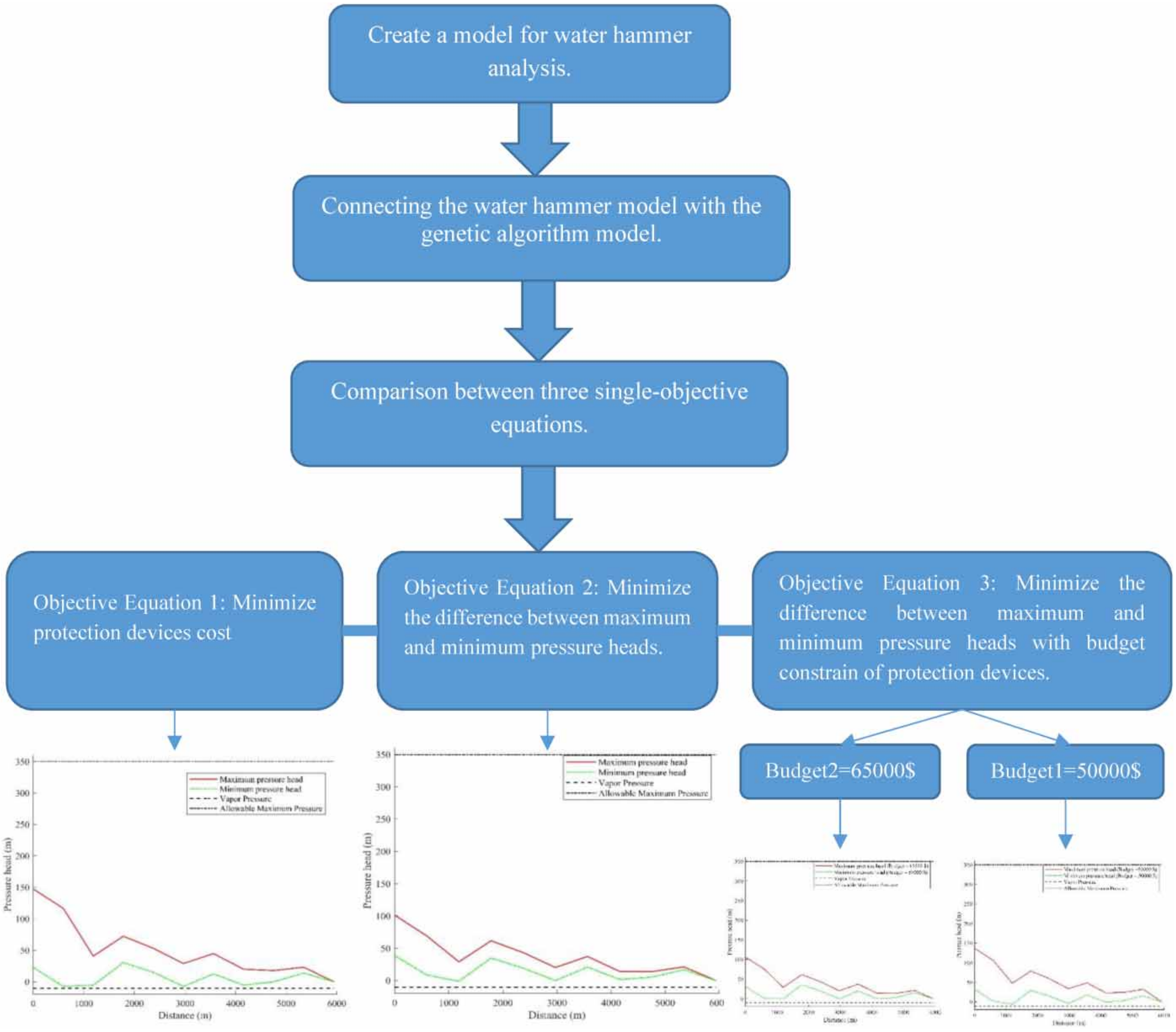
Air valves and pressure vessels are among the most important protection devices used to protect the main pumping lines due to their reliability in controlling transient pressures. The proper and rational design of the water hammer protection devices ensures high efficiency in controlling the values of transient pressures in addition to achieving acceptable cost. For this purpose, the genetic algorithm approach was adopted in the process of selecting the optimal parameters for both pressure vessels (size and orifice diameter) and air valves (orifice diameter of inlet and outlet, discharge coefficients of inlet and outlet) in addition to determining the type and location of the air valve. The performance of the proposed protection devices was verified by comparing three objective equations: (1) minimizing the cost of protection devices, (2) minimizing the difference between the maximum and minimum pressure, and (3) minimizing the difference between the maximum and minimum pressure with a specific constraint on the budget of protection devices. The study results showed that selecting the optimal design parameters for pressure vessels and air valves helps control the cost of protection devices and transient pressure values.

Key words: air valves, anti-surge air valve, genetic algorithms, hydraulic transient analysis, pressure vessel

HIGHLIGHTS

- A model was created to analyze the water hammer using the method of characteristics and it was linked with the genetic algorithm model.
- Three cases were produced to select the optimal parameters for both pressure vessels and air valves, each case depending on achieving a single objective.
- The results of the three cases were compared to choose the design that achieves acceptable cost for the protection devices with high reliability in controlling the transient pressures.

GRAPHICAL ABSTRACT



INTRODUCTION

The correct and safe design of water transmission pipes should achieve high efficiency in controlling events that cause loss or contamination of the water being transported to the user. Water hammer is an important event that occurs in water conveyance systems as a result of closing or opening a valve, due to pump-related events such as pump start-up or shutdown, or as a result of sudden power outage to the pump. One of the most significant damages caused by water hammer is leaks or pipe breakage, either due to excessive pressures exceeding the pipes' capacity or due to pressure drop inside the conduit below atmospheric pressure (liquid column separation). To achieve the aim of designing water transmission systems and main pumping lines, certain strategies are adopted such as selecting pipe characteristics (wall thickness, pipe material, diameter) or using hydraulic protection devices (Boulos *et al.* 2005; Jung & Karney 2006; El-Ghandour & Elansary 2019).

One of the most widely used hydraulic protection devices in main pumping lines is pressure vessels due to their high efficiency in controlling transient pressures, which is one of the most important features that distinguish this device from other protection devices, but one important drawback that limits the use of the pressure vessel is its need for periodic maintenance in addition to the large increase in the size of the pressure vessel in pumping lines where high positive and negative pressures occur (Lyn *et al.* 2021). The design process of pressure vessels is ideal if it achieves high efficiency in controlling transient pressures with a low tank size (Shi *et al.* 2021). The decision variables for pressure vessels specified by many studies are air volume, total tank volume, and the orifice diameter of the conveyor connected to the tank in both cases of water entering and exiting the tank (Stephenson 2002; Sang-Gyun *et al.* 2014; Miao *et al.* 2017). The conventional location of the pressure vessel in the main pumping lines, which achieves high efficiency in controlling transient pressures, is the pump discharge end.

Air valves are devices that help in getting rid of the trapped air inside the pipelines in addition to protecting the pipelines from the occurrence of liquid column separation (Wylie & Streeter 1993). The presence of air inside the pipe can cause many problems in the pumping line, such as obstructing the flow inside the pipe (Escarameia 2005). One of the most important features of air valves is their low cost and ease of installation (Zhu *et al.* 2006). Air valves can be classified into two categories: (1) traditional air valves, which have several types, some of which are used to expel small volumes of air, such as air release valves, and some of which are used to expel large volumes of air and protect water transmission pipes over long distances from liquid column separation, such as vacuum air valves and combination air valves (Ramezani *et al.* 2015); (2) anti-surge air valves or what are also known as two-stage air valves (Wu *et al.* 2015). The main purpose of these valves is to prevent water hammer resulting from the rejoining of the pressure waves (Li *et al.* 2022). The decision variables for the traditional air valve are the orifice diameter of the valve, the discharge coefficients of the valve in both cases of inlet and outlet of air, and the location and number of air valves. The decision variables for the anti-surge air valves differ from the decision variables for the traditional air valves in the presence of a special opening for the air release process, which is relatively smaller than the orifice diameter of the air inlet. Lee (1999) indicated that the discharge coefficient of the traditional air valve in the case of the air outlet with a low value has a significant role in preventing the formation of water hammer resulting from the rejoining, and that the value of the discharge coefficient of the valve in the case of the air inlet with the high value helps in effectively preventing the separation of the liquid column.

The access to optimal solution techniques based on natural selection processes (genetic algorithms (GA), ant colony optimization, particle swarm optimization (PSO)) provide great potential in supporting decision-making in engineering design problems. Often, protective devices are designed based on the long practical experience of the engineer designing water transport systems and main pumping lines. However, this design may suffer from a significant reduction in the cost of protective devices at the expense of obtaining sufficient protection from transient pressures, or it may achieve sufficient protection at the expense of cost-effective protective devices. In addition, there is difficulty in selecting the appropriate design parameters for protective devices and the suitable type for each case study. Therefore, the use of access to optimal solution techniques helps the designer engineer regardless of their practical experience to select the appropriate solution for each case study. Many researchers have focused on the idea of improving the diameters of water distribution network pipes exposed to water hammer using access techniques for optimal solutions (Jung & Karney 2004; El-Ghandour & Elansary 2018). Others have also focused on improving the design parameters of hydraulic protection devices for protecting pumping lines and water distribution networks using access techniques for optimal solutions (Lingireddy *et al.* 2000; Kim 2010). Jung & Karney (2006) presented a study to determine the volumes, locations, and numbers of both pressure relief valves and open surge tanks using both the GA approach and the PSO approach. The results showed that selecting the appropriate hydraulic protection device depends on the characteristics of the studied case. Moghaddas *et al.* (2016) used a methodology that combines the GA model with the water hammer calculation model to optimally select the parameters of both pressure vessels and air valves to achieve the smallest possible cost for the proposed protection devices. The study showed that using air valves alongside pressure vessels in pumping lines can significantly reduce the volume of pressure vessels and thus reduce the total cost of the protection devices. The study did not allow for the use of all design parameters for both pressure vessels and air valves, and the type of air valve was not included as a decision variable. The study was limited to proving that using air valves with pressure vessels can lead to a reduction in the overall volume of pressure vessels. Kim *et al.* (2017) presented a study on improving the design parameter selection of pressure relief valves using GAs. The aim of the study was to obtain the best design for the parameters of pressure relief valves to achieve the smallest difference between the maximum and minimum pressures in a water transmission line. The results of the study showed that proper selection of the design parameters of pressure relief valves plays a significant role in achieving high efficiency in controlling transient pressure values. El-Ghandour & Elansary (2019) developed a model that uses GAs to obtain optimal performance of pressure relief valves, which achieves high efficiency in protecting water distribution systems from water hammer effects. The results showed that optimal selection of the design parameters of pressure relief valves plays a significant role in achieving effective protection against water hammer in water distribution systems. Skulovich *et al.* (2014) developed a model for improving the selection of pressure vessels using a bi-level optimization approach. The aim of the study was to determine the design parameters of pressure vessels that achieve the smallest maximum pressure along the water transmission line without violating both the allowed minimum pressure constraint and the protection device budgets. The results showed that optimal selection of the design parameters of pressure vessels plays a significant role in protecting against water hammer. All studies have agreed that using optimization algorithms can provide a proper selection of design parameters for protective devices. Previous studies on the design of protective devices using optimization methods did not address the inclusion of all design parameters for both pressure vessels and air valves, which is the foundation for the current study. In addition, the type of air valves was not included as a variable in the decision variables for air valves.

In the current research, a computational model was prepared to analyze the water hammer and link it with a GA analysis model to determine all design parameters specific to air valves and pressure tanks by introducing the type of air valves as a decision variable. The aim of the current study is to achieve effective protection in controlling transient pressure values in addition to achieving an acceptable cost for protection devices, which is attained through obtaining effective protection from transient pressures, in addition to not being equal to the largest and smallest cost for protection devices. The comparison was made between three single-objective equations: minimizing the total cost of protection devices, minimizing the difference between the maximum pressure and the minimum pressure, and minimizing the difference between the maximum pressure and the minimum pressure with a specific constraint on the budget allocated for protection devices. This is to prove that the real design process should not be done to achieve a single purpose, either to obtain the lowest possible cost for protection devices or to achieve the highest performance for protection devices, meaning a significant reduction in the values of maximum and minimum pressures resulting from the water hammer, which in turn leads to a significant increase in the sizes of protection devices.

METHODS

Transient-state analysis

The transient analysis in water transmission pipelines is dependent on solving two partial differential equations, namely, the momentum equation (Equation (1)) and the continuity equation (Equation (2)) (Chaudhry 2014).

$$\frac{\partial H}{\partial t}+\frac{\alpha^2}{gA}\frac{\partial Q}{\partial x}=0, \tag{1}$$

$$\frac{\partial Q}{\partial t}+gA\frac{\partial H}{\partial x}+\frac{fQ|Q|}{2AD}=0, \tag{2}$$

where H is the piezometric head, g is the gravitational acceleration, A is the cross-sectional area of the pipe, Q is the flow rate, α is the wave speed, D is the pipe diameter, and f is the Darcy–Weisbach friction factor. Equations (1) and (2) are transformed into total differential equations using the method of characteristics yielding pairs of equations called compatibility equations (Chaudhry 2014).

$$\frac{dQ}{dt}+\frac{gA}{\alpha}\frac{dH}{dt}+RQ|Q|=0 \tag{3}$$

$$\frac{dQ}{dt}-\frac{gA}{\alpha}\frac{dH}{dt}+RQ|Q|=0 \tag{4}$$

where R is the friction term ($R=f/2AD$). Equation (3) refers to the positive characteristic with a slope of $dx/dt=+\alpha$, usually represented by the symbol C^+. As for Equation (4), it refers to the negative characteristic with a slope of $dx/dt=-\alpha$, usually represented by the symbol C^-. By representing these two equations on the $x-t$ coordinate system and complementing them using the method of finite differences, it is possible to obtain the numerical solution for head and flow at any point in the pipeline and at any moment in time. The process of calculating the unstable state starts with the initial conditions of the flow and determining the boundary conditions of the flow. In the case study, it involves a non-return valve, a pump at the source, a large water tank at the outlet, as well as air valves and pressure vessels that have been determined by Wylie & Streeter (1993) and Chaudhry (2014).

Optimization of pressure vessel and air valves

The literature used the idea of optimal selection for hydraulic protection devices to achieve a single-objective: minimizing the total cost of hydraulic protection devices (Moghaddas *et al.* 2016), minimizing the difference between the maximum and minimum pressures (Jung & Karney 2006; Kim *et al.* 2017; El-Ghandour & Elansary 2019), or minimizing the maximum pressure while considering the specified budget for protection devices (Skulovich *et al.* 2014). In the current research, a comparison was made between three equations: Equation (5) indicates minimizing the cost of protection devices with constraints on both the maximum allowed pressure and the minimum allowed pressure; Equation (6) refers to reducing the difference between the maximum and minimum pressures with constraints for both the allowed maximum pressure and the allowed minimum pressure; Equation (7) is similar to Equation (6) with the addition of a constraint specific to the budget allocated for protection devices. The main reason for the comparison process is to verify which of the three equations can achieve high efficiency in controlling transient pressures while obtaining an acceptable cost, which is the cost at which effective protection against transient pressures is obtained, in addition to not being equal to the largest and smallest cost for protection devices. The three equations are expressed as follows:

$$\min G(x) = \mathrm{Cost}(x) + N \times \max\,[H_{\max}(t, i), 0] + M \times \min[0,\; H_{\min}(t, i)], \tag{5}$$

$$\min \Delta H(y) = [H_{\max}(t,i) - H_{\min}(t,i)] + N \times \max[H_{\max}(t,i),\; 0] + M \times \min[0, H_{\min}(t,i)], \tag{6}$$

$$\min F(y) = \; [H_{\max}(t, i) - H_{\min}(t, i)] + N\; \max\,[H_{\max}(t, i), 0] + M\; \min\,[0, H_{\min}(t, i)] + P\; \max\,[\mathrm{Budget}, 0]. \tag{7}$$

Transient Equations (1) and (2) are subject to a set of algebraic constraints:

$$\begin{gathered} t = 0 \text{ and } \forall i, \\ H(t, i) = C_1 \text{ and } Q(t, i) = C_2, \end{gathered} \tag{8}$$

$$\begin{gathered} t > 0 \text{ and } i = \text{boundary nodes}, \\ f(H(t, i), Q(t, i)) = C_3. \end{gathered} \tag{9}$$

At any time step ($\forall t$) and any node ($\forall i$)

$$H_{\min,\mathrm{all}} \le H(t, i) \le H_{\max,\mathrm{all}}, \tag{10}$$

where

$$x \in (V_a, D_{\mathrm{in}}), \tag{11}$$

$$y \in (V_a, D_{\mathrm{orf}}, D_{\mathrm{in}}, C_{\mathrm{in}}, D_{\mathrm{out}}, C_{\mathrm{out}}, L), \tag{12}$$

where V_a is the volume of the pressure vessel, D_{orf} is the diameter of the pressure vessel orifice, D_{in} and D_{out} are the diameters of the air inlet and outlet orifices of the air valve, respectively, C_{in} and C_{out} are the discharge coefficients of the air inflow and outflow orifices of the air valve, respectively, L is the location of the air valve, i is the node index, t is the time index, $H_{\max,\mathrm{all}}$ is the maximum allowable pressure head, $H_{\min,\mathrm{all}}$ is the minimum allowable pressure head, M is a penalty constant that takes a value of zero if the condition $H(t, i) \le H_{\min,\mathrm{all}}$ is satisfied and a value greater than zero if the opposite is true, N is a penalty constant that takes a value of zero if the condition $H(t, i) \ge H_{\max,\mathrm{all}}$ is satisfied and a value greater than zero if the opposite is true. $H_{\max,\mathrm{all}}$ and $H_{\min,\mathrm{all}}$ are the maximum and minimum allowable pressure head, respectively, C_1, C_2, and C_3 are constants. Cost is the cost of protection devices, and P is a penalty constant specific to the budget allocated for protection devices whose value is zero if the condition $\mathrm{Cost}(x) \le \mathrm{Budget}$ is satisfied and it is greater than zero if the opposite is true.

The cost of air valves depends on the diameter of the air inlet and outlet openings in the case of traditional air valves, while the cost of anti-surge air valves depends on the diameter of the air inlet orifice regardless of the diameter of the air outlet orifice. As for the pressure vessel, its cost is determined by the total volume of the tank, and for this purpose, two polynomial equations have been developed to calculate the cost of protection devices.

$$\mathrm{Cost}_1 = 22,902.8 + 56.8 \times V_a^2 + 0.26 \times D_{\mathrm{in}}^2, \tag{13}$$

$$\mathrm{Cost}_2 = 23,232.4 + 56.8 \times V_a^2 + 0.291 \times D_{\mathrm{in}}^2. \tag{14}$$

Equation (13) is used when the traditional air valve is chosen, while Equation (14) is used when the anti-surge air valve is chosen. Equations (13) and (14) were derived based on the prices of globally manufactured air valves and pressure vessels. The cost is measured in US dollars.

GA model

GAs are a technique that simulates the natural evolution process of living organisms (Negnevitsky 2005), relying on the idea of survival of the fittest to reach the optimal solution. A main feature that distinguishes it from traditional methods in reaching the optimal solution (linear programming, nonlinear programming, and dynamic programming) is the ability to access global optimal solutions.

On the other hand, one of the major disadvantages of GAs is the difficulty in accurately determining the size of the solution space, the method of solution selection, as well as the mating method, crossover probability, and mutation probability (Sivanandam & Deepa 2008).

To achieve optimal design for the parameters of both the pressure vessel and the air valve, a model was created using MATLAB to analyze the GA and link it with another model for analyzing the water hammer. Before starting the optimization model procedures, the domains of decision variables for each protection device are determined to determine the length of each chromosome. The decision variables for the selected pressure vessel in this study are the total tank volume and the diameter of the tank outlet orifice when water is discharged from the tank. The domain for the total pressure vessel volume is chosen between 5and 40 m^3, and the domain for the diameter of the tank outlet orifice is 200–450 mm. As for the remaining variables, the air volume is considered to be 0.3 of the total volume of the pressure vessel. The area of the pressure vessel section is considered to be 5 m^2. Since the tank outlet orifice is considered to be a diffuser orifice, the losses through the orifice when water enters the tank are considered to be 2.5 times the losses when water exits the tank. The location of the pressure vessel is determined at the pump discharge end. As for the decision variables for the traditional and anti-surge air valves selected in the current study, they are the diameter of the valve orifice when air is the input, the diameter of the valve orifice when air is the output, and the valve discharge coefficients in both cases. As is known, traditional air valves have a common orifice diameter in both the air intake and air exhaust conditions. Therefore, the orifice diameter range for the air intake valve is chosen between 5 and 60 mm, while the orifice diameter for the anti-surge air valve is a ratio of the intake air valve orifice diameter ranging between 0.1 and 0.6 (Li *et al.* 2022). The discharge coefficient for both the air intake and air exhaust conditions for both types ranges between 0.1 and 1. In addition, a decision variable for the air valve location has been added, where six locations have been selected as 4, 7, 14, 22, 26, and 30 as shown in Figure 2.

The working method of the model shown in Figure 1(a) relies on the following: (1) Creating an initial random population consisting of a number of solutions (chromosomes) encoded according to the binary encoding method. (2) The model proceeds to the process of water hammer analysis. (3) Then, each chromosome is evaluated based on a fitness function that corresponds to the desired objective equation. (4) GA operations (selection, crossover, mutation) are performed to form a new population. (5) The process of water hammer analysis and GA operations is repeated on each generation until the objective is achieved or a specified number of generations is reached.

As shown in Figure 1(b), a chromosome is a collection of genes that determine the parameters of the pressure vessel and air valves. The length of each gene is determined by the range of the decision variable expressed by the gene. In the current study, the length of all genes is considered to be five encoded bits according to the binary encoding method. The selection of the type of air valve depends on the presence of a gene that takes a value of 0 or 1, as shown in Figure 1(b). If the value of the gene for the traditional air valve is 1 and the value of the gene for the anti-surge valve is 0, the model performs calculations for the water hammer with the traditional air valve. However, if the value of the gene for the traditional air valve is 0 and the value of the gene for the anti-surge valve is 1, the model performs calculations for the water hammer with the anti-surge air valve. If the value of the gene is 0 for both valves, only the water hammer analysis is performed with the pressure vessel.

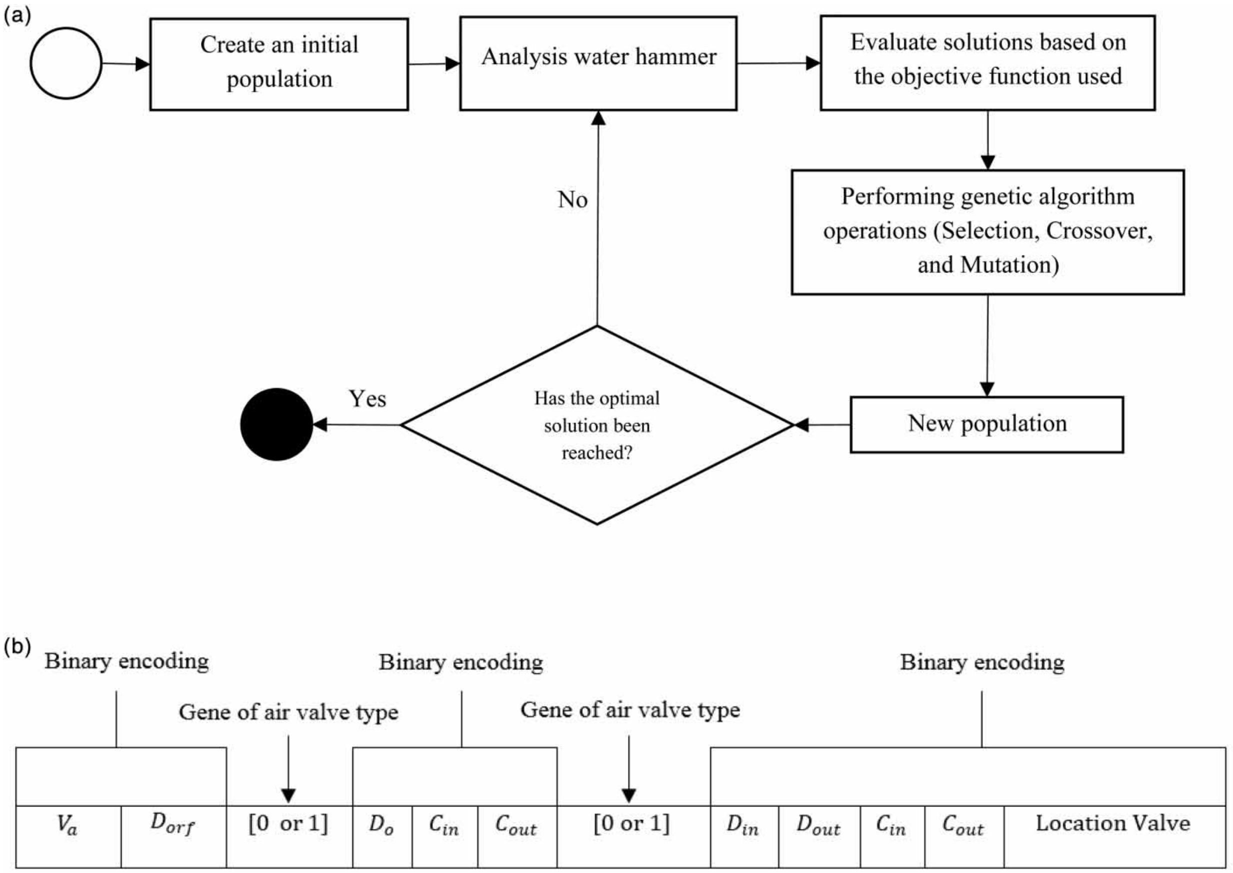


Figure 1 | (a) Flowchart of protection devices optimization using GA; (b) Diagram for each chromosome.

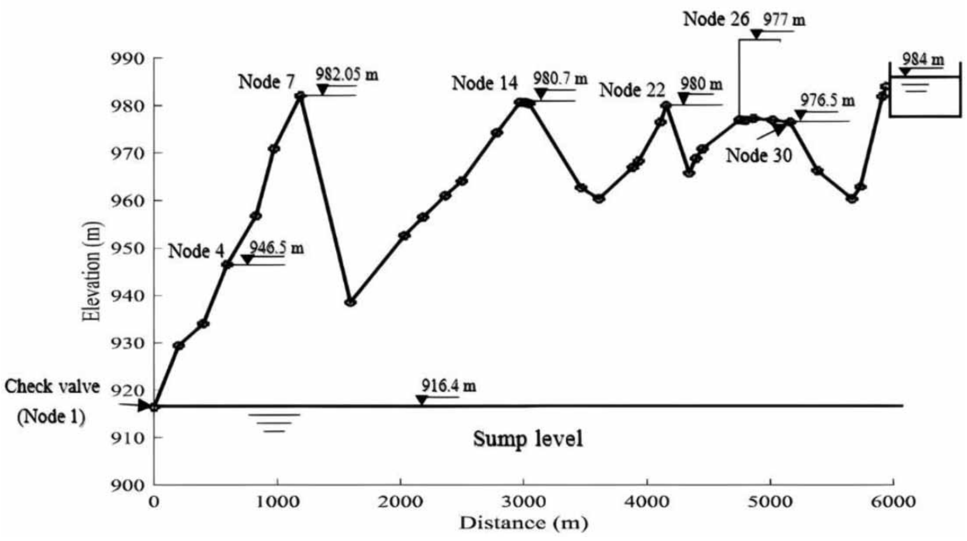


Figure 2 | Profile of pipeline (pumping line).

RESULTS AND DISCUSSION

Case study

The case study shown in Figure 2 illustrates the importance of using air valves in pumping lines that have significant changes in pipe slopes, as it is not possible for air to accumulate in smooth-flowing pumping lines (Ramezani *et al.* 2015). The used study case is the main pumping line where water is lifted by a pump from an elevation of 916.4 m to an elevation of 984 m with a pressure equal to 101.2 m and a flow rate of 0.281 m^3/s. The length of the pumping line is 5940 m, and it consists of flexible pipes connected in series with a diameter of 450 mm. The Darcy–Weisbach friction factor is 0.016, and the pressure wave propagation speed is $\alpha = 1{,}200\,m/s$. Figure 2 shows the coordinates of the pipe nodes and the partial lengths of each pipe.

The GA model has been linked to the water hammer analysis model. A population size of 40 chromosomes was used to reduce the computation time, with each chromosome having a length of 47 bits. The uniform crossover method was employed, with a crossover probability of 0.8 selected after sensitivity analysis. The mutation probability was set to 0.02 after sensitivity analysis. The optimization process ends after 70 iterations. The selection of fitter chromosomes was done using the roulette wheel method.

The scenario followed for water hammer analysis is the pump failure process, considering the presence of a check valve at the pump discharge end that closes directly due to the unavailability of the characteristic curves of the used pump. As shown in Figure 3, the highest pressure value in the studied case without using protective devices is at Node 1 and equals 300 m, which is smaller than the allowable maximum pressure value $H_{\max,\mathrm{all}} = 350$ m. It can also be observed that the studied pumping line suffers from the problem of liquid column separation along its entire length.

Protection against hydraulic transient using pressure vessel only

The most commonly used method to protect pipelines from the water hammer effect is to use a pressure vessel placed at the pump discharge end. In this case, a pressure vessel with a total volume of 55 m^3, an air volume of 16.5m^3, and a tank cross-sectional area of 10 m^2 is designed. The connection orifice between the pressure vessel and the pipe is a diffuser orifice, with a diameter of 450 mm when water exits the tank, and a diameter of 270 mm when water enters the tank. The pressure vessel is located at Node 1, a location commonly agreed upon in the literature and practical experience.

From Figure 4, it can be observed that the maximum pressure value at Node 7 is equal to 31.05 m, and this value is equal to the stable pressure value. As for the minimum pressure, it is equal to −7.47 m, which is close to the allowed minimum

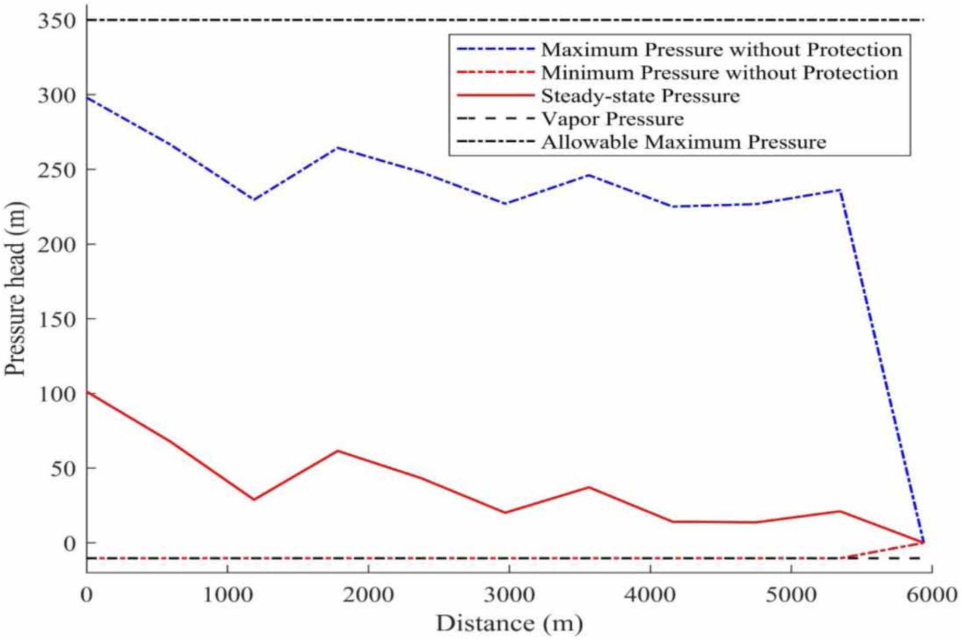


Figure 3 | Pressure head along the pumping line without protection and steady state pressure.

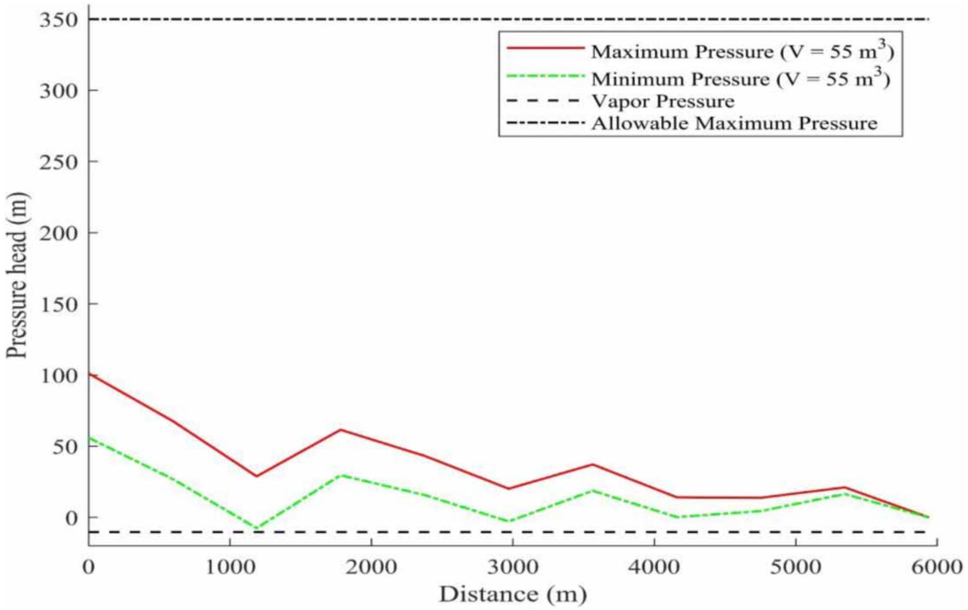


Figure 4 | Pressure head along the pumping line using pressure vessel.

pressure value $H_{\min,\mathrm{all}} = -10.36$ m. Therefore, raising the minimum pressure value at Node 7 requires a significant increase in the pressure vessel size, which, in turn, leads to an increase in the cost of protection devices. The main problem in the case study is the high values of the minimum pressure. In any case, it is feasible in such situations to use air valves that help reduce the minimum pressure value and prevent liquid column separation.

Case 1: minimizing the cost of protection devices

In this case, the parameters of the protection devices (pressure vessel, air valves) were optimized based on achieving the objective of Equation (5), which is to minimize the cost of the protection devices without violating the maximum and minimum pressure limits. Figure 5 illustrates the results of achieving the minimum cost of the protection devices using the GA, where it was found that the minimum cost for both the pressure vessel and the air valve is 33,100$.

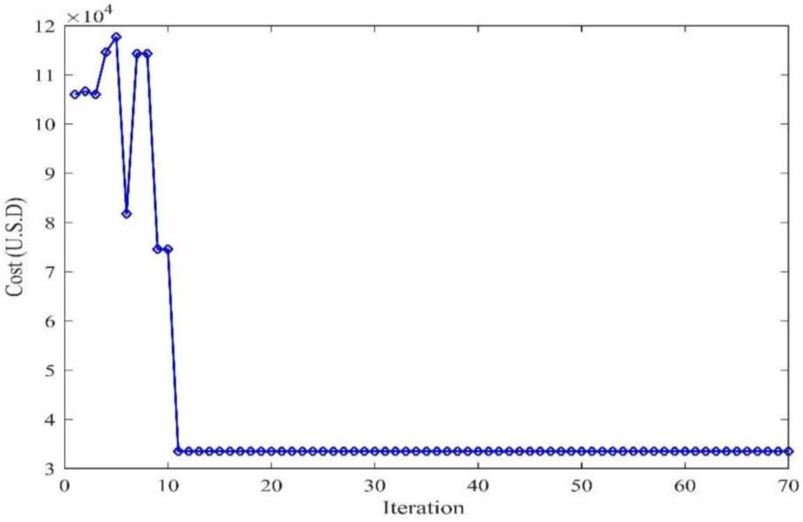


Figure 5 | Evolution procedure for Case 1.

Table 1 illustrates the design parameters for both the pressure vessel and the air valve, where the optimal location for the air valve was obtained at Node 7, and the type of air valve is the traditional air valve. The size of the pressure vessel was reduced to 75.8% compared to the case of using pressure vessels as a single water hammer protection method. It is evident from Figure 6(a) that the positive pressure value at Node 7 is 40.72 m, which is significantly smaller than the allowed maximum pressure value. The negative pressure value at Node 7 is −5.53 m, indicating that the traditional air valve was able to control the maximum and minimum pressures resulting from water hammer at node 7.

The negative pressure values at nodes 4 and 14 shown in Figure 6(b) are −7.4 and −7.62 m, respectively, which are close to the vapor pressure value. It is also noticeable that the maximum pressure value at node 1 is 147.2 m, which is due to the small size of the pressure vessel, although it is smaller than the allowable maximum pressure value.

Case 2: minimizing the difference between the maximum and minimum pressure

In this case, the operation of the protection devices parameters (pressure vessels, air valves) was carried out based on achieving the aim of Equation (6), which is to minimize the difference between the maximum and minimum pressure, provided that the constraints of the maximum and minimum pressure allowed are not violated. Figure 7 illustrates the process of achieving the minimum difference between the maximum and minimum pressures at Node 7, where the minimum difference was obtained at generation 26 with a value of 29.99 m. The parameters of both the pressure vessel and the air valve are shown in Table 2, where it was found that the type of air valve in this case is the anti-surge air valve located at Node 7. The cost of the protection devices in this case is 102,000$, which is higher than the cost of the protection devices in the Case 1 by 67.6%.

It is observed in Figure 8(a) that the maximum pressure value at Node 7 did not exceed the pressure value in the steady state. This is due to the fact that the diameter of the air outlet orifice is relatively smaller than the diameter of the air inlet orifice, which in turn leads to a slower air discharge process compared to traditional air valves.

The maximum pressure values shown in Figure 8(b) did not exceed the pressure value in the steady state for all the pump line joints in this case. As for the negative pressure values, it is observed that the negative pressure value at Node 4 is equal to 8.57 m, which is much higher than its value in the Case 1 and the value of the vapor pressure. The negative pressure value at Node 7 is −1.13 m, which is much higher than the vapor pressure value, due to the relatively large diameter of the air inlet

Table 1 | Parameters of protection devices for Case 1

Pressure vessel parameters				**Air valve parameters**					
V_{all} (m^3)	V_{air} (m^3)	D_{orf} (mm)	D_l (mm)	Valve location	Valve type	D_{out} (mm)	D_{in} (mm)	C_{in}	C_{out}
13.3	4	450	360	Node 7	Traditional	20	20	0.5	0.42

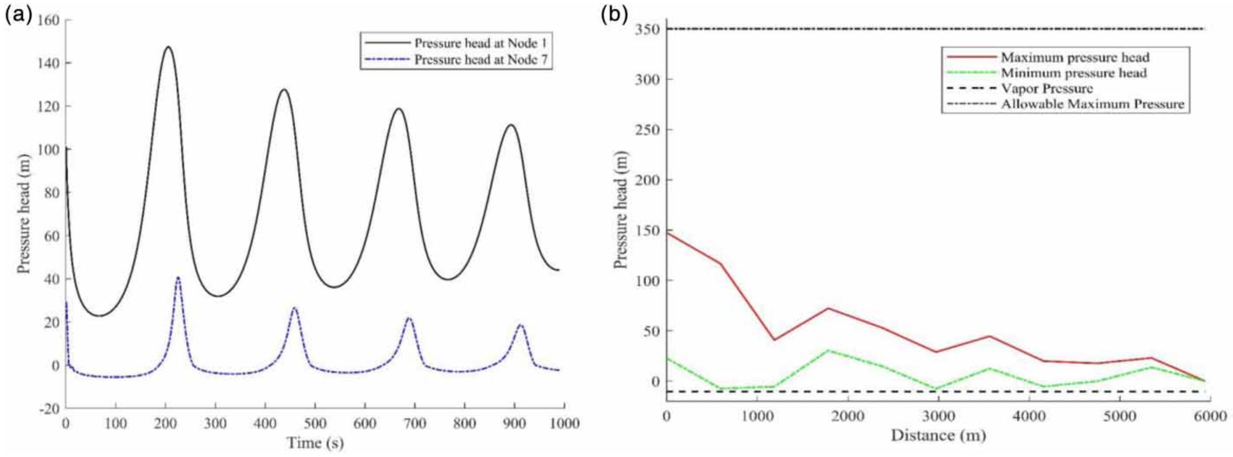


Figure 6 | (a) Variation of pressure head over time at Node 1 and Node 7 (Case 1). (b) Pressure head along the pumping line for Case 1.

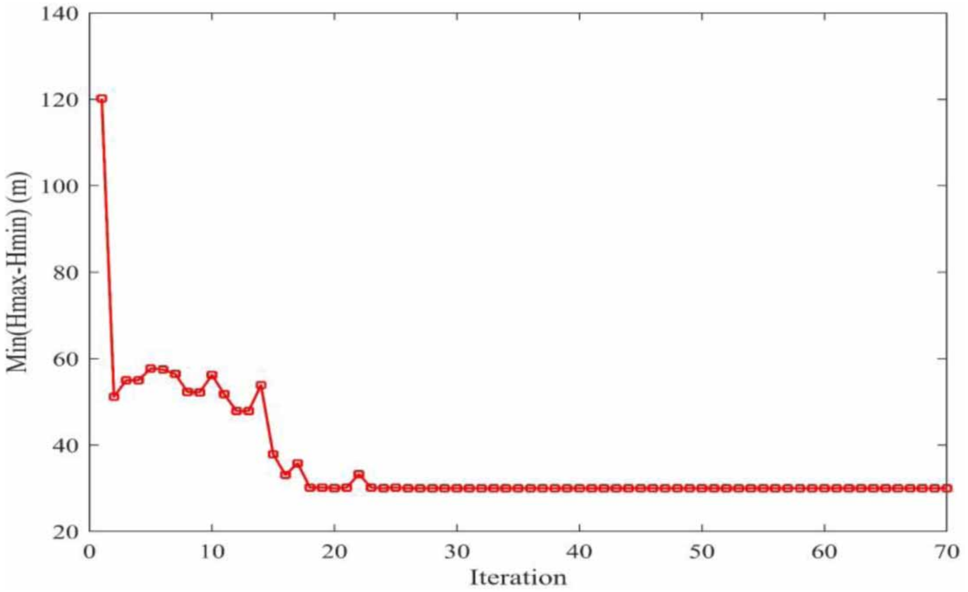


Figure 7 | Evolution procedure for Case 2 at Node 7.

Table 2 | Parameters of protection devices for Case 2

Pressure vessel parameters				**Air valve parameters**					
V_{all} (m^3)	V_{air} (m^3)	D_{orf} (mm)	D_i (mm)	**Valve location**	**Valve type**	D_{out} (mm)	D_{in} (mm)	C_{in}	C_{out}
37	11.1	320	250	Node 7	Anti-surge	20	45	0.24	0.33

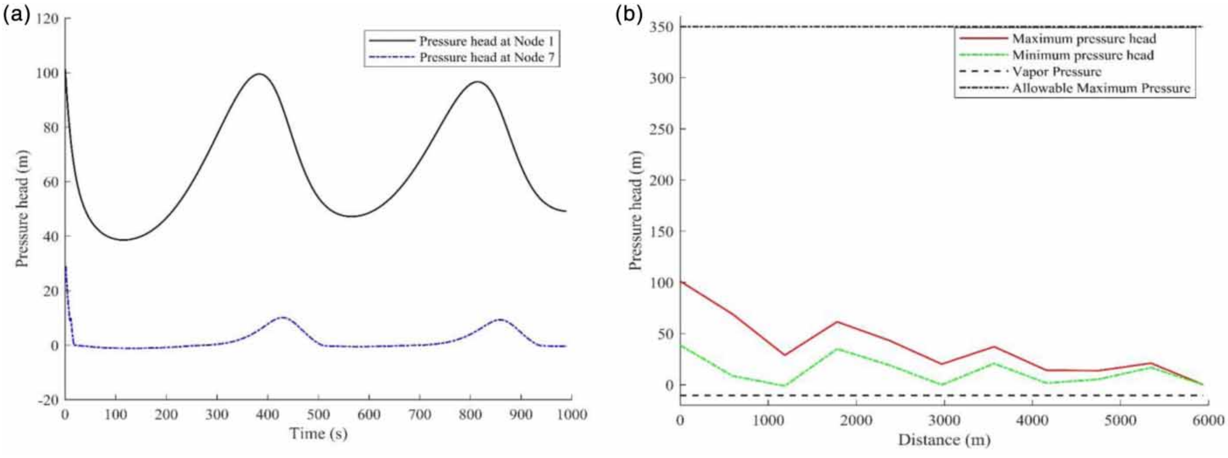


Figure 8 | (a) Variation of pressure head over time at Node 1 and Node 7 (Case 2). (b) Pressure head along the pumping line for Case 2.

Table 3 | Parameters of protection devices for Case 3

Pressure vessel parameters					**Air valve parameters**					
Budget ($)	V_{all} (m^3)	V_{air} (m^3)	D_{orf} (mm)	D_i (mm)	**Valve location**	**Valve type**	D_{out} (mm)	D_{in} (mm)	C_{in}	C_{out}
50,000	20.7	6.2	450	360	Node 7	Traditional	15	15	0.52	0.77
65,000	25.9	7.8	250	160	Node 7	Anti-surge	50	20	0.37	0.42

orifice, allowing a sufficient amount of air to enter, assisting in increasing the negative pressure value. Therefore, in this case, the transient pressures along the studied pump line were controlled more efficiently than in Case 1.

Case 3: minimizing the difference between the maximum and minimum pressure with budget constraint

The operation of the air valves and pressure vessel parameters depends on achieving the aim of Equation (7), which is to minimize the difference between the maximum and minimum pressures without violating the allowed limits of minimum and maximum pressures. In addition, the specified budget constraints for protection devices have been set at two budgets: Budget_1 and Budget_2, with values of 50,000 and 65,000$, respectively. Table 3 illustrates the parameter values for both

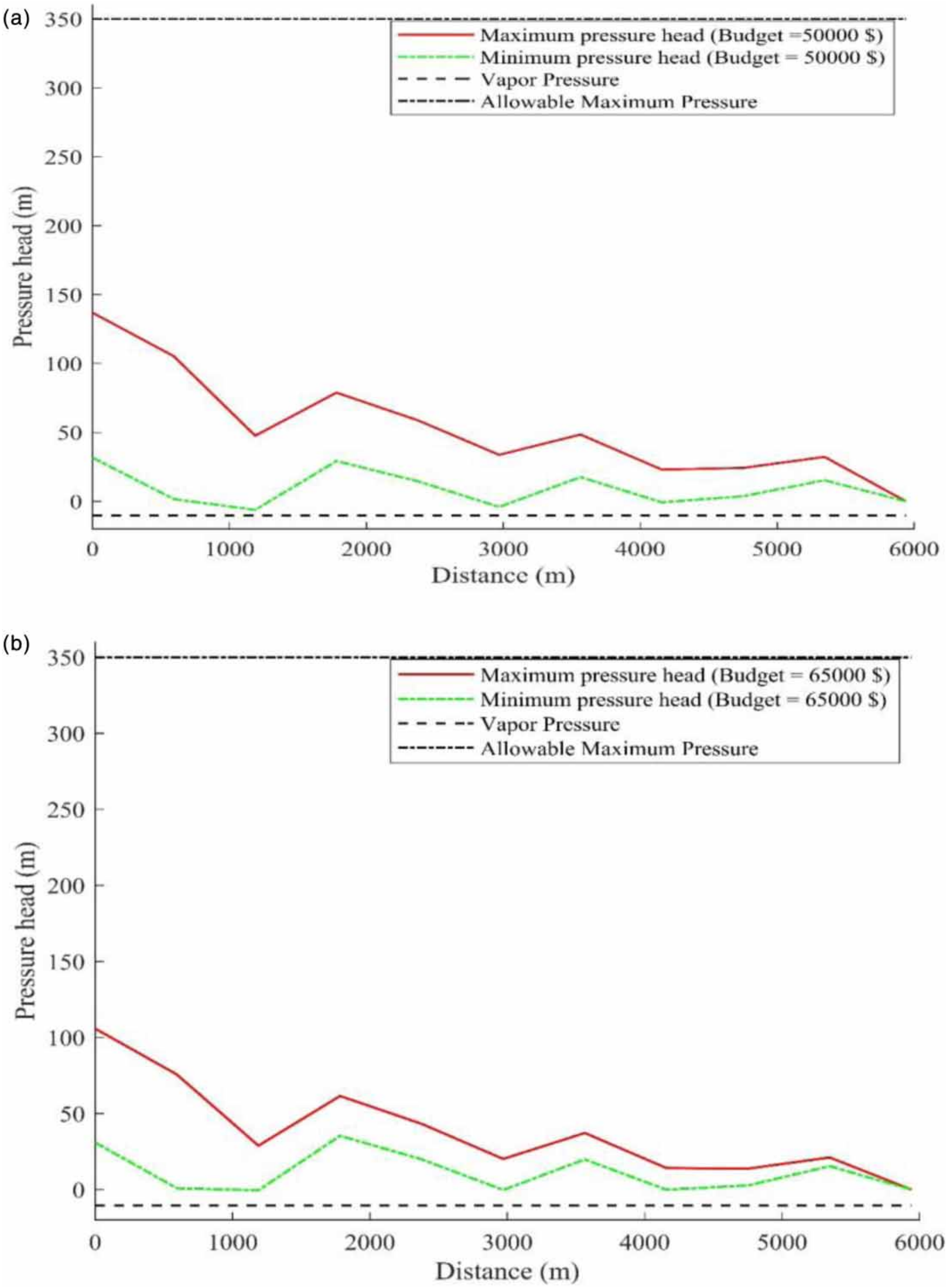


Figure 9 | (a) Pressure head along the pumping line for Case 3 ($\text{Budget}_1 = 50{,}000\$$). (b) Pressure head along the pumping line for Case 3 ($\text{Budget}_2 = 65{,}000\$$).

the pressure vessel and air valve. It was found that the type of valve for Budget_1 is an anti-surge valve, while for Budget_2 it is a traditional air valve. Furthermore, the air valve is located at Node 7 for both budgets.

From Figure 9(b), it is evident that the negative pressure value at node 7 is −0.51 m. From Figure 9(a), it can be observed that the negative pressure value at node 7 is −6.2 m. In addition, the negative pressure value at node 14 for a budget of 65,000 is −0.24 m, while for a budget of 50,000$, it is −4.1 m. This is due to the large diameter of the air inlet orifice in Budget_2 and the fact that the maximum pressures in both budgets have been significantly controlled and are much lower than the allowed maximum pressure value.

In comparison between Case 3 and both Case 1 and Case 2, Case 3 provided a higher efficiency in protecting against water hammer than Case 1, where the negative pressure values in Case 1 at Node 14 were equal to −7.62 m, while in Case 3 they are equal in Budget_1 and Budget_2, −4.1 and −0.24 m, respectively. However, the cost of protection devices in Case 3 is higher than in Case 1 in Budget_1 and Budget_2 by 46 and 30%, respectively. Comparing Case 3 to Case 2, a negative pressure value was obtained at Node 7 in Case 2 equal to −1.13 m, while the negative pressure value in Budget_1 and Budget_2 is equal to−0.51 and −6.2 m, respectively. As for the cost of protection devices in Case 2, it is higher than the cost of protection devices in Case 3 in both Budget_1 andBudget_2 by 53.6 and 40%, respectively. Therefore, Case 3 provides more logical solutions than Case 1 and Case 2 because it is practically impossible to design protection devices to achieve the lowest cost or to achieve the highest efficiency in controlling transient pressure values as in Case 2**.**

CONCLUSIONS

In the current research, a computational model was created that links the analysis of the water hammer with the dependence on the feature method and the GA approach, to obtain the optimal location, type, and design parameters for air valves (the diameter of the air inlet and outlet orifice, the valve discharge coefficient in the case of air inlet and outlet) and to obtain the optimal parameters for pressure vessel (tank volume, tank diameter in the case of water exiting the tank). A comparison was made between three single-objective equations aimed at minimizing the cost of protection devices, minimizing the difference between the maximum and minimum pressures, and minimizing the difference between the maximum and minimum pressures while adding a penalty condition related to the protection devices budget. The study revealed that the air valve, regardless of its type, plays a significant role in reducing the volume of the pressure vessel in cases of main pumping lines that require a significant increase in the pressure vessel volume to overcome the liquid column separation problem. In addition, both types of air valves have the same potential in controlling the pressures resulting from the water hammer if the design parameters and valve location are chosen correctly, but they require a verification process in the field. The comparison process between the proposed objective equations demonstrated the necessity to improve the design of protection devices based on multi-objective equations to achieve better control over transient pressure values and acceptable costs, which in turn is considered attractive for conducting future research in addition to introducing more than one protection device and using a more complex water distribution network than the current case study.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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