Numerical Simulation for Water Loss Estimation in Water Supply Pipes: Discharge Estimation and Deformation Analysis

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Abstract. In recent decades, the changing scenario in the availability and the use of water has made the efficiency of water distribution systems (WDSs) management a topic of great importance, particularly in terms of leakage detection and control. The definition of the relationships, which relates the leak outflow and the relevant hydraulic parameters has received more and more increasing attention in literature. Here, the attention is mainly focused on the analysis of the behavior of different types of leak openings in pressurized pipes, taking into account the effect of rigid and deformable materials.

INTRODUCTION

Pipes in water distribution systems are susceptible to water leaks, that cannot be directly observed due to the pipes being buried. The existence of leaks is highly costly, not only in terms of water wastage but also due to increasing costs of pumping to balance inefficient energy distribution through the network [1,2]. Moreover, it is an environmental and potentially a health and safety issue in low pressure conditions, due to contamination by intrusion of unwanted physical, biological or chemical agents. For each leak, the pressure modification in the distribution network affects the rate of water loss through the leakage, as indicated by several studies.

Leakages depend on the burst area and shape, the pressure inside and outside the pipe as well as pipe material. Basically, the higher the pressure, the larger the leak flow and vice versa. In leakage control techniques based on pressure reduction, the hydraulic model for leaks affects the reliability of the estimated cost-effectiveness of a system improvement, so the need for the definition of the relationship between leakage and functioning conditions in a damaged pipe, able to correctly capture the leak outflow for rigid and deformable pipes in different crack geometry conditions, is really felt [3, 7]. Various studies, focused on the definition of a physically meaningful hydraulic model for pressure dependent leaks in a main pipe, can be found in the literature. Despite the great efforts to find a unifying theory for leakages, the research field is still open and requires further numerical as well as experimental analysis to improve the state-of-the-art. In order to do this, the main objective of the proposed research is to investigate on the most conventional head-leakage law, through the comparison between numerical and laboratory experiments. The attention is focused of the head-discharge relationship and on the head-leak area variation.

NUMERICAL AND EXPERIMENTAL SETUP

Laboratory Experiments

The experiments were conducted at the Environmental Hydraulic Laboratory of the University of Enna Kore (Italy), where a small water distribution network is located. The WDN is composed of three main loops (M=3) of high-density polyethylene (HDPE 100 PN16) pipes (nine internal nodes, N=9, one external node, S=1, and thirteen pipes, L=13) having nominal diameter (DN) of 63 mm; each pipe is about 45 m long. For a detailed description of facility see De Marchis & Milici. (2019) and De Marchis et al. 2016. In Fig. 1 is reported a schematic representation of the WDN, where it can be observed that the network is equipped with pressure transducers, multi-jet water meters and electromagnetic flow meter.

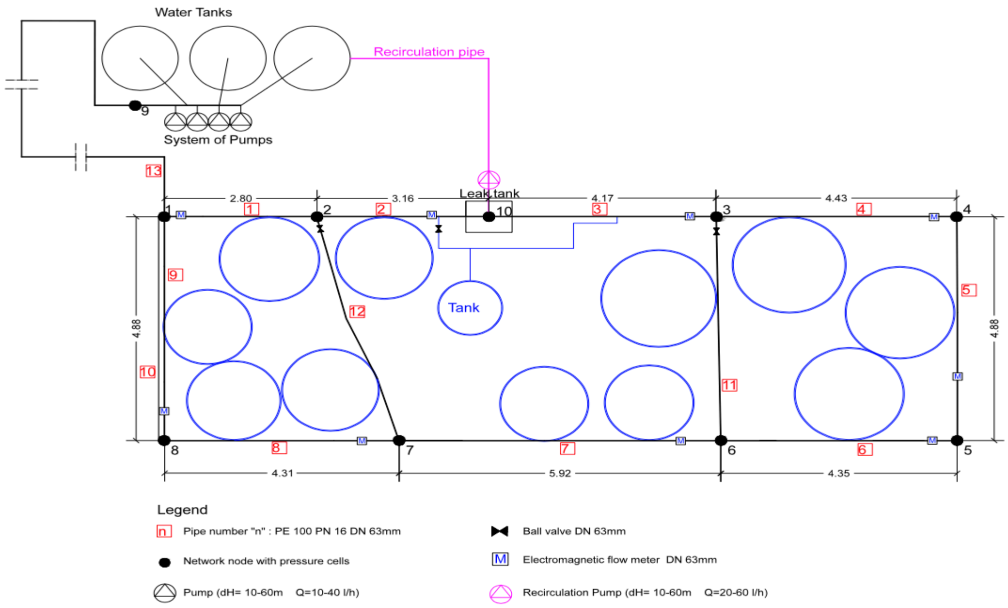

FIGURE 1. Layout of the experimental water distribution network

Numerical Experiments

To investigate on the head-area leakages and on the head-discharge relationships, the laboratory experiments were reproduced numerically by means of a commercial software Ansys, able to simulate both the fluid dynamics and the structural analysis. Basically, the flow field inside the pipe was simulated using the Fluent software module, whereas the deformation analysis was studied using the toolbox of Ansys known as Mechanical.

In Figure 2 is plotted a schematic representation of the computation domain. At the inlet section the mean velocity profile obtained by the experiments was imposed; at the outlet the pressure, achieved thanks to the experimental setup, was imposed; the leakages were simulated thanks to the hole located in the middle of the leak trunk and here the atmospheric pressure condition was used. In all the solid boundary of the pipe the classical wall law is enforced. The imposed condition is coherent with the chosen of the standard k-ε turbulence model used to perform RANS (Reynolds Averaged Navier-Stokes equations) simulations.

Leak Shape and Dimension

In order to investigate the relationship between the leak outflow and the water head as a function of the crack shape, several experiments were conducted considering cracks of different shape and size. Specifically, two set of cracks were investigated: circular and rectangular transversal cracks. In table 1 details about the leakages are reported. The two sets of experiments were designed with the aim to have different geometries maintaining almost the same leak area: for example, the test cases T1 with a rectangular burst of 1.5 x 10 mm, has an area A_0=0.007 equal to that considered in the test case C1 (circular track), having a diameter equal to D=4.35 mm. For each experimental test the head at the inlet node of the network was modified by means of the pump station from 1.0 to 5 bar, with a step of 0.2 bar, in order to have a detailed variation of the leak outflow as a function of the water head.

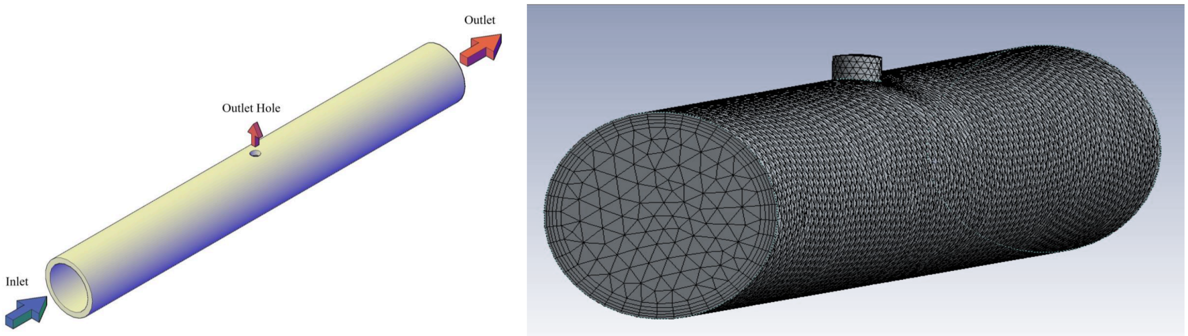

FIGURE 2. Layout of the computational domain and of the computational grid.

TEST CASE	SHAPE	LENGTH (D/L) [mm]	A_0 [mm^2]	A_0/A_P
T1	Rectangular	10	15	0.007
T2	Rectangular	20	30	0.014
T3	Rectangular	30	45	0.022
T4	Rectangular	40	60	0.029
T5	Rectangular	50	75	0.036
T6	Rectangular	60	90	0.043
C1	Circular	4.35	15	0.007
C2	Circular	6.16	30	0.014
C3	Circular	7.57	45	0.022
C4	Circular	8.74	60	0.029
C5	Circular	9.77	75	0.036
C6	Circular	10.7	90	0.043

TABLE 1. Details about the leak characteristics. Length represents the diameter for circular leaks, whereas represent the transverse dimension for the rectangular leak. For the rectangular shape the width of the leak is equal to 1.5 mm. A_0 is the leak area at the atmospheric pressure. A_P is the internal pipe diameter.

RESULTS

For each experiment, the instantaneous values of the pressure and discharge were averaged in time, thus to achieve a couple of values to be plotted in the plane Leak discharge vs Pressure. In his way, it is possible to build curves where the leakage of the flow rate is analyzed in light of the pressure, since data were collected at the same time. Fig. 3 shows the comparison between experimental and numerical results. As shown, the numerical simulations are in good agreement with the experimental results.

Based on the pressure distribution within the pipe, especially close to the holes, a structural analysis was performed aiming to investigate on the deformation of the leak hole. Substantially, the achieved results are coherent with the observation of Cassa et al. 2010, where longitudinal and circular cracks were analysed. The analyses of the deformations were carried out starting from the determination of the Von Mises stresses. In Fig. 4 are reported an example of deformation of the circular and rectangular hole.

The stresses analysis versus the pressure shows that the rectangular cracks are generally characterized by highest values of deformation than circular holes. Moreover, in circular shapes the stress concentrations increase in a roughly linear fashion with increasing hole size and pressure; on the other hands in rectangular leak shapes the linear trend is not observed and the stresses is affected by a spreading of the data. Further analyses are required to confirm the achieved results.

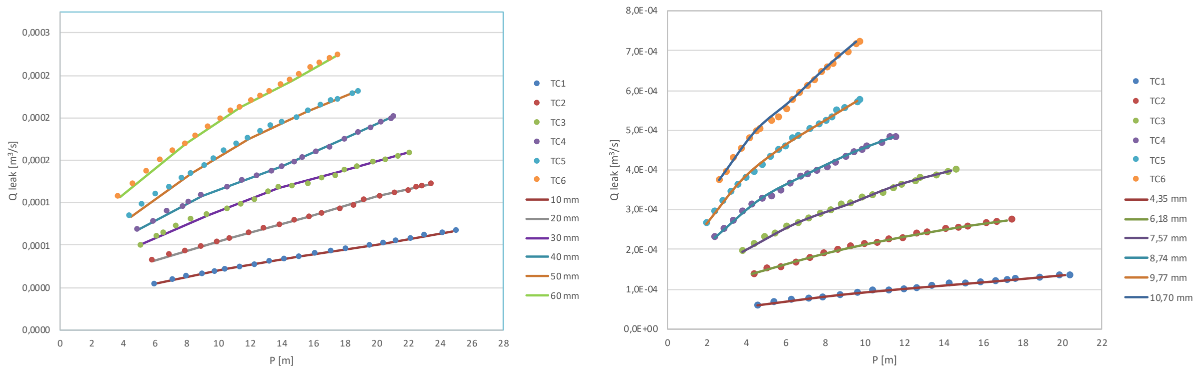

FIGURE 3. Comparison between Head-Discharge curves obtained with numerical and laboratory experiments. Line: Numerical results; symbols: laboratory results. Left panel: circular leaks; Right panel: rectangular leaks.

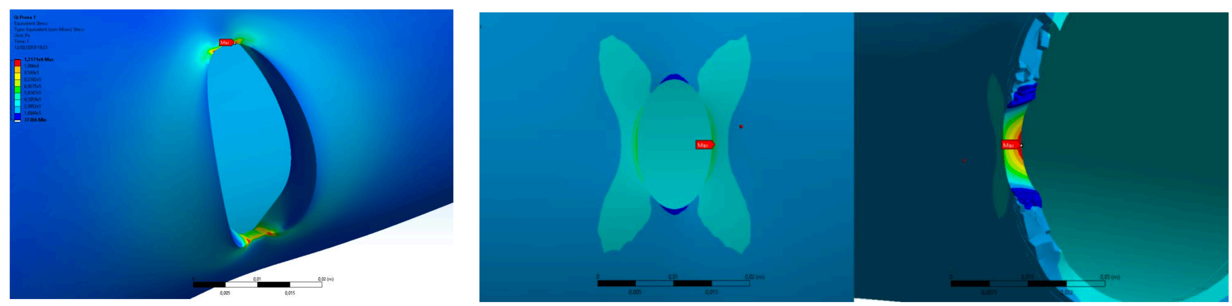

FIGURE 4. Stresses and scaled up deformation of the rectangular (left panel) and circular (right panel) hole.

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