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Application of nodal pressure measurements in leak detection

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ABSTRACT

Leaks are inevitable phenomena that are present in all water distribution systems (WDSs). The locations of leaks are determined through various methods, such as physical inspection of pipes, acoustic listening devices, and hydraulic network equations. Leak can be located by measuring the nodal pressure in a pipe, which is more effective and less expensive than measuring the amount of discharged water. These locating techniques focus on the direct relationship between leak and pressure. This study aims to devise a new method for locating a single leak in an entire WDS pipe line. The exact location of the leak is identified by analyzing the differences in the pressure of the pipes. In the proposed model, the leak refers to the beginning and end nodes of the pipe. The minimum number of pressure measurements to form a relative leak index is two. However, in this case two nodal pressure measurements is too few and the number of pressure measurement should be increased. Therefore the next option for the number of measurements is three. Although the real leaky pipe is in the list, it cannot identify the actual leaky pipe from two pseudo leaky pipes. So, the number of pressure measurements is increased to four. In a network with a moderate size, in least four nodal pressure measurements are required to detect the leak location.

1. Introduction

Leak reduction is a complex problem that requires investigation of different areas of a water distribution system (WDS). Leak control has become a top priority for water utilities because of the economic and environmental costs associated with water loss. Leaks cause substantial economic damage to the WDS because they typically result in massive water loss [1]. The physical defects in the pipeline network may also affect the quality of water [2] or may even cause serious environmental pollution [3]. The costly expansion of the WDS may be avoided or delayed by controlling and reducing the volume of leaks [2]. Therefore, the exact location of the leak in the entire WDSs must be determined as quickly as possible.

New technologies and methods have been developed to determine the exact locations of leaks and reduce the water loss significantly [4]. However, none of these innovations has been successful in identifying the exact leak location. Most techniques can locate leaks only in a limited area of the system, depend on network parameters that are often used for initial estimations, rely on the difference between the calculated and measured pressure in the leak flow [5], and may require a part of the WDS to be isolated or even shut down. Several models have been developed to incorporate pressure-driven demand analysis into the evaluation of network reliability. Todini and Pilati [6] described the pressure-driven simulation of a network using the following system of equations based on energy and mass balance conservation.

Inverse transient analysis has been adopted to calibrate the WDS [7]. This method estimates unknown parameters by examining the transient pressure data and minimizes the difference between the observed and calculated variables through an optimization model [8].

Walski et al. [9] used a genetic algorithm to calibrate the pipe roughness and joint demand. Wu and Sage [10] identified the sensitive points and potential leak locations in the pipe network by adopting a genetic algorithm and free data.

Nasirian et al. [11] have reported a successful usage of Genetic Algorithm (GA) with a combination of the Step by Step Elimination Method (SSEM) to find the leaky node. They have reported that there is no guaranty to find the leaky node even if the fitness parameter takes pretty low values. In their research, leak detection has been carried out in two artificial and one experimental networks. At first the networks are analyzed by the GA optimization method to make the nodal pressures as close as possible to the measured ones in some selected nodes. Through this analysis, it is revealed that the demand of some nodes will be remained unchanged so in the next stage of analysis they will be omitted from

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Nomenclature

H_i	head of node i without the presence of leak
H_i^k	head of node i with the presence of leak in node k
ΔH_i^k	head difference of node i due to leak in node k $(=H_i-H_i^k)$
$\Delta H_{\max}^k$	maximum head with the presence of leak in node k
LI_i^k	leak index for node i when the leak occurs in node k
$LI_{i/j}^k$	relative leak index which is equal to the ratio of leak index in i to j when the leak occurs in node k
Q_r^l	magnitude of real leak discharge
Q_s^l	magnitude of simulated leak discharge.

the list of potentially available nodes as the leaky ones. Repeating this procedure, more nodes will be omitted through different stages until the real leaky node will be identified.

This study aims to detect leak in pipes that may or may not have leak by examining the differences in their nodal pressures. The leak is assumed to be in the middle of a pipe and can be detected only by measuring a few pressure nodes.

2. Leak index

In the monitoring of a WDS two conventional quantities are frequently measured. They are namely nodal pressure heads and pipe flow rates. In the developed methodology only pressure measurements are required to detect and locate leaks in a WDS. On the contrary to other methods, this method, which does not require flow measurements, is based on the parameter of the “leak index” which will be introduced afterwards.

In order to understand the leak effect on the pressure variations of a WDS two kinds of analysis namely with and without the presence of a leak should be performed. Although leak may occur either in a pipeline or in a node, in the current paper it is assumed that the leak takes place in the middle of a pipe. Due to leak out of a node, there will be a pressure decrease in each node. For example, the pressure difference between two cases of no leak and leaky conditions can be calculated as the followings:

$$\Delta H_i^k = H_i - H_i^k \tag{1}$$

where ΔH_i^k is the head difference of node $i$due to leak in node k. Then the leak index LI_i^k is defined in a non-dimensionalized form by the following equation:

$$LI_i^k = \frac{\Delta H_i^k}{\Delta H_{\max}^k} \tag{2}$$

in which $\Delta H_{\max}^k$ is the maximum head difference among the whole nodes or pipes of the network which most likely occur in the leaky node or pipe. This index shows an important characteristic of the WDS. The leak index has its maximum value in the leaky node in most of the cases. When nodal pressure measurement is carried out in a certain node, the numerator of Eq. (2) can be calculated. To normalize the variation of pressure changes in two cases of no leak and leaky conditions, it is required to know the exact location of the leak as it appears in the denominator of Eq. (2). As a matter of fact, it is impossible to measure this value, because the location of the leak is unknown and the pressure reading in other nodes of the network will lead to no useful information. However, to get rid of denominator, a relative leak index $LI_{i/j}^k$ is introduced, which is actually equal to the ratio of leak index in i to j when the leak occurs in node k. It has the following formulation:

$$LI_{i/j}^k = \frac{\Delta H_i^k/\Delta H_{\max}^k}{\Delta H_j^k/\Delta H_{\max}^k} \tag{3}$$

Or it can be expressed in terms of leak indexes of nodes i and $j$as:

$$LI_{i/j}^k = \frac{LI_i^k}{LI_j^k} \tag{4}$$

The advantage of this equation is that the numerator and denominator are pressure decrease in nodes i and j, respectively, due to a common leak in an unknown node k where we are actually looking for. It should be noted that the relative leak indexes are defined for two cases of real and simulated leaks. For the case of real leak which is assumed to occur in the middle of an unknown pipe where we are actually looking for, the relative real leak index for any two nodal pressure measurements can be obtained by the use of Eq. (4), which is shown by $(LI_{i/j}^k)_r$ where k is the number of leaky pipe. In the current paper k is equal to 35. On the other hand, the simulated leak based on a number of discharges for the whole pipes of the network, should be analyzed. The relative simulated leak index for the same nodal pressure measurements can be obtained for each pipe which is shown by $(LI_{i/j}^{k'})_s$ where k' is the number of simulated leaky pipe which is assigned to each pipe of the network once at a time. The real leaky pipe will be definitely among the simulated leaky pipes.

3. Selected network

The proposed method in the current paper can be applied to WDSs and/or transmission systems. In other words, any form of arrangement in pipes, in term of the numbers, forms and sizes can be analyzed to determine the leak location. Additionally, the current method can be applied to a WDS with a few numbers of leaks. The type of WDS is not considered as a limitation for application of the proposed methodology. Previous investigation has shown the ability of the current methodology in analyzing a transmission line which was designed to collect the water from a number of irregularly distributed wells. The results are not shown in this paper.

The hypothetical rectangular network of Poulakis et al. [12] is used in this study (Fig. 1). This network comprises one reservoir, 50 pipe sections and 30 junction nodes. The diameter of the pipes varies between 300 mm and 600 mm. The horizontal and vertical pipes are 1000 m and 2000 m long, respectively. The piping roughness height has a nominal value of 0.26 mm for all pipes, and each junction node has a flow rate of 50 l/s.

4. Methodology

To examine the capability of the proposed methodology a hypothetical leak is considered in an arbitrary pipe. Then a number of nodes should be considered for the pressure measurements. Comparison of $(LI_{i/j}^k)_r$ and $(LI_{i/j}^{k'})_s$ can be used to identify the leaky pipe. In an ideal situation when $Q_r^l = Q_s^l$ for the leaky pipe, $(LI_{i/j}^k)_r = (LI_{i/j}^{k'})_s$.

A reasonable assumption for the magnitude of real leak is 1% of the total demand in the network. The hypothetical real magnitude of leak is random, not an integer value in term of l/s and unlikely equal to the simulated one. For the current case it is assumed that