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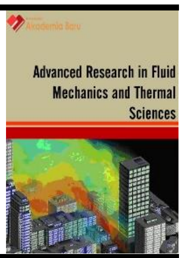

Experimental and Numerical Investigation of Flow Hydraulics and Pipe Geometry on Leakage Behaviour of Laboratory Water Network Distribution Systems

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ABSTRACT

As the leakage behaviour of water distribution network is considered a critical and life-threatening issue, so this behaviour of water distribution network systems has been investigated experimentally and numerically, based on the effects of different positions and flow rates of the leakage outlets, and taking into consideration the flow hydraulics and pipe geometry. A laboratory model of the actual water distribution network studied was constructed. The laboratory water distribution network model is horizontal and has 16 loops with a total length of 30m in different diameters. The leakage position in the laboratory water distribution network was altered between main, sub-main, and branch pipelines with different flow rates. The characteristics of the ideal laboratory water distribution network with no-leakage were first studied; and the water distribution network system parameters were calculated theoretically using the Hardy-Cross method with seven iterations. The studied water distribution network system was simulated using computational fluid dynamics technique, Ansys. Fluent 18.2. The aim was to modify the old water distribution network by sensing the pressure values using dispersed pressure sensors. Also, from the pressure map of the laboratory water distribution network, the leakage position, if any, could be located. Depending on the sensed pressure, the control circuit was programmed to close the corresponding solenoid valves. The leakage flow rates were 0.1, 0.25, and 0.4 L/s; and changed between the main and sub-main pipes. The maximum pressure drop was around 500pa at the node directly preceding the leakage point at leakage flow rate 0.4 L/s. The performance of the used solenoid valve was simulated using the Matlab-Simulink technique. The simulation results showed the response to stepdown control signal was over-damped with steady state error of 2% and settling time of 0.6 s.

Keywords:
Water distribution network; water leakage; solenoid valve; computational fluid dynamics (CFD); Matlab

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1. Introduction

A consistent supply of clean water is the first and most critical community service that people need. A safe supply of potable water is the basic necessity of mankind; therefore, water supply systems are the most important public utility Creaco and Pezzinga [1]. The network distribution system is used to supply water from its source to the point of usage Ahmad Fuad *et al.,* [2]. The leakage is defined as (the amount of) water which escapes from the pipe network by means other than through a controlled action.

Meniconi *et al.,* [3] explained the analysis concerning the importance in numerical models of unsteady friction and viscoelasticity to transients in plastic pipes with an external flow due to a leak. Tests are based on laboratory experiments, and the use of different numerical models. Daniel Paluszczyszyna, *et al.,* [4] modelled and simulated the water distribution systems using quantised state system methods (QSS). Daniel Paluszczyszyn *et al.,* [5] developed the water network model reduction software. The application can be integrated into other concepts applied to water distribution system or it can be used as a standalone tool for the purpose of model simplification only.

Creaco and Pezzinga [6] explored the simulation and optimization modelling, topology and partitioning, water quality, and service effectiveness. Creaco and Pezzinga [7] had shown how water pipe replacements and control-valve installations could be optimized in water distribution networks to reduce leakage, with minimum nodal pressure constraints. Santonastaso *et al.,* [8] proposed a general framework to adjust water distribution network (WDN) by applying algorithms to account for the real positions of isolation valves.

Avi Ostfeld [9] verified that the water distribution system is a complex assembly of hydraulic control elements connected together to convey quantities of water from sources to consumers. Alsharqawi *et al.,* [10] studied the aging water distribution networks in the US to verify that they were approaching the end of their useful life; and that more than 240,000 pipeline breaks were estimated to occur every year. Starczewska *et al.,* [11] showed the presence of pressure transients which are common in operational water distribution systems required closer analysis to assess their impact by recording the occurrence and the differences in transient pressure behaviour in complex WDS.

Del Giudice and Di Cristo [12] used three different sensitivity-based methods for selecting the relevant sensor locations in water distribution networks. The results showed that there were no marked differences between the three methods. Kumar *et al.,* [13] presented that the estimation of pipe roughness coefficients was an important and should be carried out before using any water distribution network model for online applications. Galuppini *et al.,* [14] showed that realtime pressure control was commonly adopted by water distribution network management to reduce leakage. A numerical description of the dynamic behaviour of the water distribution network (WDN) was introduced. Misiunas *et al.,* [15] presented an algorithm for burst-pipe detection and location in water distribution networks based on the continuous monitoring of the flow rate at the entry point of the network; and the pressure at a number of points within the network.

Fontana *et al.,* [16] indicated that a common strategy for leakage reduction in water distribution networks (WDNs) was the use of pressure-reducing valves (PRVs). As already well known, a relationship between pressure and water losses can be established, according to which reducing pressure results in reduced losses. Romano *et al.,* [17] detected automatically the leakage bursts in water distribution system. Latchoomun at al. [18] investigated in the laboratory the leakage characteristics of unburied pipes. Also, Latchoomun *et al.,* [19] estimated the pumping energy loss related with leak of different types in the piping system.

Van Zyl [20] theoretically modelled the relation between the pressure and the leakage in water distribution systems. Paez *et al.,* [21] proposed a non-iterative method to perform the simulation of water distribution systems with pressure-driven demands using EPANET2, without the need to use its programmer's toolkit. Straka *et al.,* [22] studied the distribution networks and their classifications, showing a possible connection between the producers and consumers in two categories. The first was the economic side; the other side, the product distribution. Latchoomun *et al.,* [23] proposed a new model of developing old water distribution networks based on the estimation of the leakage from MNF and the burst frequency of AZPs.

Mair *et al.,* [24] analysed the impact and effect of improving the data from other sources for creating water distribution system models. These investigations showed that hydraulic WDS models with a mean pressure error of 3m could be created by knowing a percent of 30% of pipes with a diameter ≥250 mm. Athanasios *et al.,* [25] presented the description of the technical and physical features of the AE leak detection methodology using its pros and cons and all the demands of this technique. Mircea Dobriceanu [26] performed a SCADA system for water distribution stations to monitor and control their technological parameters. Konnur *et al.,* [27] had made a quick review of the methods of analysing and designing of multi-reservoir and multi-junction water transmission networks which are considered among the vital elements for every water supply system. D'Ambrosio [28] studied mathematical programming methods in water networks optimization. Among the major topics, they focused on two different and related problems; one described by the notion of network design, while the other one was applied in terms of network operation. Marko Blažević *et al.,* [29] investigated the various methods of leak detection in an underground network of municipal water distribution system.

From the previous survey and discussed papers, the authors claimed that there was a gap in the investigated leakage behaviour of small water distribution networks with the effects of hydraulic flows and pipe geometry. Also, there were gaps in the possible ways of treatment of leakages, especially in aged water distribution networks. The used pressure sensors permitted the authors to figure out the pressure distribution in conventional (ideal) networks, as well as in networks with leakages. Moreover, the water distribution network pressure map could be drawn in two cases, ideal with no-leakage and with leakage cases, so as to standardize the leakage effect. The network performance was investigated in two cases: at peak hours and off-peak hours. The water distribution network was modified with control circuit to sense the pressure values and close all the pipelines were channelled to the leakage outlets by solenoid valves where required. Finally, the study of the water distribution network used theoretical, experimental, and numerical techniques to obtain the behaviour values of small laboratory water distribution networks with, and without, leakage effects. Also, the simulation of the used solenoid valves enabled the estimation of the secondary leakage through these valves.

2. Theoretical Background

With respect to distribution network analysis, the conventional theoretical tool is known as the Hardy-Cross method [30]. The Hardy Cross method is an iterative technique for equations of flow, the continuity of flow (the flow-in is equal to the flow-out at each junction), and the continuity of potential (the total directional head lost along any loop in the system is zero) [31]. The Hardy Cross method depends on simple mathematics and it iteratively corrects the mistakes in the initial estimate used to solve the problem (self-correcting) [32]. The theoretical results of Hardy Cross method were obtained after seven iterations and listed in Table 2.

3. Experimental Work

Figure 1 shows the CAD drawing and Figure 2 shows the photo of the laboratory water distribution network. The studied water distribution network consisted of main, sub-main, branch pipelines, and branching nodes which created 16 loops. The main pipeline was 1inch in diameter and 3m long; the sub-mains were 0.75inch in diameter and 12m in total length; while the branches were 0.5inch in diameter and 15m total length. Ball valves were used in the laboratory water distribution network to control the flow rate and the direction.

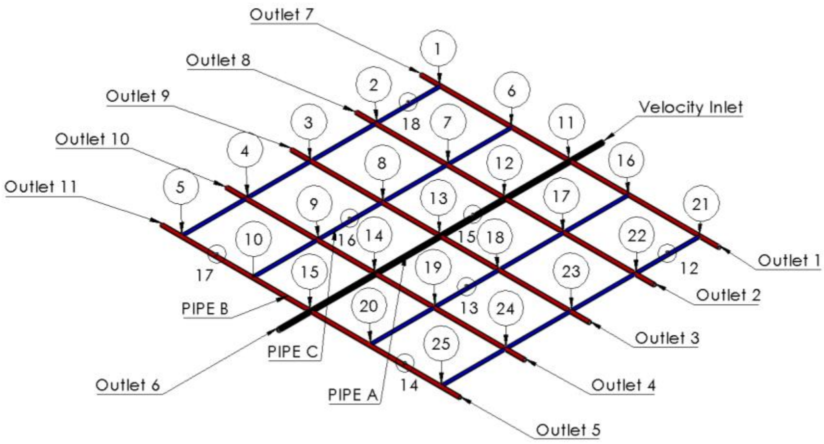


Fig. 1. CAD drawing of the laboratory distribution network

Fig. 2. Real photo of the laboratory water distribution network

Figure 3 shows the ball valve which was installed to discharge the water with different flow rates exit from the distribution network as leaky water. The leakage ball valve was placed on the main and sub-main pipelines to experimentally investigate the most critical leakage cases in the water distribution network analysis.

The measured pressure values via pressure sensors were transferred instantly to be recorded on the computer; to give a real picture of the pressure map through the whole network. One flow meter was fixed and changed between the main, sub-main, and branch pipelines to measure the flow rates [33]. A control unit was designed with a programmed code, using the Arduino for a specified function. As the pressure sensors sensed the pressure drop to a certain pre-set value, the signals from control unit initiated the solenoid valves to close all pipelines which directed the flow to the leakage outlets. Meanwhile, this technique is important to save considerable amounts of water losses. The studied laboratory water distribution network meets all the requirements of the model (geometrically, kinematically, and dynamically similar); except that it was constructed horizontally in the laboratory with no potential head and neglected hydraulic gradient energy.

Figure 4 and Table 1 illustrate the components and their specifications of the studied laboratory water distribution network. The flow was discharged from water tank to the water distribution network by ½ hp centrifugal pump (H=18m, Q=22L/min and 2850rpm).

Fig. 3. Photo of the ball valve at the main pipeline to simulate the leakage outlet

(a) Flow meter sensor (b) Pressure sensor (c) Solenoid valve

Fig. 4. Photos of sensors and valve of the laboratory water distribution network

Table 1
Specifications of flow meter sensor, pressure sensor, and solenoid valve

Flow meter sensor (Sea YF-S201)	Pressure sensor (Flying Elephant SE0006)	Solenoid valve (Adafruit ADA997)
Range:1-30 L/min Water pressure: ≤1.75 MPa Working voltage range: DC 5～18 V Load capacity: ≤10 mA（DC 5V） Operating temperature range: ≤80℃ Operating humidity range: 35%～90%RH (no frost)	Supply voltage:5.0VDC Output: 0.5~4.5VDC Working current: ≤10mA Pressure range: 0~1.2MPa Proof Pressure: 2.4MPa Burst Pressure: 3.0MPa Op. Temp.: 0~85℃ Storage Temp.: 0~100℃ Measure error: ±1.5%FSO Full temp. range error: ±3.5%FSO Response: ≤0.9S	1/2'' nominal NPS Working pressure of fluid: 0.02-0.8 Mpa Working temperature of fluid: 1oC - 100oC Voltage: 6VDC to 12VDC Current: 500mA Materials: Stainless Steel/Poly-oxy-methylene Operating mode: Normally closed Filter Screen: Stainless Steel Inlet Filter Usage: Water

3.1 Control Circuit and Algorithm

Pressure measurements were recorded by pressure sensors through Arduino Mega. When the leakage was triggered, this caused a pressure drop and the controller determined the location of the leakage and identified the pipe number from the node where the pressure was decreased. Then the controller sent a signal to close all the solenoid valves in the pipelines which directed the water flow to leakage locations. Moreover, an alarm was sent to the related person about the leakage location. Figure 5 shows the flow chart of the control algorithm. Figure 6 shows the schematic wiring and the connections of the control circuit components, and the interaction communicating signals between these components. These two figures summarize the used methodology of the studied experimental work. The control circuit consisted of a relay module (2 channel), Arduino Mega 2560 R3, a relay driver module RK4, a power distributer, LCD and, voltage current monitor gauge DSN-VC288.

3.2 Experimental Procedures

In small scale network like that under consideration, the friction is high and consequently the losses are also high and this is a general trend in small pipes. Also, all the fittings, elbows and other minor losses sources have a considerable effect. The most influenced pipelines of the network due to leakage must be determined, hence the leakage has different impact on the pipelines of the network. The response of the solenoid valve to the control signal command must be investigated.

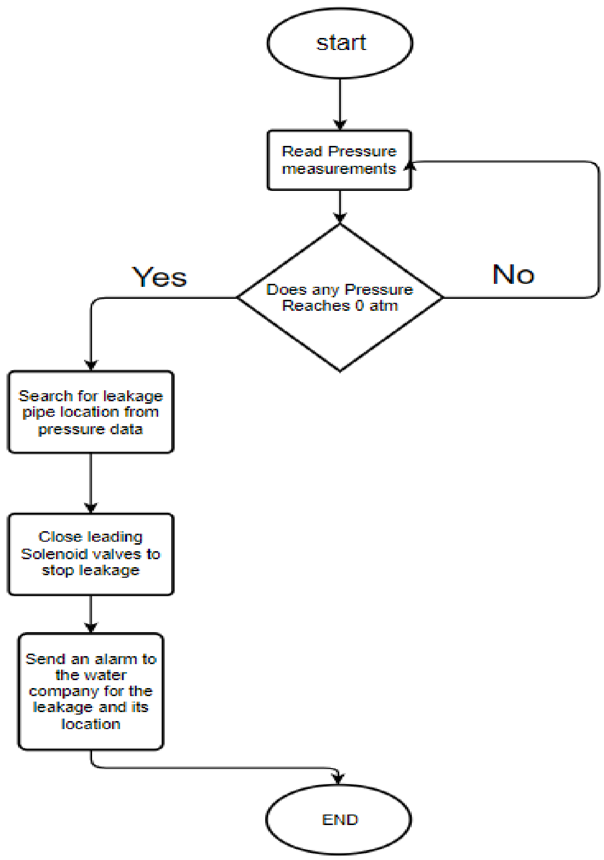


Fig. 5. Flow chart of Arduino control algorithm to control the leakage by solenoid valves using pressure signals

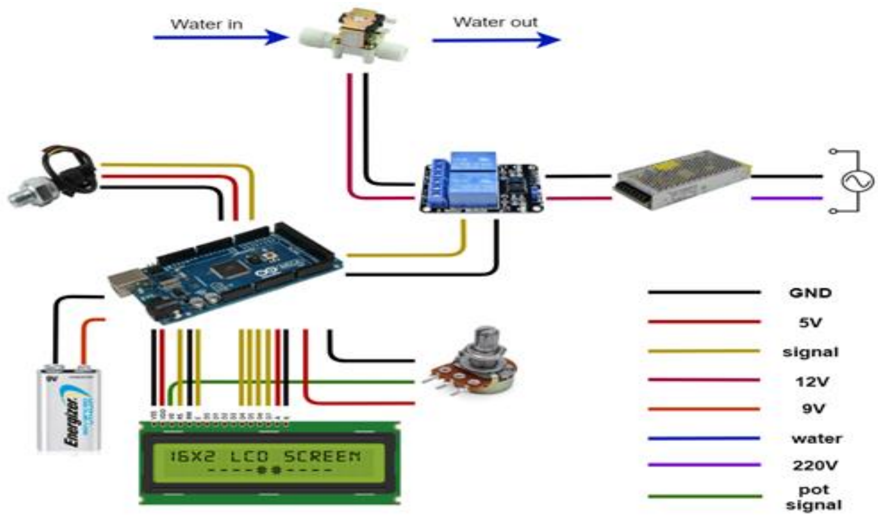


Fig. 6. Schematic drawing of the network control circuit

The experimental test is performed for conventional laboratory water distribution network without leakage. The pressure and flow rate values in different nodes and pipelines are recorded as reference values. Open the ball valve which discharges the water out of network as a simulation of leakage. The throttle area of the ball valve is adjusted to certain leakage flow rate by measuring the water volume in calibrated container and stop watch to measure the time. After adjusting the leakage flow rate, the solenoid valves at leakage position are observed to determine its speed of response. The leakage flow rate is changed and the values of flow rates and pressures are recorded and the response of the solenoid valves are detected [34].

4. Numerical Simulation

The numerical simulations were performed in the case of no-leakage of the water distribution network to enable the detection of the ideal behaviour of the network, as a first case [35]. After that, the computations were performed with leakages at different points along the network, as a second case [36].

The numerical model was mapped on a commercial CFD solver Ansys Fluent 18.2. Parametric studies of velocity, pressure, and eddy viscosity profiles were investigated. Also, vector display of water flow along the different locations of the network (pipes and nodes) gave a detailed picture of the flow in the network. The Phase Coupled SIMPLE (PC-SIMPLE) algorithm was used for the pressure-velocity coupling discretization while the body force was used for pressure discretization [37].

The initial conditions were uniform fully developed velocity profile at pipe inlet. First-order upwind discretization scheme was used for the momentum equations, turbulence kinetic energy (k), and turbulence dissipation rate (ε). All the iterative solutions were performed in double precisions. An inlet flow rate boundary condition was used at the pipe inlet [38]. Using flow rate at inlet (0.1, 0.25 and 0.4 L/s), and pressure at outlet (atmospheric pressure) as boundary conditions, are the common ways of formulating pipe network flow problems. The usual no-slip boundary condition was adopted at the pipe wall. To avoid divergence, under-relaxation technique was applied. The under-relaxation factor for pressure was 0.3, for momentum was 0.6, and those for turbulence kinetic energy and its dispassion rate were 0.8. The solution was assumed to have converged when the continuity and velocity residuals reached nearly 10-4, which was a promising value in the solution, according to Ansys fluent manual. The numerical solution typically required 480 iterations [39].

The water distribution network consisted of 1inch-pipe with inner diameter of 26.24 mm and length 2500mm which is the main pipe, 0.75inch-pipe with inner diameter of 20.57 mm and length 1000mm, which were the sub-main pipes; 0.5inch-pipe with inner diameter of 15.47 mm and length 500mm which were the branch pipes. For leakage a 12 mm inner diameter pipe was assumed as a source of leakage. All these pipes and their fittings were PVC.

Figure 7 shows the locations of the leakage in the water distribution network. The number of leakage outlets was 7: one leakage position at the main pipeline (number 15), two leakage positions at the sub-main pipelines (number 14 and 17, symmetric positions), two leakage positions at external branch pipelines (number 12 and 18, symmetric positions) and two leakage positions at internal branch pipelines (numbers 13 and 16, symmetric positions).

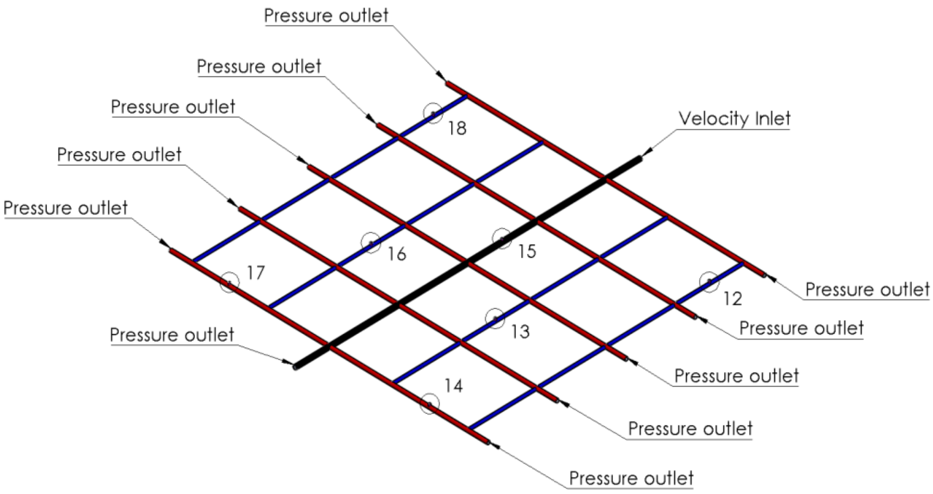
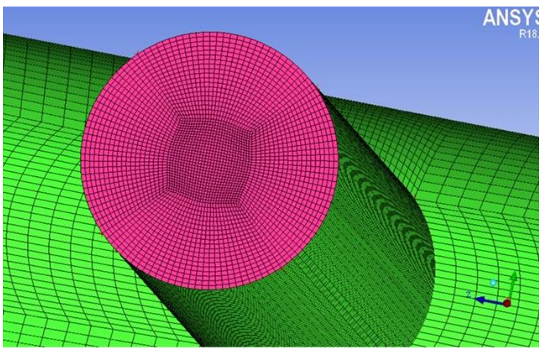
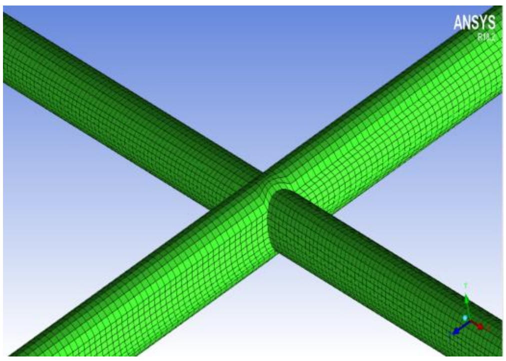


Fig. 7. Water distribution network leakage outlet locations

Figure 7 also shows the distribution network boundary conditions. The boundary conditions were assumed to have an inlet velocity of 2 m/s, and outlets with atmospheric pressure. All turbulence parameters were set to 1% turbulent intensity with equivalent hydraulic diameter [40]. Figure 8 demonstrates that the meshing was done in ICEM CFD using blocking technique with one million Hexa elements, with angle quality criteria greater than 27 and determinant 2x2x2 quality criteria greater than 0.3 which are acceptable according to ICEM CFD user manual for Fluent solver [41].



(a)



(b)

Fig. 8. Distribution network mesh configuration (a) leakage outlet mesh (b) zoom in mesh at any node

The mesh grid stability test was carried out in order to ensure accurate and precise simulation results, and to also save required simulation time. The model was tested using three different mesh numbers to obtain mesh grid stability and variables steadiness at the optimum mesh grid number. The pressure value at different nodes was the preferred parameter used to determine the required mesh number. Figure 9 shows that 1 million elements were the acceptable number of meshes due to the changed variables (node pressure) which became constant at this number [42].

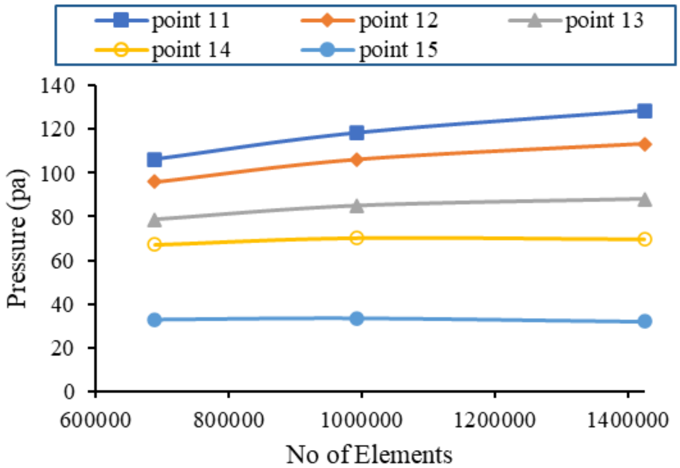


Fig. 9. Pressure variations with mesh grid numbers at network nodes 11-15

The software Ansys Fluent was used for solving the governing equations. This package utilizes a method of control volume theory to convert the governing equations to algebraic equations so that they can be highlighted numerically. The governing equations (continuity, momentum and energy) associated with the standard k-ε model (Turbulent kinetic energy equation, Dissipation rate equation) used the default values of the empirical constants [43].

Table 2 shows the theoretical (Hardy-Cross using Darcy-Wesibach method) and numerical (Ansys, Fluent) results in ideal case (simulated by allowing all outlets from 1 to 11 opened) with no leakage in the water distribution network. The results show an agreement between the theoretical and numerical results. The theoretical calculation was an iterative method with 7 steps of iterations until the head losses in the studied loop tended to zero but the number of iterations in the numerical calculations equalled 480 iterations.

Table 2
Theoretical and numerical flow rates at different loci of network

Outlet no/Flow rate	Theoretical (Kg/s)	Numerical (Kg/s)
1	0.1718	0.16182
2	0.1365	0.12084
3	0.0919	0.07143
4	0.0510	0.04405
5	0.0398	0.03052
6	0.3779	0.48447
7	0.1718	0.16182
8	0.1365	0.12084
9	0.0919	0.07143
10	0.0510	0.04405
11	0.0398	0.03052

5. Experimental Error and Uncertainty Analysis

The precision of the recorded experimental results must be investigated to be confirmed. The measuring devices must be calibrated primarily then their uncertainty can be estimated depending on their accuracy and dependent errors. The uncertainty analysis can be calculated and depends on the error of direct measured data.

$$U_P = \sqrt{\left(\frac{\partial P}{\partial x} \times U_x\right)^2 + \left(\frac{\partial P}{\partial y} \times U_y\right)^2} \tag{1}$$

where UP is the uncertainty of the studied parameter (P) which depends on the variable parameters (x, y) and the errors of these variables (Ux, Uy). Kline *et al.,* [44] showed that the experimental measuring data had certain error range depending on the accuracy of the measuring device. The measured data were water pressure, water flow rate, and response time of the solenoid valve. The accuracies for used devices are listed in Table 3, according to the manufacturer.

Table 3
Uncertainty for all measuring devices

Device	Model	Accuracy	Range	Error
Flowmeter Sensor	Sea: YF-S201	± 0.1 L/min	1 - 30 L/min	1.8 %
Pressure Sensor	Flying Elephant:SE0006	± 0.01 MPa	0 - 1.2 Mpa	1.5%
Solenoid Valve	Adafruit: ADA997	Response time (open): ≤ 0.15 sec Response time (close): ≤ 0.3 sec	Pressure: 0.02-0.8 Mpa Temperature: 1-100 oC Voltage: 6-12VDC	2%
Calibrated flask	-	$\pm$ 20 ml	0 – 5000 ml	4 %

6. Results and Discussions

Firstly, the numerical results should be validated by experimental results at different leakage flow rates of different nodes, in the case of leakage in main pipeline of the network. Secondly, the numerical results of the network performance and flow velocity vectors at all nodes under different leakage positions (sub-main and main) and flow rates were investigated. Finally, the performances of the solenoid valve and its time step response were investigated.

Figure 10 shows the experimental and numerical pressure results at nodes 16 to 20 of the distribution network in the case of leakage at outlet 15 located in the main pipeline. The pressures at nodes 16 to 20 were recorded numerically and measured experimentally at different leakage flow rates at outlet 15. Experimental and numerical results showed that the pressure values from nodes 16 to 20 decreased due to the leakage flow rate increase. The difference in pressure values between the experimental and the numerical had different ranges, depending on the nodes' positions. Node 18 was the highest affected pressure node; at this node the difference between the numerical and experimental results ranged from 13% to 21%. Node 18 location was in the nearest pipeline, parallel to the main pipeline which contained the leakage outlet. Nodes 16, 17, 19, and 20 showed little differences between the experimental pressure results and numerical pressure results.

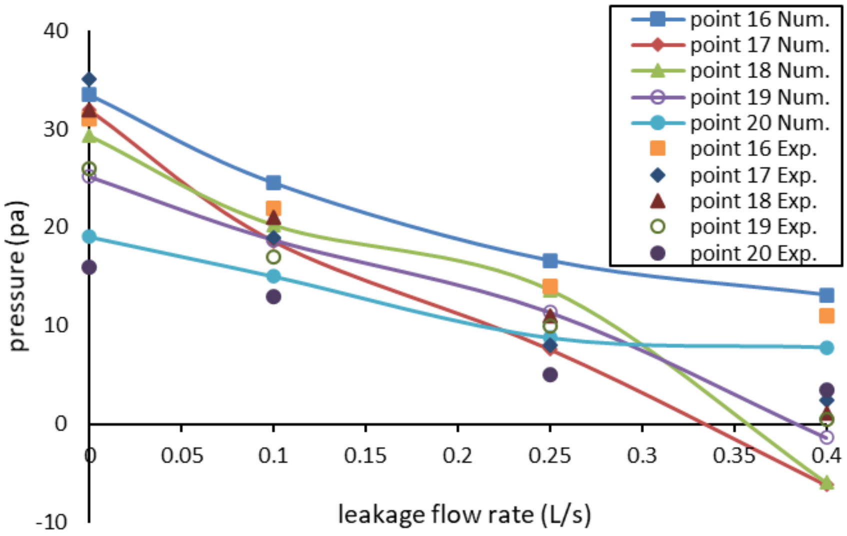


Fig. 10. Validation for the numerical code with experimental work for the pressure at nodes (16-20) versus outlet 15 leakage flow rate variations

Figure 11 shows the experimental and numerical pressure results at nodes 11 to 15 of the distribution network in the case of leakage at outlet 15 in the main pipeline. The pressures at nodes 11 to 15 which were located along the main pipeline of the distribution network were recorded numerically and measured experimentally at different leakage flow rates at outlet 15. Node 13 was the highest pressure-drop affected node due to the leakage flow rate variations at the main pipeline of the distribution network. Also, at this node the difference between the numerical and experimental results ranged from 9% to 25%. Node 13 location was aligned with outlet leakage 15 and was the nearest node to this outlet.

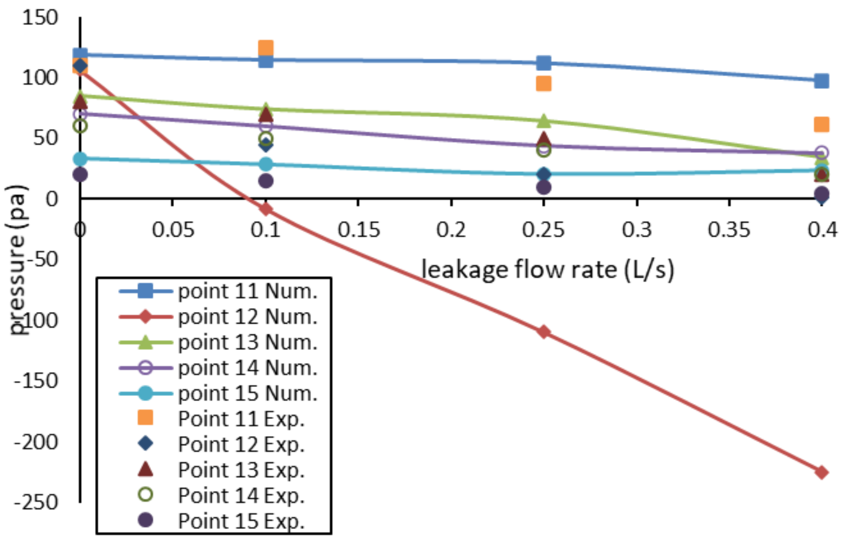


Fig. 11. Validation for the numerical code with experimental work for the pressure at nodes (11-15) versus outlet 15 leakage flow rate variations

6.1 CFD Simulation due to Leakage at Sub-Main Pipeline

Outlet 14 of the leakage outlets was located at the sub-main pipeline of the water distribution network which was perpendicular to the main pipeline and between nodes 20 and 25. The leakage flow rate at outlet 14 could be varied to study its response on the network behaviour by measuring the pressure at different network nodes. These leakage flow rate variations enabled us to draw a map of pressure variations in the network to locate the most affected regions and record the different network effects with this leakage position.

Figure 12 shows the pressure variation at nodes 21 to 25 with leakage flow rate variation at leakage outlet 14. As the leakage flow rate at outlet 14 increased, the pressure at node 25 was extremely influenced and decreased sharply, especially at high leakage flow rate; because this node located at the start or the end (according to the flow directions) of the corresponding sub-main contained the leakage outlet. Nodes 21, 22, 23 and 24 had little pressure variation effect with leakage flow rate variation at leakage outlet 14. Pressure at node 25 was highly affected due to the fact that this was the corner node of the closed loop that contained the leakage location.

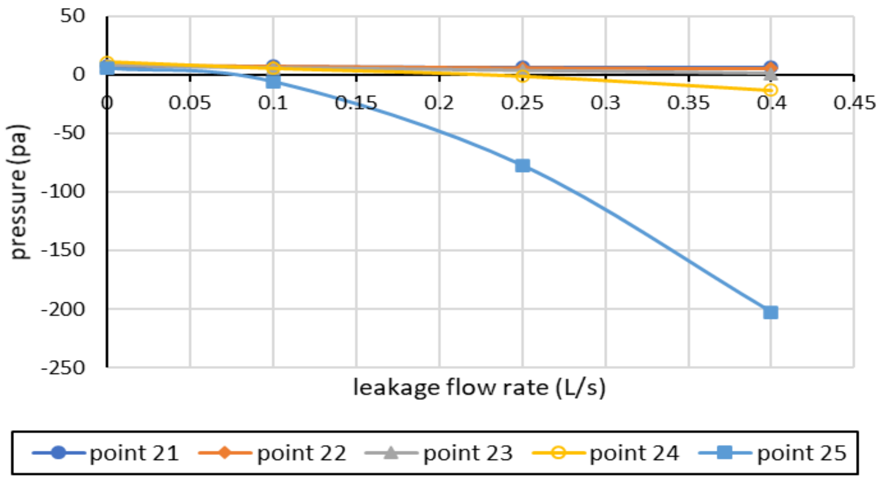


Fig. 12. Pressure at nodes (21-25) versus outlet 14 leakage flow rate variations

Figure 13 shows the pressure variation at nodes 16 to 20 with leakage flow rate variation at leakage outlet 14. As the leakage flow rate at outlet 14 increased the pressure at node 20 decreased sharply, especially at high leakage flow rate because this node was the other end (with node 25) of the sub-main pipeline containing the leakage outlet. Nodes 16, 17, 18, and 19 had little pressure variation effect with leakage flow rate variation at leakage outlet 14.

Figure 14 shows the pressure variation at nodes 11 to 15 with leakage flow rate variation at outlet 14. The nodes 11 to 15 were located at the main pipeline of the distribution network. As the leakage flow rate at leakage outlet 14 increased the pressure at nodes 11 and 12 remained nearly constant. The pressure at nodes 13, 14, and 15 decreased with same trend as the leakage flow rate increased. So, the leakage flow rate variation at outlet leak point in the sub-main pipeline had an apparent effect on the pressure in the main pipeline, especially at nodes located at the end of the main pipeline.

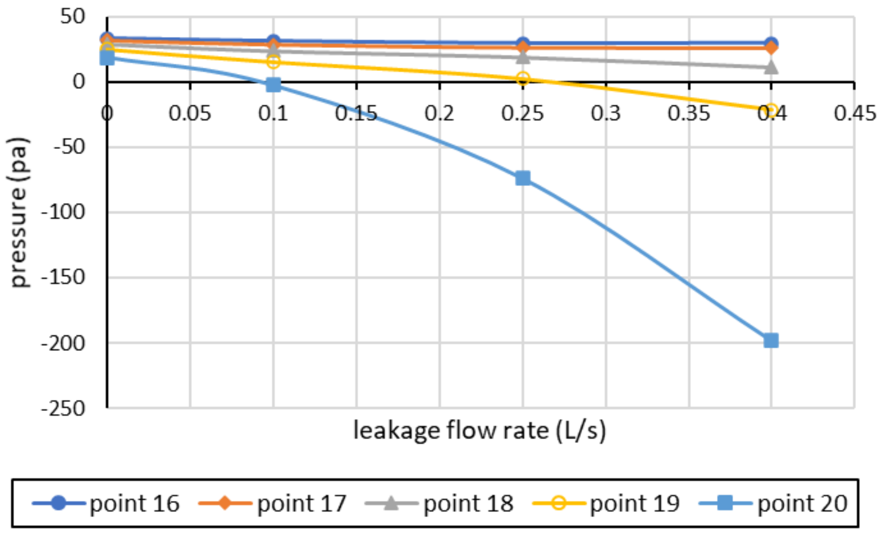


Fig. 13. Pressure at nodes (16-20) versus outlet 14 leakage flow rate variations

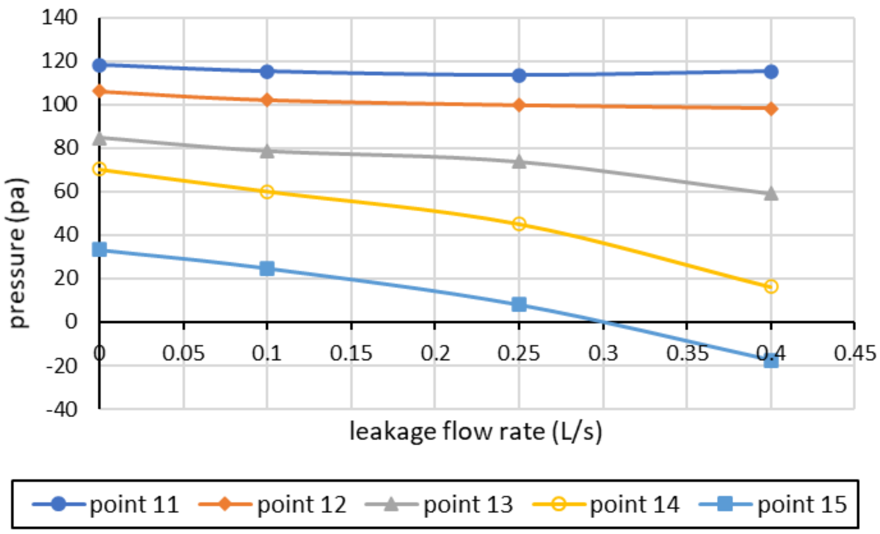


Fig. 14. Pressure at nodes (11-15) versus outlet 14 leakage flow rate variations

Figure 15 is the histogram of the pressure variations at all water distribution network nodes as a result of leakage flow rate variations at designed leakage outlet 14 at the external sub-main of the distribution network. From the analysis of the pressure variations, the effect was observable in all the nodes at alignment with the corresponding sub-main pipeline containing the leakage outlet 14. The effect decreased in nodes located in the line parallel to the corresponding sub-main pipeline; as the distance from sub-main pipeline increased the leakage effect decreased. Also, the effect was noticeable at nodes located at the apex in the closed loops that contain the designed leakage outlet 14.

These figures indicate that each node had been affected by different performance outcome, according to the leakage position and the leakage flow rate. The negative pressure at nodes 20 and 25 indicated that the pressure values at these nodes were vacuum pressures and the air bubbles were formed at these nodes which influenced the streaming of the flow results in the decreasing of the flow area. Also, the negative pressure caused back flow and flow separation at these nodes as a leakage which was apparent in the velocity vector contours.

Figure 16 shows the velocity vectors at different nodes of the distribution network in the case of the leakage at outlet 14 in the external sub-main pipeline of the network. The studied pipeline alignment was in x-axis direction which was perpendicular to the main pipeline. The maximum flow rate in laboratory distribution network was 0.4 L/s. Figure 16 (a) and (b) illustrate the velocity vectors of the fluid flow at nodes 20 and 25. Nodes 20 and 25 were the extreme nodes of the chosen sub-main pipeline of the network containing the leakage outlet 14. Figure 16 (a) and (b) show that the flow direction in this pipeline was directed from nodes 20 and 25 to the leakage outlet 14 due to the sudden drop in pressure value that resulted at leakage outlet. Also, this pipeline fed another loop by water in negative x-axis direction through node 20 but due to leakage the flow was reversed in opposite direction (positive x-axis) which caused trouble-shooting at this loop. So, in this case, two solenoid valves were initiated to close the pipeline discharges from flowing to the leakage location. Figure 16 (d) shows the velocity vector at node 19. At this node 19 the flow separation and vorticity appeared specially at sharp edges which was considered of a considerable leakage value. Figure 16 (c) shows the velocity vector at node 14 in the main pipeline. Node 14 velocity vector demonstrated that the maximum flow at this pipeline and the flow direction in negative Z-axis direction. Also, the vorticity, circulation, and separation occurred at nodes aligned with the main pipeline [45].

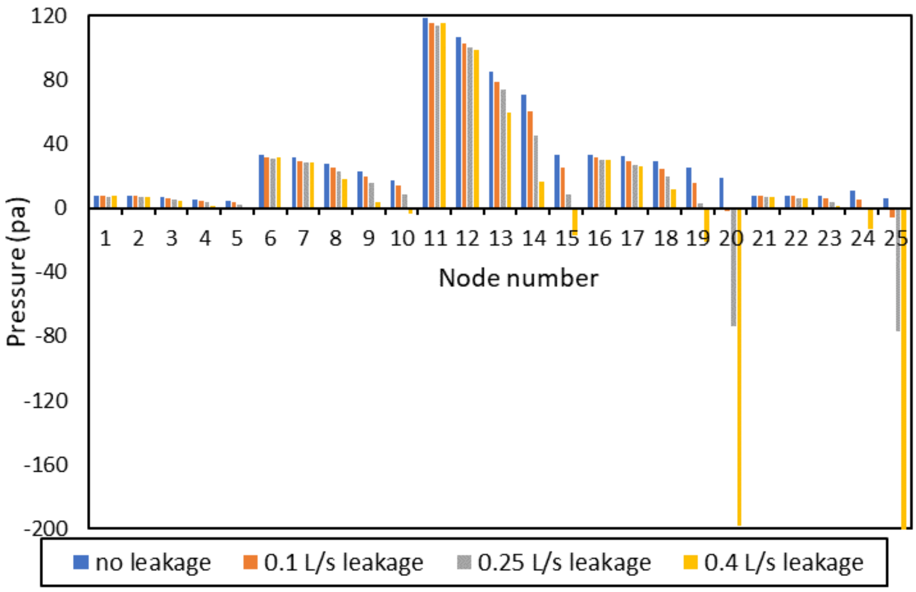


Fig. 15. Histogram of pressure variations at all network nodes due to leakage flow rate variations at outlet 14

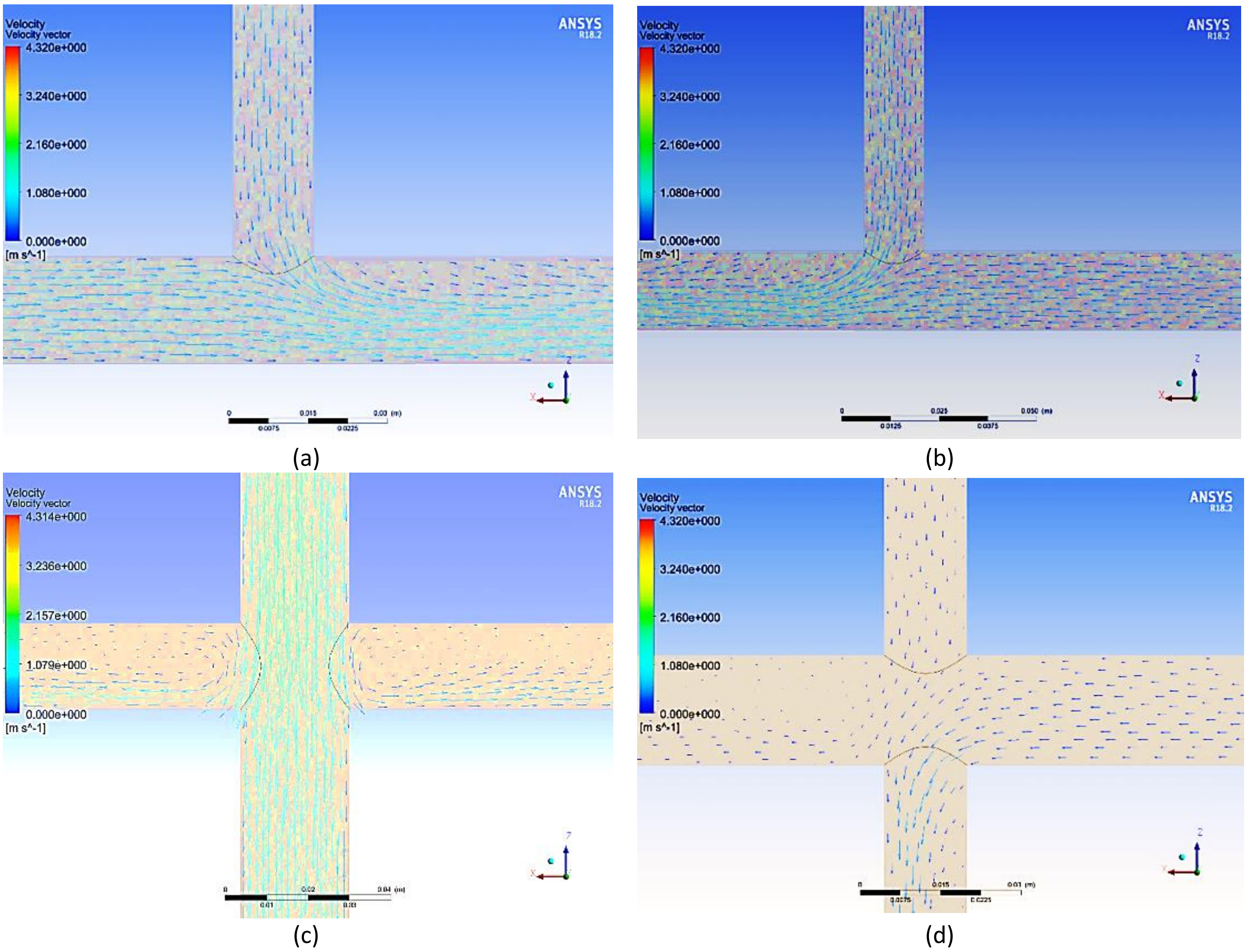


Fig. 16. Velocity vectors on different nodes with leakage flow rate 0.4L/s at outlet 14 (a) Node 20 (b) Node 25 (c) Node 14 and (d) Node 19

6.2 CFD Simulation of Leakage at Main Pipeline

Leakage outlet 15was located in the leakage design framework at the main pipeline of the water distribution network between nodes 12 and 13. This case was significant because the leakage in the main pipeline caused noticeable change in the network behaviour and influenced water consumptions everywhere in the network. These leakage flow rate variations enabled us to draw a map of pressure variations in the network at different conditions to locate the most affected regions.

Figure 17 shows the pressure variation at nodes 21 to 25 with leakage flow rate variation at leakage outlet 15. Outlet 15 was located at the main pipeline between nodes 12 and 13. As the leakage flow rate at leakage outlet 15 increased the pressure at nodes 22, 23, and 24 decreased to low values but at high leakage flow rate; the slope of the pressure variation of node 23 was higher than other two nodes 22 and 24. The pressure variations curved at nodes 21 and 25 with outlet 15 leakage flow rate variations having small variations.

Figure 18 shows the pressure variation at nodes 16 to 20 with leakage flow rate variation at leakage outlet 15. As the leakage flow rate at outlet 15 increased the pressure at nodes 17, 18, and 19 decreased to low values with different trends. At low leakage flow rate, point 17 had a greater slope and its pressure decreased sharply with leakage flow rate variation. At high leakage flow rate, node 18 had a greater slope and its pressure sharply decreased as leakage flow rate increased. The pressure values at nodes 16 and 20 due to leakage flow rate variations at outlet 15 had little variations.

Figure 19 shows the pressure variation at nodes 11 to 15 with leakage flow rate variation at leakage outlet 15. The nodes 11 to 15 were located at the main pipeline. As the leakage flow rate at outlet 15 increased the pressure at node 12 decreased sharply to low values. The pressure variations at nodes 11, 13, 14, and 15 with leakage outlet 15 flow rate variations had little variations.

Figure 20 the histogram shows the pressure variations at all nodes as a result of leakage flow rate variations at designed leakage outlet 15. The leakage effect was obvious in all extreme nodes of the branches parallel to the part of main pipeline containing the leakage outlet 15. The effect was noticeable at corner nodes of the two loops that contained the designed leakage outlet 15 in a pipeline considered as a common pipe between these loops due to leakage.

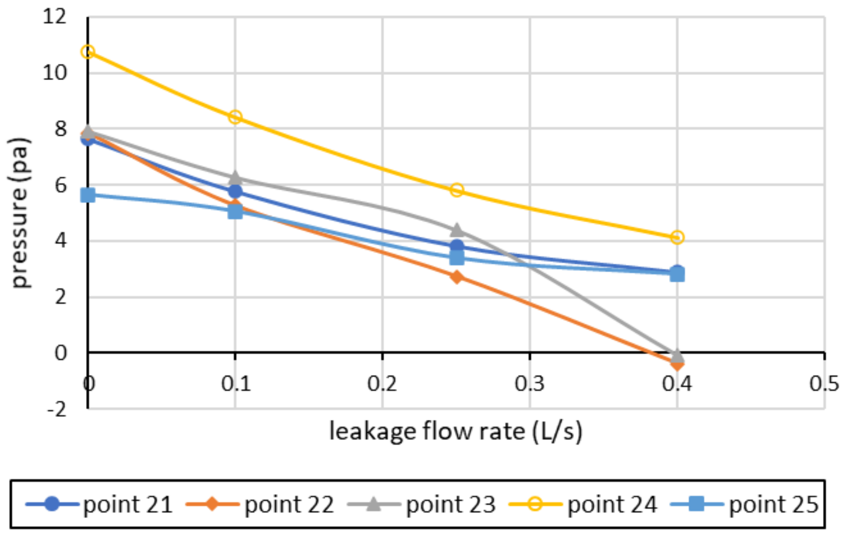


Fig. 17. Pressure at nodes (21-25) versus outlet 15 leakage flow rate variations

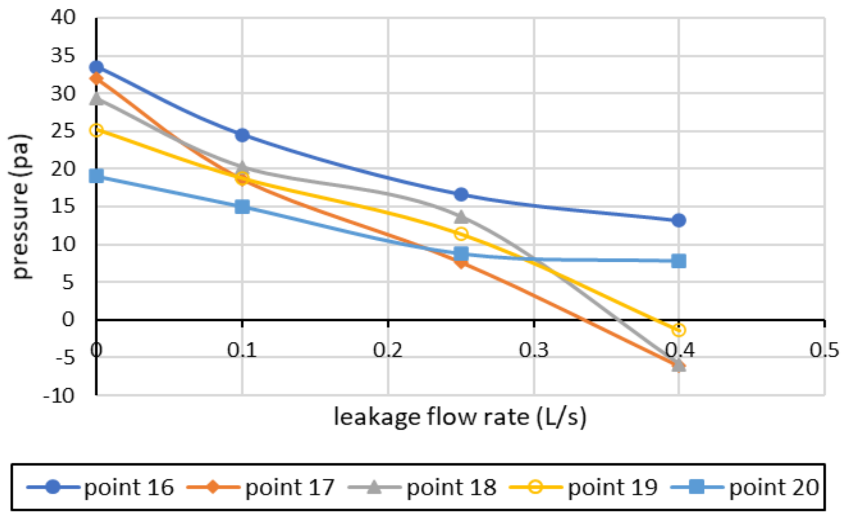


Fig. 18. Pressure at nodes (16-20) versus outlet 15 leakage flow rate variations

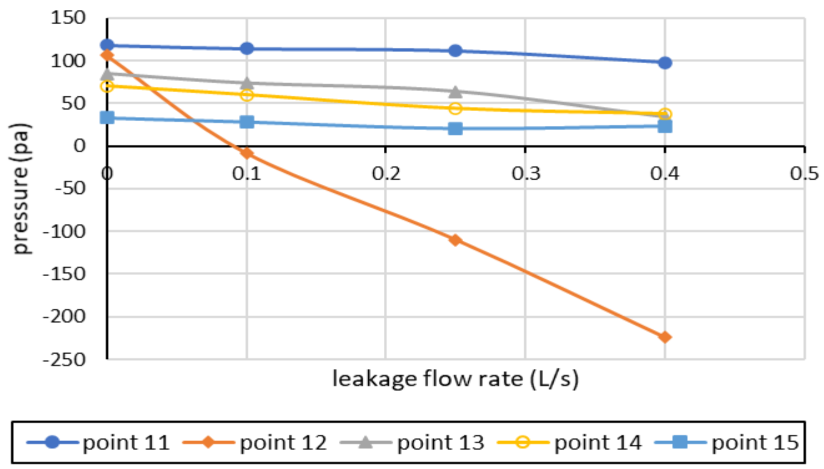


Fig. 19. Pressure at nodes (11-15) versus outlet 15 leakage flow rate variations

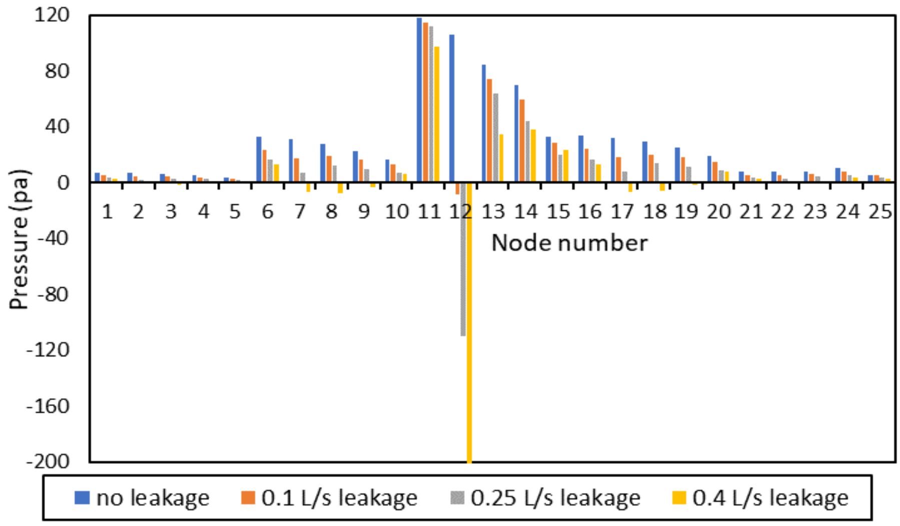


Fig. 20. Histogram of pressure variations at all network nodes due to leakage flow rate variations at outlet 15

Figure 21 shows the velocity vectors at different nodes of the distribution network in case of leakage at outlet 15 in the main pipeline of the network. Figure 21 (c) and (d) illustrate the velocity vectors of the fluid flow at nodes 12 and 13. Nodes 12 and 13 were the extreme nodes of the main pipeline of the network containing the leakage outlet 15. Figure 21 (c) and (d) show that the flow direction in this main pipeline was unidirectional from node 12 to node 13 so that the pressure drop due to leakage in this main pipeline had no effect on the flow direction. So, in modification of the distribution network to save water from leakage one solenoid valve was fixed before the leakage point on the main pipeline and was used to block the direction to the leakage location. Figure 21 (a) and (b) show the velocity vector at node 17 and 7 in the closest pipeline parallel to the main pipeline containing the leakage. Also, the flow was directed to these nodes to circulate in the loops and finally lead to the leakage outlet. As a result, this was considered the lowest pressure in the network. At these nodes 7 and 17 the flow separation and vorticity appeared specially at sharp edges as a distribution node which were significant in the total leakage calculations and had symmetric flow configurations.

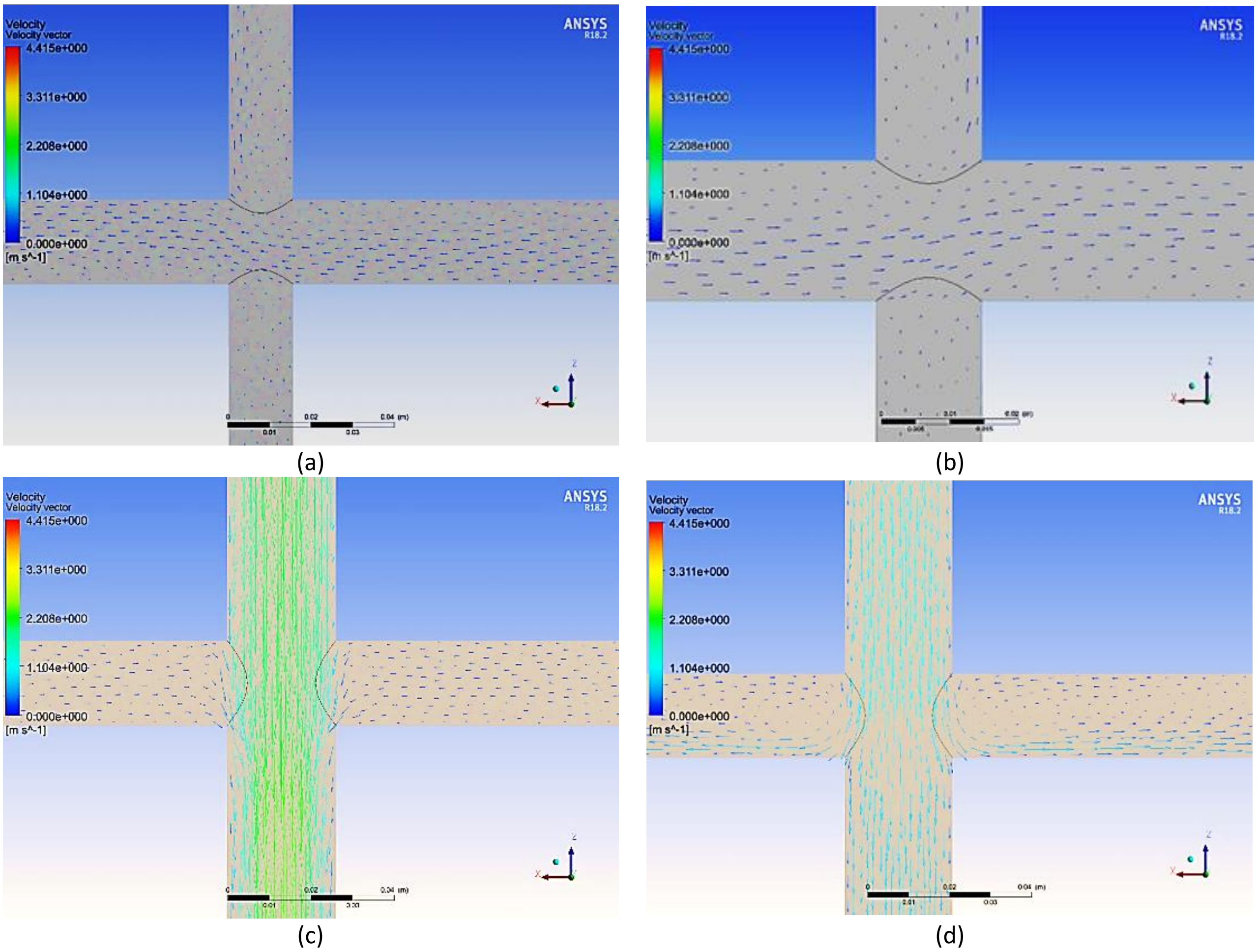


Fig. 21. Velocity vectors at different network nodes at leakage flow rate 0.4L/s at outlet 15 (a) Node 17 (b) Node 7 (c) Node 12 and (d) Node 13

7. Matlab Simulation of Solenoid Valve

Simulink is a program for simulating any system depending on the derived mathematical model of that system; like the integrated distribution network system or any component of the network as the solenoid valve. The solenoid valve was actuated by the control circuit due to leakage close the pipeline which directed the flow to the leakage position. The valve actuation response time was investigated due to this response time which was a major factor in total leakage calculation. The leakage flow would directly affect the pressure response characteristics of the solenoid valve [46].

Leakage during and after the solenoid valve closing reduced the efficiency and changed the performance of the water distribution network control. The leakage in the solenoid valve was mainly caused by the clearance between the plunger and the casing of the valve at the end of the valve operation, due to the delay of valve time response and the elongation of closing time [47].

The solenoid valve performance was investigated by deriving the mathematical model of the valve (non-linear differential equations). The deduced mathematical model was used to develop computer simulation programme for the studied valve by Matlab-Simulink. The mathematical model consists of continuity equation, flow rate equations, and equation of motion. The valve time response was studied under the effect of step pressure signal [47]. The continuity equation in the valve chamber can be represented as

$$Q_i - Q_o - A_f \frac{dx}{dt} - \frac{V+Ax}{B}\frac{dP}{dt} = 0 \tag{2}$$

The valve water inlet flow rate can be calculated as follow

$$Q_i = C_d A_i \sqrt{\frac{2}{\rho}\left(P_p - P_i\right)} \tag{3}$$

The valve water exit flow rate can be calculated as follow

$$Q_e = C_d A_e \sqrt{\frac{2}{\rho}(P_e - P_a)} \tag{4}$$

The moving parts can be moved under the action of pressure forces, magnetic force, spring force, inertia force, viscous force and limiting force.

$$P_i A_f - P_e A_b + F_m - F_L = m\frac{d^2x}{dt^2} + f\frac{dx}{dt} + k(x + x_o) \tag{5}$$

The moving part is limited mechanically by the valve body material and a counter reaction force is developed as

$$F_L = \begin{cases} |x|K_L + f_L \dfrac{dx}{dt} & x \le 0 \\ 0 & x > 0 \end{cases} \tag{6}$$

The magnetic force depends on magnetic field intensity and the magnetic resistance as

$$F_m = \frac{1}{2}\phi_{air}^2 \frac{1}{\mu_o A} \tag{7}$$

Figure 22 displays the pressure response of the water flow through the solenoid valve due to the step drop of pressure in the main pipeline as a result of leakage in this line. The simulation showed the step response of the solenoid valve integrated in the distribution network along the main pipeline as the flow pressure in the main pipeline step decreased from 1.8 bar to zero bar (gauge pressure). The solenoid valve in the main pipeline closed immediately the way of flow to the leakage outlet as the drop of pressure was recorded.

Figure 22 shows that the exit water pressure from the solenoid valve reached a steady state value equal to the leakage pressure. The response showed over damped high oscillation with a small steady state error about 2%. The steady state error indicated that the valve did not close completely and the leakage still remained but with small amounts. The results showed also the settling time of the valve as nearly 0.6 sec. This time was taken into consideration when calculating the total of the leaked amount of water.

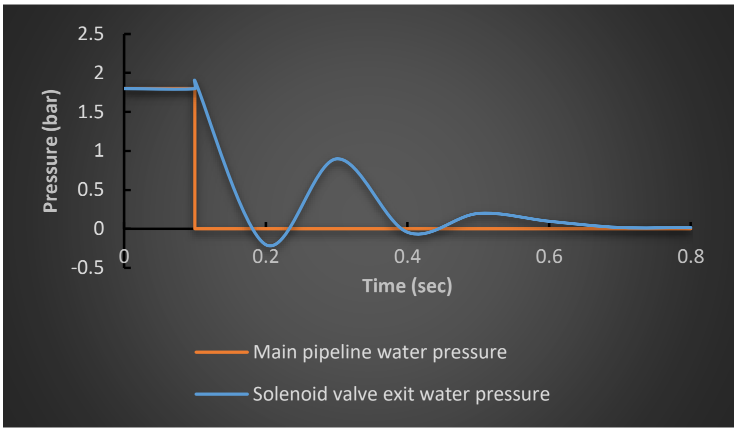


Fig. 22. Solenoid valve response to main pipeline water pressure step down variation

8. Conclusions

This paper proposes a new technique of investigation on the effects of water leakages on water distribution network performance. This experimental investigation was carried out theoretically and numerically. There is an agreement between the experimental and numerical results, with margins of error ranging from 9% to 25%, according to the distance and the path from the leakage outlet to the effected nodes. Theoretical calculations used the Hardy-Cross method with seven iterations. Numerical simulation used Ansys Fluent 18.2 which had the benefit of a good approach in this study with 480 iterations. The leakage flow rates had values 0.1, 0.25, and 0.4 L/s; and changed between the main and sub-main pipes. The research work was limited to small values of leakage flow rate due to the small dimensions of the laboratory network. The maximum pressure drop was 500pa at the node directly preceding the leakage outlet at the leakage flow rate 0.4 L/s of the main pipeline. The most affected nodes were those near to the leakage outlet. The leakage at the main pipeline in the water distribution network was considered the most critical leakage case. The flow direction was reversed and the flow separated in certain leakage cases. The pressure sensors sensed the pressure values and sent signals continually to the control circuit. The control circuit, according to the programmed control algorithm, gave orders to close the pipelines; directing the flow to the leakage outlet by solenoid valves. The cost, the solenoid valves, and pressure sensors fixation with linkage to the control circuit were considered the difficulties that could be encountered when applying this method to a real world situation. According to the nodes pressure drop and their positions, the accurate loci of leakage could be determined. The performance of the used solenoid valve was simulated using Matlab-Simulink technique. The simulation results showed the valve response to step down pressure control signal was over damped high oscillatory with a small steady state error of 2% and settling time 0.6 sec.

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