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Internet of Things Based Monitoring System of Leaks in Water Supply Networks Using Pressure-Based Model

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Abstract: Leaks in water distribution networks impose several impacts on economy, freshwater resources, water quality, health and safety. Fast leak detection and reparation is a key for lowering its negative impacts and associated costs with conventional detection techniques. This study has been used a pressure-based model to detect leaks events and its coordinates based on pressure and flow measurements. Pressure and flow data for systems that having leaks in their structure were analyzed and compared with data generated from non-leaking systems using EPANET software packages. An extension package of EPANET software (EpanetWaterGen) has been used as it has the advantage of its ability to better simulate leaks. The results show the ability of the model to detect leaks in a small and large water distribution networks with uncertainty level associated with low pressure change. The developed leak detection model utilizes pressure and flow sensors and enables the network managers and administrators to optimally place the sensors in a manner to increase efficiency and optimize cost. The system allows operators to detect leak location and volume of lost water, thus enabling a better and more efficient response to leaks, such that the network managers can address and respond to most urgent leaks and optimize the time end efforts of technical and maintenance personnel.

Keywords: Leak Detection, EPANET, Water Distribution Network, Pipeline.

1 Introduction

in many part of the world [1-3]. While only 2.5% of the total available water on the earth is freshwater, only a small part of this percentage is easily accessible since most of freshwater is stored as glacier or deep groundwater [4]. Many studies show that water utilities lose more than 60% of produced clean water before it reaches the customers and show the need for water utilities to integrate efficient water management system in order to reduce the amount of lost water during the supply period [5-7]. However, the amount of lost water depends on the maintenance and management of water distribution system and may vary significantly among systems [8]. Water loss in pipes has several impacts on i) economy where estimated economic damage due to water losses has been estimated to be approximately $14 billion/year with a 33% of it occurring in developing countries, ii) health and safety where contaminated substances can enter into the water distribution network through leaks [9-11], iii) quality of water reaching the customer due to the continuous aging of the distribution systems [12]. However, fast and accurate leak detection process is a key for lowering lost water in distribution systems to meet demands with low cost and minimum water resources extraction. Using the internet of things (IoT) to handle the sensor data from water distribution networks will accelerate detection processes and minimize any possible costs as IoT has been used in many water applications[13, 14].

Several attempts have been proposed for identifying and detecting leaks in water networks based on the analysis of acoustic and vibration signals on pipe lengths [15-17]. Analysis of pressure data obtained from pressure sensors distributed over a water network obtained from the EPANET hydraulic modeling system have also been performed to predict leak size and location with acceptable degree of uncertainty [18]. Many works have analyzed transient pressure records based on inverse transient analysis to detect leaks with an accuracy between 4-15% of the total length of the pipes [19]. The pressure data obtained during the occurrence of transitory event were analyzed and compared with the calculated parameters by means of the minimization difference. The difficulties associated with the non-linearity

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exists in water network models and few available measured parameters led to a high uncertainty in model-based leak detection and isolation techniques [20]. Pressure-based models and sensitivity analysis for leak detection have met several difficulties associated with nodal demand uncertainty, noise in measurements and water distribution network complexities [21]. There were many attempts to improve pressure-based models for leak detection by comparing several isolation methods, mass balance with measured flow and fuzzy analysis of the residual between measurement with and without leaks [22, 23]. A computer-based model has been used for detecting multiple leaks in difficult situation such as seismic damage by using pressure and flow data [24]. The model has improve the detection efficiency for multiple leaks in the field and verified using small scale water distribution network. The method has detecting leaks coordinates without the ability of a continuous monitoring during a regular distribution.
EPANET software package has been widely used in water network hydraulic modeling as it has a public domain and several studies have used EPANET to model water leakage [25-29]. The model simulates hydraulic calculations based on demand at each node where water flow and pressure are measured at each node [25]. The model does not have a specific tool for simulating leak in the water distribution systems but the emitter property of junction nodes can be used to simulate leaks [28]. However, EpanetWaterGen is an extension of the EPANET package for automatic water distribution network models generation, which has the advantage of its ability to better simulate leaks [28].

RESEARCH SIGNIFICANCE

Maintenance, rehabilitation and replacement of pipes in water supply systems is considered expansive for water service providers due to the involved items, and hence the infrastructure may continue to deteriorate. As in most cases speed and quality of pipes repair is needed during leaks events. There is a need for an efficient method for leak detection and determination in order to minimize repair cost and detection delay. In this paper we have presented a pressure-based model for leak determination in order to help water service providers to monitor water supply networks in a continuous base and alarm operators for any leak event during water supply.

2 Methodologies

Water leakage in a hydraulic system (q) has been presented in a pressure-driven model[25]:

$$\boldsymbol{q_i = \beta_i L_i P_i^{\alpha_i}} \qquad \textbf{(1)}$$

Where q_i is the leakage of pipe i, β_i is the leakage coefficient, $L_i$represents pipe length, P_i is the pressure in the pipe i, and α_i is the leakage exponent. However, a new algorithm has been developed to express leakage precisely and this algorithm is used in the simulation model of EPANET[31]. In order to represent leakage in a pipeline and water distribution network, EpanetWaterGen extension tool has been used. This extension has an ability to represent leakage without adding additional demand rather by adding a leak valve open to the atmosphere using[32]

$$Q_i = C_i P_i^{\,n} \qquad (2)$$

Where Q_i is the leakage discharge at node i, C_i is the emitter coefficient and $P_i$is the mean pressure of exponent n. C and n have been assumed to be 1 (valid for different materials) and 0.5 (the value valid for metallic pipes), respectively [25]. Hazen-William equation has been used as the default formula during the analysis in order to obtain head loss in metric units according to the formula:

$$\boldsymbol{h_f = \frac{10.65\ L\ Q^{1.85}}{C^{1.85}\ d^{4.87}}} \qquad (3)$$

Where h_f is the head loss, L is the pipe length, Q is the flow rate, C is the Hazen-William coefficient, and d is the pipe diameter. The input data used during the simulation were the pipe length and dimeter, roughness, total head and leakage exponent and coefficient.
Leak detection for a single pipeline with one leak has been analyzed using the energy equation. Pressure sensors were installed in the model and the obtained data were compared with a pipeline without leakage. We have assumed that head loss has only resulted from the friction and the pressure profile is linear along the pipeline. Mass balance equation has been used for leak detection within a water distribution network that having one leak[33]:

$$\boldsymbol{\sum_{p\in P_n} q_{n,p} = C_n^{rel},\ \ \forall_n \in N} \qquad (4)$$

Where P_n is the set of pipe connected to the node n, and $q_{n,p}$ is the flow rate of water into node from pipe P, and C_n^{rel} is the water demand at node n, and N the set of all nodes in the pipe network.
Smart meters were installed on each demand source to count consumption and the network has been divided into regions. Inflow and outflow waters have been recorded for each region in a daily basis and first alarm of leakage occurrence is identified where the total flow does not equal zero. Pressure based methodology has been used further in order to determine leakage spatially [34].

3 Discussions

3.1 Single Leak Detection for Pipelines Using Pressure Sensors

Detecting leak for single pipe with one leak has been analyzed using pressure sensor based on energy equation. The assumptions made during the experiments were based on a continuous records of pressure readings over time, head loss resulted only from friction, and the linearity of the pressure along the pipe. The first run was performed on a single pipe line and pressure sensors were distributed on equal intervals of 10 meters with no leaks assumption. The pressure and flow measurements are presented in Fig. 1 and Table 1.

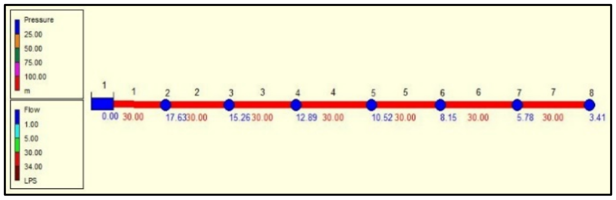

Fig. 1: Single pipe with pressure sensors (7 sensors) every 10m without leaks.

The flow values are presented in liter per second (LPS) metric, and the pressure head is presented in meter. The pressure decreased with increasing distance of sensors from the source mainly due to friction and the water flow remains constant.
Each Section has a length of 10m and is numbered from 1 to 7. Water velocity (***v***), head loss (h_L) and the friction factor (f_f) were constant through the pipeline.

Table 1: Physical and hydraulic parameters for a single pipe line of 100mm diameter and constant flow rate (f) of 30 LPS where no leak is exist.

	f (LPS)	*v* (m/s)	h_L (m/km)	f_f (-)
1	30	3.82	236.95	0.032
2	30	3.82	236.95	0.032
3	30	3.82	236.95	0.032
4	30	3.82	236.95	0.032
5	30	3.82	236.95	0.032
6	30	3.82	236.95	0.032
7	30	3.82	236.95	0.032

Pressure values varied when a single or multiple leaks occurred along the pipe line. A leak in the pipe has been identified based on the sudden drop in pressure and based on the gathered pressure data and location, the leak was accurately identified (Fig. 2 and Table 2). There was a significant flow change and noticeable change in the head loss after node 4 resulting from the changing in friction factor and velocity. We have noticed a drop in the pressure profile at the leak position (Node 5) at the moment when the leak occurred which should be considered as the first alarm for the leak The ability of the sensors to detect the leak when the leak occurs instantly is important to allow for immediate response and attempt to contain or repair the leak; this is immediately detected once the pressure change is observed.

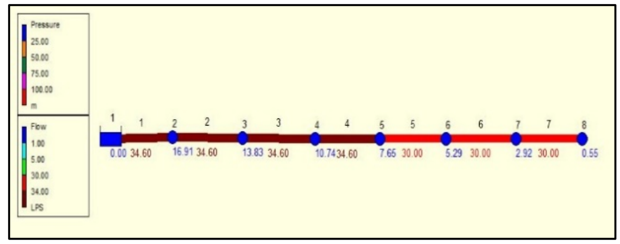

Fig. 2: Single pipe with pressure sensors (7 sensors) every 10m with one leak at node 5.

The flow values are presented in liter per second (LPS) and the pressure head is presented in meters. The pressure decreased with increasing distance of sensors from the source mainly due to friction and the flow remains constant. Table 2 presents data on the change in water velocity (***v***), head loss (h_L) and the friction factor (f_f) for a single pipe line of 100mm diameter after one leak is identified, where the flow rate (f) has started to change at node 5. Each Section has a length of 10m and sections were numbered from 1 to 7, as shown in Table 2.

Table 2: presents the values of v, h_L and f_f in the seven sections

	f (LPS)	***v*** **(m/s)**	h_L **(m/km)**	f_f **(-)**
1	34.6	4.41	308.64	0.031
2	34.6	4.41	308.64	0.031
3	34.6	4.41	308.64	0.031
4	34.6	4.41	308.64	0.031
5	30	3.82	236.95	0.032
6	30	3.82	236.95	0.032
7	29	3.82	236.95	0.032

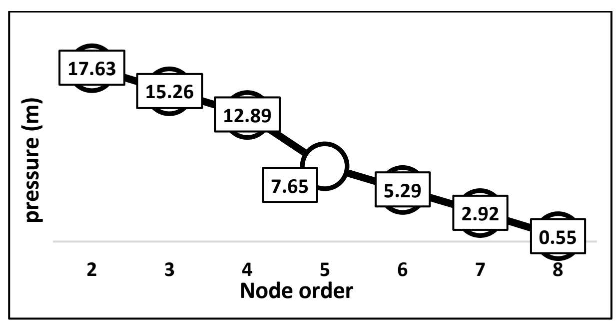

Fig 3: Instant reading for the pressure variation at moment of leak occurrence**.**

Actual leak events were verified after the first alarm by analyzing pressure data set obtained from the distributed pressure sensors over the network. The data are compared with pressure reference records of the network over a sufficient period of time Fig. 4 and 5.

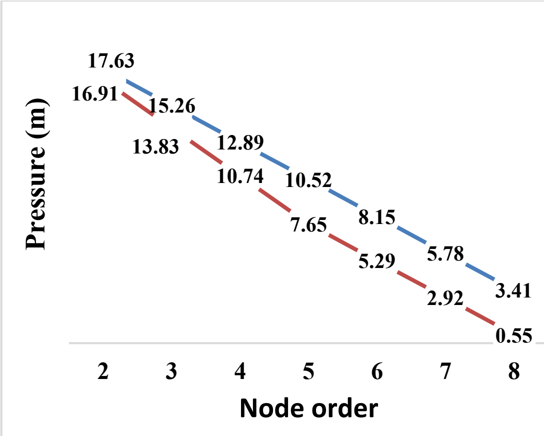

Fig. 4: Pressure change along the pipe line with leak (in red) and without leak (in blue).

The approximate change in pressure was 28% in comparison with the reference pressure records denoted that a substantial leak has occurred. Due to the change in pressure caused by friction, pressure change caused by leak event has been identified for percentages exceeding 20%. This value represents the maximum percentage of pressure change that can occur without leak event. The recommended action after the sudden drop in pressure records is to isolate the leak section in the pipes or loop in the water network for further pressure monitoring to avoid unrealistic leak detection activity.

3.2 Detection of A Single Leak in Awater Network

The water distribution network has been designed without leak and pressure, water inflow and outflow at each node has been recorded (Fig. 5). Leak detection for water distribution network has been temporally identified at mass unbalance event, where the total flow in each water network division does not equal zero. The base line records of flow measurements are obtained by installing smart flow sensors on each demand source or loop and inflow and out flow water are recorded and compared with data after leak event as shown in Figure 6.

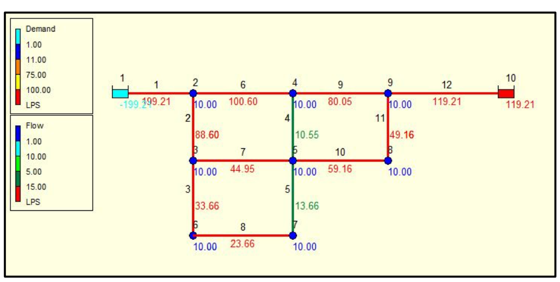

Fig. 5: Water distribution network with no leaks and 8 demand sources.

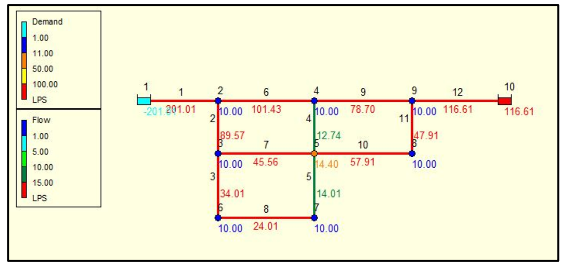

Fig. 6: Water distribution network with one leak and 8 demand sources (leak on node).

The results confirmed that there was a loss in this network equals to 4.4 LPS which can be detected once it occurs (Fig. 6, Table 3).

Dividing large water distribution network into regions minimizes the flow sensors installation for cost control purposes and spatial determination of leaks can be performed by analyzing pressure data from installed pressure meters in each pipeline. A realtime data analysis tool can record any leak event using mass balance approach and pressure drop algorithm.

Table 3: Supply and consumption for the network.

Demand	**No leak in the network**	**With one leak in the network**
2	10	10
3	10	10
4	10	10
5	10	10
6	10	10
7	10	10
8	10	10
9	10	10
Q_{out}	119.21	116.61
Q_{in}	199.21	201.01
Total	0	-4.4

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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