The Effect of Different Transient Trigger Methods on the Performance of Double Controlled Hydraulic System

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Abstract. Most of pressurized liquid pipelines are threatened by the hazards of a physical phenomenon that likely occurred in the hydraulic system when flow characteristic is rapidly changed. This change will make local energy imbalance which induced pressure wave travelling along the hydraulic system. Further, many devices are designed to control the hydraulic transients event. But, these devices still have incomplete performance because they dont be verified under different transient trigger conditions. In this paper, the performance of double controlled hydraulic system is verified by changing the transient trigger methods. Where, the double control of this system consisting of air vessel and HDPE forward configuration bypass. Moreover, four transients trigger scenarios are performed in this study and the performance of the hydraulic system for each scenario is investigated experimentally and numerically. Further, the experiments are revealed that the performance of hydraulic control system is highly affected by the way of the hydraulic transient is generated. Finally, the experimental and numerical results are well convergent by a total percentage is (92%).

Keywords
Hydraulic transients, water hammer, HDPE bypass, double controls hydraulic system, transient trigger methods, transient flow.

Nomenclature

| Symbol | Definition                  | Greek | definition                     |
|--------|-----------------------------|-------|--------------------------------|
| a      | Wave celerity               | A     | Rotational speed ratio         |
| C      | Constant                    | B     | Torque ratio                   |
| D      | Pipes diameter              | θ     | Pipe inclination angle, rotational angle |
| DAQ    | Data acquiescing system     | Y     | Pumps discharge ratio          |
| EPDM   | Ethylene propylene diene monomer |       | Superscript                    |
1. Introduction

Most of modern industrial trends to use the pipeline system to transport the oil, gas, water and chemical liquids because the pipeline is least expensive, most effective, and adaptable to complicated topographies compared the others transportation means. In such application, the safety of the pipeline is highly important matter but the hazards of transient phenomena are frequently threatening the safety of the pipeline system. These transient conditions may be induced due to the chattering valves or after pumps shut down [1]. Indeed, all the pressurized systems inevitably practice the water hammer conditions over the operating systems life because the flow has to be altered due to the processes of starting up or shutting down, equipment breakdown, operational adjustments, earthquakes, human error or other disturbances [2]. However, this phenomenon has a diverse and catastrophic impact on the hydraulic system components and environment [3]. For example, the oil and gas transportation pipeline has to be safely guaranteed against the hydraulic wave shock and expose the pipeline to the leakage hazard which causes economic losses and environmental pollutions [4], [5]. Evidently, this phenomenon is occurred due to the sudden or quickly changes in the flow velocity which may induce genuine negative and positive pressures in the pipelines [6], [7]. Consequently, the induced pressure wave will be oscillated in the pipeline at a speed close to the sound speed in water or oil and travelled forth and back within the pipeline increasing the risk of pipes implosion and explosion [8], [9]. Yet, the frequency and amplitude of the oscillated wave is affected by the pipeline conditions such as roughness, depositions, potential leakages and corrosion so that some researchers used the hydraulic transient methodology to assess the piping system by analysing the damping pressure wave pattern [10]. Alternatively, the uncontrolled hydraulic transients events may cause destructive damages to the mechanical and civil infrastructure of the hydraulic system so that maintaining the hydraulic transients in the safe limit is the goal of most designers in this scope [9]. Thus, more investigations are made in the literatures to describe an effective strategy to control the hydraulic transient and eliminate the
catastrophic effect of water hammer. Where, some modifications are applied to the fundamental hydraulic system components (pumps or pipeline) so as to enhance the water hammer impedance of the system [11],[12]. For instance, the increasing of pumps inertia will reduce the severity of induced water hammer and suppress pumps runaway speed [13]. Moreover, the modification of pipelines specification is another parameter affecting the hydraulic transient events. Where, the using of the polymeric pipes instead of metallic pipes contributes by improving the surge damping performance of the hydraulic system because of the viscoelastic mechanical behaviour [14],[15],[9],[16]. The most popular of such polymeric pipes are the polyvinyl chloride (PVC), high density polyethylene (HDPE), and glass reinforced fibre plastic (GRP), the understanding of their features and the hydrodynamic behaviour is illustrated in some literatures [17]. However, the using of viscoelastic (polymeric) pipes cause wave attenuation and energy dissipation due to the superior physical properties that directly affect the induced pressure wave such as viscoelasticity, fluid-structure interaction (FSI), friction and Poisson ratio [18],[19],[20],[21]. The polymeric pipe configuration may differ to produce new condition, where replacing of short section by polymeric and inserting polymer tube into the main pipeline cause remarkable surge suppression [22],[23]. On the other hand, the surge control devices like air vessel, surge tank, air valve and check valves play crucial role by mitigating the water hammer impacts [24],[25],[26],[27],[28]. On the whole, the majority of literatures have dealt with water hammer phenomenon from the perspective of control strategy regardless the triggering method of the pressure wave in the system.

In this study, the effect of changing the transient trigger method on the induced pressure wave for double control hydraulic system will be investigated. Where, four different transient trigger scenarios are applied to hydraulic system controlled by air vessel and HDPE forward configuration bypass. The scenarios of pumps trip, simultaneous valve and pump shut-in, end valve closure, and double valves consequently close are used to verify the performance of air vessel and HDPE forward configuration techniques in the hydraulic systems.

2. Experimental work

The experiment rig is designed and manufactured in the Ahdeb Oil field in Iraq and a complete hydraulic system is built with high pressure components to bear the high amplitude of pressure surges during the transients condition. Where, all implementation and measurements devices are reliable and calibrated to verify their efficiency and ensure the ability to perform the study. The setup and distribution of hydraulic components of this experiment is shown the photograph in figure 1 and explained the schematic in the figure 2.

![Figure 1](image_url)  
**Figure 1.** The photograph of the experiment setup which include 1: the pump, 2: flowmeter, 3: air vessel, 4: pressure transmitter, 5: HDPE forward configuration.
Figure 2. The schematic of the whole system.

In which, 1: upstream reservoir (lake), 2: the pump, 3: check valve, 4: pressure transmitter, 5: flowmeter, 6: air vessel, 7: ball valve, 8: HDPE pipe, 9: downstream tank, 10: data cable, 11: data acquiescing system (DAQ), 12: computer, 13: drainage pipe.

2.1. Hydraulic components

High pressure centrifugal pump (Sulzer) is used to perform the experiment and generating water hammer events in the hydraulic system where more details about this pump is listed in the table 1. The pumps intake is connected to upstream large water lake (50×25×2 m) by using (4 inches) suction steel pipeline besides a filter to supply clean fresh water to the hydraulic system. Then, (3 inches) steel pipeline is used as pumps bypass to protect the pump against the reversed pressure waves during the transient and to compensate the vacuum pressure in the discharging pipeline when the pumps shutting down. As well as the pump is equipped with priming tank to recharge the pump and filling the volute casing before starting up to decrease the initial power required. While, discharging flange of the pump is connected to high pressure check valve to prevent the backflow to reach the pump.

| Table 1. The pump specifications. |
|----------------------------------|
| Value    | Unit |
| Head (H) | 29.4 M |
| Discharge (Q) | 150 m³/h |
| Rotational Speed (N) | 2958 Rpm |
| Power (P) | 75 Kw |
| Temperature | 88 C |
| Outlet pipe diameter (DN) | 4 inch |

On the other hand, the discharging pipeline is consisting of two different material pipes, the main line is a carbon steel pipe (DN100) and four pipes is welded to construct (45 m) length of pipeline. The second pipe is the HDPE bypass which is branched from the main line and re-joins again after the midline valve to provide more damping effects on the pressure wave. Further, the main line is equipped with (14) high pressure flanges (WN-RF) class 300 to carry the flowmeter, valves and others extensions. As well as another eight small flanges are used to connect the pressure gauges and air vessel. In the downstream end, the discharging pipeline is connected to closed downstream tank (15 m³) to preserve downstream high pressure contributing by magnifying the hydraulic transient condition when the pumps stop. Finally, there is a drainage pipe installed in the downstream end to discharging the water out or relief system pressure after at the end of each case.
2.2. Double controls hydraulic system
The hydraulic system is controlled by double control techniques; the first control technique is using the air vessel, while the second control technique is activating the HDPE forward configuration bypass. Regardless the other control means like check valve and pumps bypass, these two different control techniques give more flexibility to the hydraulic system because each control can be activated or isolated optionally according the research condition. For one thing, the double controlled system can be run both techniques together or individually. Moreover, the air vessel has the capacity of 100 liters and (25 bar) maximum pressure and its membrane type is EPDM (ethylene propylene diene monomer). This device is very effective to suppress both the negative and positive pressure. Where, the positive wave is absorbed due air compressibility feature, while the negative pressure is compensated by pressurized water in the vessel. On the other hand, the HDPE forward bypass is another important technique used to damp the pressure wave due to the viscoelastic mechanical behavior of HDPE materials. This technique is configured by HDPE pipe (D=0.0762 m, L=7 m) and the HDPE soft joints are welded thermally by Electro Fusion Welder (Brutsch type) and then coupled with carbon steel flanges. The HDPE pipe has check valve in its downstream end to prevent the back flow to pass through the HDPE bypass, while it has ball valve in the upstream end to control the status of using this technique either be isolated or activated. This technique is only allowing to the forward flow and restricted to the back flow through the HDPE bypass.

2.3. Measurement and data collection
The HDPE bypass is constructed from high pressure (3inches) HDPE pipeline and (7m) in the length. This pipe is connected with soft joints and flanges by using Electro Fusion Welder. Thereafter, the HDPE flanges are coupled with carbon steel flanges to connect the HDPE bypass in to the main steel pipeline. The upstream end of HDPE pipeline is connected to the main steel pipeline by ball valve in order to make the use of HDPE bypass optional. Whereas, the downstream end of the HDPE bypass is connected to the main line by check valve so as to prevent the reversed flow to pass and allow only for forward flow to pass through the HDPE bypass.

2.4. Operational scenarios
There are four operational scenarios or transient trigger methods are performed in this experiment. Each scenario has some operational actions that may differ than the other scenarios but defiantly there are some actions that common and repeated in all scenarios. The first trigger scenario supposes generating the hydraulic transient conditions by action of pumps trip only. The second scenario is performed by pumps trip and midline valve simultaneously close. The third scenario supposes triggering the transient events by end valve closure only. The last scenario is made by closing the end valve and the midline valve consequently. As a result, the procedure of carrying out of each scenario is summarized in the table 2. In order to perform anyone of the following four scenarios, the vertical sequence of that scenario can be followed. Hence, these scenarios can be arranged in the following sequence as referred in this paper: first scenario refers to pumps trip scenario; second scenario refers to simultaneous valve and pump shut-in scenario; third scenario refers to end valve closure scenario; fourth scenario refers to double valves consequently close.

Table 2. The operational scenario procedure.

| Action                                      | Scenarios |
|---------------------------------------------|-----------|
| Ensure all joints, and bolts are connected properly. | √         | √         | √         |
| Ensure all equipment is in good conditions.  | √         | √         | √         |
| Ensure the valve position on the right way.  | √         | √         | √         |
| Ensure the connection of transmitters to the | √         | √         | √         |
DAQ and computer.

| Step                                                                 | ✓  | ✓  | ✓  |
|----------------------------------------------------------------------|----|----|----|
| Priming the pump and filling up the volute casing.                  |    |    |    |
| Activate the control devices individually or together               |    |    |    |
| Start the LabVIEW program and record data                          | ✓  | ✓  | ✓  |
| Start up the pump against discharging closing valve, after 5 seconds open the discharging valve gradually. |    |    |    |
| Filling the priming tank to be prepared to next running time.       | ✓  | ✓  | ✓  |
| Observe the pressures in the LabVIEW interface until the pressure become stable and steady state is achieved. |    |    |    |
| Stop the pump suddenly.                                             | ✓  | ✓  | ×  |
| Close the midline valve simultaneously                              | ×  | ✓  | ×  |
| Close the end valve rapidly                                         | ×  | ×  | ✓  |
| Close the midline valve consequently                               | ×  | ×  | ×  |
| Activate the pumps bypass consequently                             | ×  | ✓  | ×  |
| Observing the LabVIEW if fluctuation is stabilized stop the program and save results | ✓  | ✓  | ✓  |
| Open the midline valve gradually                                    | ×  | ✓  | ×  |
| Open the drainage valve to release the pressure from the tank and pipeline and prepared to next experiment | ✓  | ✓  | ✓  |
| Repeat the experiment at least three times in order to ensure the accuracy and uncertainty. | ✓  | ✓  | ✓  |
| Collect the recording data and analysis the results                 | ✓  | ✓  | ✓  |

3. Software and theory

In order to validate the experimental work, numerical study is performed by using the commercial Bentley Hammer software. It is graphical interface software programmed basing on the method of characteristic (MOC) methodology to solve the governing equations [29]. It is advanced numerical simulator and represent very efficient tool to analysis the water hammer problems due to the simplification of modelling the complicated cases for different transient conditions [30], [31]. Moreover, Bentley hammer is compatible for the model of other hydraulic software like WaterGEMS and WaterCad to save time and reduce the transcription errors. In this software, the computational optimal time step is automatically setting according to designing and operational condition which achieves high accuracy and less simulation time. Further, the friction formulation is well modelled in the Bentley Hammer software ranging from steady state to quasi-steady to unsteady friction model.

3.1. Method of characteristic

The method of characteristic (MOC) is the most common used the numerical explicit integration scheme to solve the classical hydraulic transient model [32], [19]. Where, the pair of hyperbolic quasilinear partial differential equations of continuity and momentum can be converted into four ordinary differential equations by using the method of characteristic [33], [34]. The MOC consider the change of the wave celerity direction during the transients so that it supposes two characteristic
equations represent the water hammer wave propagation in x-t plane along the positive and the negative lines as shown in the figure 3 [35].

Where, the positive characteristic equation \( \left( C^+ \right) \) along the line \( \frac{dx}{dt} = a \) is:

\[
\frac{g}{a} \frac{dH}{dt} + \frac{dV}{dt} + \frac{\rho |V|}{2D} + \frac{g}{a} V \sin \theta = 0
\]

While, the negative characteristic equation \( \left( C^- \right) \) along the line of \( \frac{dx}{dt} = -a \) is:

\[
-\frac{g}{a} \frac{dH}{dt} + \frac{dV}{dt} + \frac{\rho |V|}{2D} - \frac{g}{a} V \sin \theta = 0
\]

In which, \((g)\) is the gravity, \((\alpha)\) is the wave celerity, \((H)\) is the piezometric head, \((V)\) is the fluid velocity, \((D)\) is the pipe diameter, and \((\theta)\) is the pipe inclination angle.

![Figure 3. The characteristic lines of MOC.](image)

However, the positive and the negative wave equations (1 & 2) can be solved by adopting first order finite difference technique. Then, the general solution of head and velocity at the intermediate points (point P) related to initial points (R and S) can be determined as follows [35]:

\[
H_P = \frac{1}{2} \left[ H_R + H_S + \frac{g}{a} \left( V_R - V_S \right) \right] - \frac{\alpha}{g} \Delta t \sin \theta \left( V_R + V_S \right) - \frac{\alpha^2 \Delta t}{g^2} \left( \frac{1}{V_R} - \frac{1}{V_S} \right) - \frac{\alpha}{2D} \left( \frac{V_R}{V_R} + \frac{V_S}{V_S} \right)
\]

\[
V_P = \frac{1}{2} \left[ V_R + V_S + \frac{g}{a} \left( H_R - H_S \right) \right] - \frac{\alpha}{g} \Delta t \sin \theta \left( V_R - V_S \right) - \frac{\alpha^2 \Delta t}{g^2} \left( \frac{1}{V_R} + \frac{1}{V_S} \right) + \frac{\alpha}{2D} \left( \frac{V_R}{V_S} + \frac{V_S}{V_R} \right)
\]

In which, \((f)\) is the Darcy-weisbach friction factor; the subscripts \((P, R \text{ and } S)\) refer to the parameters on that points as illustrated in the figure 3.

3.2. Valve theory

The valves are complicated devices which may contribute by hydraulic transients control, and various types of valve may use to achieve this purpose such as ball valve, air valve, and check valve and so on. Where, the midline valve locate between two pipelines as shown in figure 4, the first part represents the last section of the first pipe denoted as \((j, n+1)\) and the positive characteristic condition \( \left( C^+ \right) \) is prevailing of this section and equation (1) is governing there, while for the section \((j+1, 1)\) represent the first section of second pipe and the negative characteristic condition \( \left( C^- \right) \) is prevailing and the equation (2) is governing there to obtain.

\[
V_{P_{j,n+1}} = C_{4j} + \sqrt{\left( C_{4j} \right)^2 + C_{4j} \left( C_{3j} + C_{1j+1} \right)}
\]

\[
V_{P_{j,n+1}} = C_{4j} \sqrt{\left( C_{4j} \right)^2 - C_{4j} \left( C_{3j} + C_{1j+1} \right)}
\]

Where, the \( C_n \) is a quantity that remains constant during each time step and calculated as:
In case of fully closed valve, the instantly velocity becomes zero and the pressure head can be concluded basing on the energy equation and the prevailing boundary condition to become:

\[ H_{P_{j,n+1}} = \frac{C_{3j}}{C_{2j}} \]  \hspace{1cm} (10)

In case of end valve closure, the negative characteristic equation is neglected and only the positive characteristic equation (2) is applied for this condition.

\[ \text{Figure 4. The midline valve condition.} \]

### 3.3. Pumps theory

When the pump failure due to any inadvertent action, the rarefactions waves will be transmitted downstream in the discharging pipe and in same time the pressure wave will travel upstream toward the pump causing change in the operation zone and pump parameters. So that the pump characteristics are described in dimensionless relations based on the rated value of each parameter as \( h = \frac{H}{H_{t}}, \ v = \frac{Q}{Q_{t}}, \ \alpha = \frac{N}{N_{t}} \), and \( \beta = \frac{T}{T_{t}} \). In which \( h \) is the head, \( Q \) is the discharge, \( N \) is the rotational speed, and the subscript \( d \) refer to the properties in the rated condition.

On the other hand, the dimensionless homologous relation between \( h \) or \( \beta \) from a side and \( \alpha \) from another side is difficult to handle because of both values \( (\alpha \ and \ \beta) \) are very fluctuated in the amount and direction. Instead, new relations have been presented to overcome this problem as well as it could describe the complete characteristic curve of pump as follow:

For the rate of head: \( WH = \frac{h}{\alpha^2 + v^2} \)

Also for the rate of torque: \( WB = \frac{\beta}{\alpha^2 + v^2} \)

Both curves \((WH \ and \ WB)\) will be plotted against the angle \((\theta)\) in the abscissa which is represented as: \( \theta = x = \pi + tan^{-1}(\frac{v}{\alpha}) \) as shown in figure 5. Notably, these curves \((WH \ and \ WB)\) not only well correlated but also have similar trends for the same specific speed.
4. Experimental results and discussions

The experiment is performed by applying four different transient trigger scenarios which are pumps trip scenario, simultaneous valve and pump shut-in scenario, end valve closure scenario, and double valves consequently closed scenario. Where, each trigger scenario is implemented twice for uncontrolled technique (when the air vessel and HDPE bypass are deactivated) and for controlled technique (double controlled is activated). Then, the pressure variation during each trigger scenario is timely recorded by the pressure transmitter at three different points along the experiment pipeline as illustrated in the schematic figure.

4.1. Pumps trip scenario

The transient conditions can be triggered in this scenario when suddenly power failure occurred to the running pump. The surges have been recorded in three different points along the pipeline (as mentioned before) for specified period of time. Yet, the pressure is almost similar in the all measuring points so that one measuring point is sufficed to describe the transient events in this scenario. Consider the figure 6 to explain the transient events during this scenario. A while after starting up, the pressure in all points trends to behave as straight line within a period of time, this means the steady state is achieved and the system is ready to practice the transient conditions. So that after 10 second the pressures of the whole system are dropped suddenly and reaches to negative value due to power failure of the pump. For uncontrolled technique, the pressure is rising up to the max value owning to the effect of reversed pressure wave. The pressure will be oscillated between the positive and the negative values throughout the system and the pressure wave travelled forward and backward consequently. After period of time, the amplitude and frequency of pressure wave is mitigated and the oscillation is damped due to the friction losses and downstream tank effects. On the other hand, for controlled technique that both air vessel and HDPE bypass are activated in this technique. Where, the pressure wave is exposed to double damping effect that causing soft behaviour of pressure wave. It can be noticed the pressure wave that produced in double controlled technique is not exceed the surge limit (closing pressure limit). As a consequence, this technique is experienced better control and damping effect which leads to soft and safe operational procedure. For instance, the pressure wave is appeared for the first transient cycle only, thereafter the amplitude and frequency of the wave is vanished and the pressure of hydraulic system is dropped steadily to zero. Notably, this technique has good damping percentage for maximum pressure (36%) besides the minimum pressure mitigating percentage is (63%) for the first measuring point.

4.2. Simultaneous valve and pump shut-in scenario

This scenario supposes when the power failure happens and the pump stopped suddenly, the midline valve responds and closes simultaneously. In this scenario, the discharge pipeline is divided into two regions with different transients events. The first zone is defined as the region before the midline valve.
While, the second zone represents the part of discharging pipeline after the midline valve. Therefore, the pressure variation of each zone will be discussed separately.

**Figure 6.** The pressure variation due to pumps trip scenario.

*First zone condition.* For uncontrolled technique, consider the figure 7 where the pressure in the first zone dropped suddenly to the minimum pressure due to the effect of power failure of running pump and the pressure reside a period of time in the minimum value because the closure of midline valve prevent the reversed wave to develop in this region. After a while, the pump bypass is opened and pressure wave transport forward from upstream reservoir to discharging pipeline bypassing the pump. This pressure wave will rise up the pressure to maximum value and generate wave fluctuation in this region which is damped quickly due to the shortness of pipeline section as well as friction and minor losses. However, for the case of double controlled technique, both the air chamber and HDPE bypass are activated in the hydraulic system in this case so that the hydraulic transient conditions exposed to double control technique to mitigate the transients and damp the surges. Moreover, the energy loss that occurs in the first transient region owing to power failure will be compensated by instantly response of air chamber as well as the live water comes from the upstream reservoir bypassing the pump to neutralize the negative pressure. While the positive surge will be damped in the HDPE bypass beside the air chamber. Thus, the maximum pressure in this double controlled technique maintains the acceptable range and doesnt exceed the surge limit. Further, the damping percentage of the maximum pressure is (28%) and for the minimum pressure is (54%).

*Second zone condition.* For uncontrolled technique, consider the figure 8 that is dropped slightly due to pumps failure and then raised up suddenly owing to the effect of simultaneous midline valve closure. Moreover, the transient events in the second region will be damped due to the contrasted
effect of two generated pressure waves, besides the effect of downstream tank to absorb the pressure wave so that the pressure in this region doesn’t exceed the surge limit. For controlled technique, the transient conditions witnessed less damping ratio related to the effect of air vessel and HDPE techniques. It can be noted in the figure 8 the trend of uncontrolled technique and control technique have the same profile. Not only this but also the maximum pressure has been slightly damped by a percentage of (9%) only and the negative pressure by (47%).

![Figure 8. The pump and valve simultaneous shut-in scenario in 2nd zone.](image)

### 4.3. End valve closure scenario

There is another method to trigger the transient events in the hydraulic system by closing the downstream end valve rapidly and maintain the pump running normally. After the steady state is satisfied and the pressure profile become steady, the transient conditions are triggered by sudden valve closure as shown in the figure 9. As a result, the pressure profile of uncontrolled technique will be rising up quickly in the whole system owing to the water column theory then it is fluctuated between the positive and negative values until the damping effect overcome the transients conditions. However, the positive pressure reaches the extreme value and exceeds the surge limit by percentage of (175%). Moreover, the pressure wave will be dissipated in the system after a period of frequency due to the pipe friction and joints and valve losses as well the effect of the closed ends.

For uncontrolled technique, the impact of damping will be more availed in case of activating the double control technique. The variety of control technique makes the hydraulic system more reliable and balanced because of the different features of each technique for instance: the air chamber affects the amplitude of surge wave, while the HDPE affect the frequency besides the amplitude of surge wave. Along with this fact, observe the figure (9) again that describes the behaviour of surge wave during the uncontrolled technique for a period of time. Its clearly to note that applying this technique will enhance the hydraulic system performance to be rapidly neutralized and the peak wave will be dismissed. Further, the maximum pressure is damped by percentage of (53%). Whereas, the negative pressure is also damped by percentage of (300%) in the three measuring points respectively.

### 4.4. Double valve consequently closed scenario

The hydraulic transient condition is triggered by the action of closing the end valve following by midline valve closure. This double valve closure action divide the discharging pipeline into two zones with different transient condition developing.

First zone condition. This zone is defined as the part of the pipeline locates before the midline valve position up to the pump. In particular, consider the figure 10 that describes the transient condition in the first zone. For uncontrolled technique, its clearly to observe the pressure is rising up suddenly due to the end valve closure action. Afterward the pressure is dropped due to negative pressure but the action of midline valve closure will interrupt the dropping path and make the pressure rise up again owing to the interaction between two opposite waves. This interaction will make the damping process
faster in the first zone compared to the scenario of end valve closure only. For controlled technique, the activation of air vessel device and HDPE bypass will aid to mitigate the water hammer events in the double controls hydraulic system. In this zone, both air chamber and HDPE bypass are dominant and important and play a crucial role in the damping matter. Again, consider the figures 10 to assess the influence of double controls technique on the water hammer development. Where, the maximum pressure has got good damping percentage as (52%), whereas the minimum pressure has got (20%) compared to uncontrolled technique.

![Figure 9](image1.png)

**Figure 9.** The pressure variation during the end valve closure scenario.

![Figure 10](image2.png)

**Figure 10.** Double valve consequently closed scenario in the 1st zone.

Second zone condition. The second zone pressure profile is unlike the first zone where this portion of pipe will be totally isolated from both sides and there is no any energy come in or out of these boundaries. For uncontrolled technique, consider the figure 11 that illustrates the pressure behavior in the second zone where the pressure is rising up first due to end valve closure and then drops due to pressure wave travels upward toward the pump and leave negative pressure behind. The reversed wave will be interrupted by midline valve closure and this action will make the pressure rise up again. Afterward the energy of pressure wave will vanish and the negative pressure resides and become dominated there. Further, the maximum pressure has damped by percentage of (37%) in this zone compared to uncontrolled case of end valve closure scenario. Despite of the advantages of implementation of this scenario but the negative pressure in the second zone represent a remarkable drawback of this scenario which cant be overlooked. For controlled technique, the influence of air vessel and HDPE bypass is slight in the second zone. However, the HDPE bypass role is more effective than that of air vessel in this zone. The HDPE bypass lets the pressures pulses passed into the
second zone, make it more turbulent and transient. Despite of isolating the second zone but its surely got some damping effects either direct or indirect way. Where the maximum pressure has got (7%) damping percentage and the minimum pressure has got (27%) damping percentage compared to uncontrolled technique.

![Figure 11. Double valve consequently closed scenario in the 2nd zone.](image)

4.5. Scenarios comparison

In order to make reasonable comparison of different trigger scenarios, a certain classification needs to be considerable. In some transient trigger scenarios, the transient events are propagated similarly along the pipeline which it can be dealt as a single zone such as pumps trip and end valve closure scenarios. Whereas, the transient condition divide the pipeline into different zones during the other two trigger scenarios. So that, the comparison will be preliminary classified into two types; the first comparison will be made for single zone scenarios, while the second will be made for double zone scenarios.

4.5.1. Single zone comparison. The scenarios of pumps trip (1st scenario) and end valve closure (3rd scenario) represent a single zone scenario because the hydraulic transient events are similar along the entire length of the pipeline. Moreover, observe the figure 12 that illustrates the effect of each transient trigger scenario on the pressure wave profile for double controlled hydraulic system. Its clearly to notice that the end valve closure scenario generates maximum pressure higher than that of pumps trip scenario. On the contrary, the negative or minimum pressure is dominant and important in case of pumps trip scenario. Yet, it is less effective in case of end valve closure scenario. On the other hand, the pressure trend fluctuation in case of third scenario is continued for a period more than that of first scenario which is damped and neutralized faster. However, the general streamline of pressure trend is propagated upwardly in case of end valve closure scenario due to the effect of pumps running during the transient which contributing by the pressure building up. Unlike the pressure trend which is vanished downwardly in case of pumps trip scenario.

4.5.2. Double zone comparison. There are two transient trigger scenarios have two different transient zones, where the closure of midline valve will divide the discharging pipeline into two zones having different events. So that the scenario of simultaneous valve and pump shut-in (2nd scenario) and the scenario of double valve consequently close (4th scenario) have two zones of hydraulic transient condition. The first zone refers to the discharging pipeline before the midline valve and the second zone refers to the region behind the midline valve. For first zone, consider the figure 13 that illustrates the comparison between the second scenario (simultaneous valve and pump shut-in) and the fourth scenario (double valves consequently close). Its clearly to notice that the maximum pressure is higher during the fourth scenario because the closing of end valve induce positive wave propagated upward and make the pressure increase. But the action of closing the midline valve consequently will interrupt the positive pressure propagation and let the pressure little reduced and then raising up again.
due to the reflection of pressure wave of midline valve closure. However, during the second scenario the pressure dropped due to the pumps failure which induces negative pressure in the pipeline but the action of closing the midline valve simultaneously will interrupt the negative pressure propagation and induce positive pressure in the system. In brief, the second scenario has lower negative pressure while the fourth scenario has higher positive pressure by percent of (34%) and the both scenarios go to divergence in the end of the transient period.

![Figure 12. The comparison of single zone scenarios.](image1)

For second zone, consider the figure 14 that describes the comparison between the second and the fourth scenarios in the region behind the midline valve. It can be claimed that the second scenario is more effective and has better performance than the fourth scenario. Where, the second scenario has the superiority by (47%) percent for the maximum pressure and (53%) percent for the minimum pressure. However, the pressure trend of fourth scenario is suddenly raised up due to the closing of end valve and the wave travelled upwardly but the sequent action of closing the midline valve make this region is isolated and the negative pressure resides this zone except the impulses wave that pass through the HDPE bypass will contribute by the damping and neutralizing the surge fluctuation in this region. On the contrary, pressure trend of the second scenario is suddenly dropped due to the action of pumps trip but the action of closing the midline valve simultaneously will make the pressure raised up then this pressure wave will be absorb and eliminated in the downstream tank.

![Figure 13. The comparison between the second and fourth scenarios in the first zone.](image2)
5. Numerical Results and literature validations.
The experimental results are validated by using Bentley hammer software to ensure the reliability of the concluded results. As long as the current work is also compared with the published researches in this field to state the scope of this study and explain the convergence and the divergence paths between two studies.

5.1. Numerical results
A complete numerical study has been performed to verify the experimental results. All the boundary conditions of experimental work are considered in the simulation setup of the Bentley hammer software. Moreover, the performance of the double controlled hydraulic system is discussed for four different transient trigger scenarios.

5.1.1. Pumps trip scenario. After the steady state condition is achieved (first 10 seconds duration) as shown in the figure 15, the transient events are triggered by suddenly stop the pump. This action generates negative pressure in the pipe and makes the pressure trend dropped to minimum value. Owing to the pressure difference between the pipeline and the pressurized downstream tank the pressure wave will be reversed and inducing positive pressure handle the pressure trend to the maximum value. However, the double controlled system is reacted to this condition and the air vessel release the pressurized water to compensate the lack of energy in case of negative pressure prevailed and in same time the vessel absorb the positive wave by the feature of air compressibility. Not only the air vessel but also the HDPE forward configuration technique contributes by damping the pressure wave due to the feature of viscoelastic wall. On the other hand, the numerical results in this scenario are well convergent to the corresponding experimental result illustrated in the figure 6 for the controlled technique.
5.1.2. *Simultaneous valve and pump shut-in scenario.* The transients conditions are initiated due to the simultaneous action of pumps trip and midline valve closure in this scenario. The pressure trend during the double controlled technique in the first zone of the second scenario is illustrated in the figure 16. Where, the pressure trend takes the straight line shape in the first 10 seconds which represent the steady state condition before the transient. After that the pressure is suddenly dropped due to the action of pumps trip but this dropping is no longer prevailed because of the interrupting of midline valve closure effect. This interaction between two different actions has considerable contribution by improving the hydraulic transient performance and damping the induced surges. However, the numerical results in this scenario are well harmonic with the corresponding experimental results of the controlled technique (the red colour trend) that described in the figure 7.

![Simultaneous valve and pump shut-in scenario](image)

**Figure 16.** The transient events during the controlled technique of the simultaneous valve and pump shut-in scenario in the first zone.

5.1.3. *End valve closure scenario.* In this scenario, after the steady state is achieved, the pressure trend is raised up suddenly due to the action of end valve closure and then fluctuated because of pressure wave travelling forth and back in the pipeline as shown in the figure 17. Moreover, the behavior of pressure wave during the numerical simulation is similar to that of corresponding experimental results that presented in the figure 9. So that the same reasons and explanations that mentioned in the experimental results can be adopted here to clarify the behavior of pressure wave during the transient condition in this scenario.

![End valve closure scenario](image)

**Figure 17.** The transient events during the controlled technique of the end valve closure scenario.

5.1.4. *Double valves consequently closed scenario.* In this scenario, after the period of steady state condition, the pressure trend raised up suddenly in the first zone due to the action of end valve closure
and the pressure reach the maximum value. After that the pressure is decreased due to the reflection of pressure wave toward the other side but the falling path of pressure wave is interrupted by consequently close the midline valve which induce positive pressure again in the pipeline as shown in the figure 18 where the peak of pressure trend has two local maximum point represent both valve closure action. Moreover, this numerical result has the same general trend and profile of the corresponding controlled technique of the experimental results that illustrated in the figure 10 for the first zone of this scenario.

![Figure 18. The transient surges during the controlled technique in the first zone of the double valves consequently closed scenario.](image)

5.2. Published work comparison

The phenomenon of hydraulic transients is broadly investigated in the literatures but still have many unknowns need to be covered. Hence, it is very difficult to point out extensive study including different transient trigger methods like the current study. However, most of literatures use one transient trigger method to investigate the other parameters. Therefore, the comparison study will be divided into categories according to the method of triggering the transient.

The first comparison will be based on the end valve closure scenario that used by Garg [9]. While the second comparison will be made with the study of Rohani [36] basing on the pump trip scenario.

5.2.1. Garg study comparison

The current study is verified by the comparison with the experimental study of Garg [9]. Where, both studies have many common boundary conditions. the Garg study used two materials pipes consisting of reinforced fiber plastic (GRP) and mild steed pipe in different configuration as a water hammer control. While, the end valve closure scenario is used to trigger the transient events in both studies. However, consider the figure 19 that illustrated the pressure wave trend for both studies. In order to make this comparison applicable, precise and reliable, a dimensionless relation of head-time trend is presented to minimize the difference in the boundary conditions between the two studies.

5.2.2. Moreover, The y-axis represent dimensionless head which is calculated from the ratio of observed head variation into theoretical Joukowsky overpressure 

\[ \frac{(H - H_2)}{H_{Jowk}} \]

where \( H \) is the instantly pressure head during the water hammer, \( H_2 \) is the hydrostatic head at the end of transient, whereas \( H_{Jowk} \) is Joukowsky overpressure can be calculated by using equation (11).

\[ \Delta H = \sqrt{(a/g)} \Delta V \]  \hspace{1cm} (11)

Whereas the x-axis represents the time dimensionless which represent the ratio between instantly times into the whole period of transient. Further, the boundary condition of each study that used in this comparison is listed in the table 3. However, Its clearly the both studies have similar trend during the transient events and the convergent percentage is (58) for maximum pressure, and the minimum pressure convergent percentage is (97%) between both studies.
Table 3. The boundary condition of both studies.

| Parameter          | Current study | Garg study |
|--------------------|---------------|------------|
| Transient trigger scenario | End valve closure | End valve closure |
| Materials used     | Steel and HDPE | Steel and GRP |
| velocity           | 2.03 m/s      | 1 m/s      |
| Wave celerity      | 1200 m/s      | 900 m/s    |

Figure 19. The comparison between the current study and Garg study.

5.2.3. Rohani comparison study. In order to describe the pressure variation after the pump trip, the current study is compared with Rohani study [36]. The first cycle of the pressure fluctuation is compared between both studies for period of time described dimensionless as shown in the figure 20. However, the pressure trend after pumps failure has the same profile for both studies but the profile of pressure described by Rohani is softer than that of the current study and the total convergence between both studies is (76%). This difference may be attributed to the using of double pumps in Rohanis study which make the pressure variation is gradual or softer.

Figure 20. The comparison between the current study and Rohani study.

6. Conclusions
- The double controlled hydraulic system performance is highly affected by changing of transient trigger scenario.
The double hydraulic transient system has better performance during the third transient trigger scenario (the end valve closure scenario), where the damping effectiveness is improved by percent of (53%) for maximum pressure and percent of (300%) for the minimum pressure compared to pure transient case (uncontrolled technique).

The double hydraulic transient system exhibited worse damping performance in the second zone during the fourth trigger scenario (double valve consequently closed scenario) where the damping enhancement is only (7%) percent for maximum pressure and (27%) percent for minimum pressure compared to non-damped case.

The performance of double hydraulic system in the first scenario (pumps trip) is better than that of second scenario (simultaneous valve and pump shut-in scenario) and the superiority percentage for the first scenario is (8%) for maximum pressure and (9%) for minimum pressure compared to the second scenario.

For both the second and fourth scenarios, the performance of doubled controlled hydraulic transient system in the first zone is better than that of second zone.

The experimental and numerical results are reasonable convergent by a percent of (95%) basing on the maximum pressure value.

Further investigations to verify the performance of the hydraulic transient control systems is needed such as pipes rupture, leakage, and contaminant.

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