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EXPERIMENTAL STUDY OF MIXING PHENOMENON IN WATER DISTRIBUTION NETWORKS UNDER REAL-WORLD CONDITIONS

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Abstract

Various studies have shown that mixing at the junction of water distribution networks (WDNs) can be neither complete nor instantaneous. Many studies have also been carried out to find the parameters that have a significant effect on the mixing phenomenon by experimental and numerical investigations. The Reynolds ratio of inlet flows, the Reynold ratio of outlet flows, the pipe size of junction's legs (junction configurations), and the type of junction (cross or double-t) are among the most important factors mentioned in these studies. Other studies also focused on developing mixing models. However, these studies and models were based on experimental conditions in which the pipe size was about 25 mm, and the pressure was about 30 kPa. Despite the fact that these models provide acceptable results on the laboratory scale and all of them have been validated based on laboratory results, many researchers still acknowledge that studies on the effects of real conditions of urban WDNs on the mixing phenomenon are lacking [1], [2] and [3]. The pipe size of junctions and the pressure inside the network are distinguishing features of real urban WDNs and laboratory setups that were used in previous studies. Therefore, this research investigates the effect of pipe size and pressure on the mixing phenomenon in a cross junction with the same pipe sizes in all four legs under real-world conditions. Flow rates and pressures were selected based on a statistical study conducted on the Quebec City WDN and previous research work, in which the pressures were 5, 140, 320 and 430 kPa, and the flow rates were a combination of 1.50, 2.00, 2.25, 2.50 and 3.00 LPS in each inlet and outlet pipes. In other words, the Reynolds number in the experiments was between 21,000 and 43,000, and the Reynolds ratio of inlet flows as well as the Reynolds ratio of outlet flows were 0.5, 0.8, 1, 1.25 and 2. In this network, two cross junctions with the same pipe size in each junction's legs of 100 and 150 mm were investigated. Salt was used as a traceable solute, and conductivity meters were used to measure the salt concentration in pipes. In this series of experiments, only one inlet had salty water. The mixing was characterized by the dimensionless concentration in outlets, defined as the observed conductivity in one of the outlet flow divided by the inlet salty water conductivity (after subtracting the conductivity of tap water for both measurements). The results showed that the pressure had only a little effect on mixing, since the dimensionless concentration changed by about 0.05 when considering the low pressure of 5 kPa as compared to the experiments with the other pressure values, while this variation dropped to about 0.02 for all pressures above 140 kPa. Between 100 and 150 mm, the pipe size modified the dimensionless concentration by about 0.035. Taking into account the uncertainty of the experiments, it can be concluded that pressure and pipe diameters (100 and 150 mm) have an insignificant impact on the mixing phenomenon.

Keywords
Water Distribution Networks, Water Quality, Mixing Phenomenon, Numerical Modelling, Junction, Pressure, Pipe Size.

1 INTRODUCTION

Water quality modeling in water distribution systems (WDSs) is one of the main tools to help control and enhance drinking water quality. In the existing commercial software of WDSs' water quality modeling, it is assumed that mixing in junctions occurs completely and instantaneously; however, researchers found that not only is this assumption wrong but also, in many cases, the mixing is totally imperfect in junctions [4], [5] and [6]. Therefore, two series of research were conducted: the first, to find out the effective parameters of the mixing phenomenon and the second, to develop models considering imperfect mixing at junctions.

In the first category of research, O'Hern et al. (2005) studied the mixing phenomenon in cross junctions with the help of a physical model in the laboratory [2]. In their experiments, the Reynolds number (Re) was about 43,000, and two circular 50 and 12.5 mm pipes were used. They observed that the mixing is less complete when the pipe dimension increases. The mixing phenomenon was also investigated in a 3x3 pipes grid network with pipe sizes of 12.5 to 50 mm and a Reynolds number of 40,000 [7]. Ho et al. (2006) realized that the mixing in cross junctions decreases slightly as the velocity increases for a fixed pipe diameter [7]. Ho et al. (2007) used the K-Epsilon turbulent model for their numerical simulations and figured out that the Schmidt Number is the most important factor in RANS turbulent models [8]. Besides, Romero-Gomez et al. (2008) used the value of Schmidt number suggested by Ho et al. (2007) to perform a numerical simulation of mixing with unequal inlet and outlet flow rates [3]. Meanwhile, Webb and van Bloemen Waanders (2006) stated that the LES model is not dependent on the Schmidt number, while they as well believed that the mixing is caused by both bulk flow (advection) and turbulent diffusion at the impinging interface [9]. McKenna et al. (2007) worked on the ratio of Re for inlets in the laboratory with pipe sizes of 12.5, 25, 32, and 50 mm [10]. In addition to considering the turbulent flow, McKenna et al. (2008) used high-speed photography to study the mixing phenomenon for laminar and transient flows (500 < Re < 5,000) [11]. van Bloemen Waanders et al. (2005) also considered the mixing in laminar flow and found that the mixing in laminar flow is not complete [6]. Thereafter, Braun et al. (2014) statistically investigated the WDN of Strasbourg, France, and found that laminar flow frequently happens in large areas of the network [12]. Accordingly, the mixing phenomenon in cross junctions was considered under the laminar and transitional conditions (500 < Re < 7,500) with pipe sizes of 16, 25, 32, and 50 mm by Shao et al. (2019). Shao et al. (2019) figured out that the pipe diameter has a great influence on the mixing [13].

In the second category of studies, there are two types of models for simulating the mixing phenomenon: empirical and mechanistic. AZRED is the first empirical model that could project the solute concentration based on the inlet concentrations and the Re ratios of inlets and outlets [14]. Austin et al. (2008) carried out experiments in the Re range of 10,000 to 42,000 to develop their model, while they used extrapolation for Re greater than 42,000 [14]. Ho (2008) proposed the model EPANET-BAM as a mechanistic model to study the mixing in cross junctions [15]. This author focused on the inlet and outlet Re ratio by changing the flow rate and only considered the advection term of the transport formula [15]. Yu et al. (2014) experimentally and numerically studied the mixing phenomenon within cross junctions with different pipe sizes [16] and [17]. Shao et al. (2014) proposed a model for the mixing phenomenon in cross junctions based on experimental findings with two configurations: opposing inlets and adjacent inlets [18]. More details of the effective parameters and models were presented in the paper by Yousefian and Duchesne (2022) reviewing the research about the mixing phenomenon in WDSs [1].

As mentioned in the previous paragraphs, most studies on the mixing phenomenon were carried out under the laboratory scale and conditions, while the developed models should be applied to real-world conditions. Besides the fact that the pipe diameter is one of the effective parameters that greatly impact the mixing phenomenon, pipe diameter and pressure are two distinguished differences between laboratory and real-world conditions in WDSs. Therefore, in this research, two pipe diameters of 100 and 150 mm, which are the most used pipes in Quebec City WDN, along with pressures of 5 and140 kPa (used to develop the existing models), and 320 and 430 kPa (encountered in real WDNs) were selected to investigate the effect of real-world pipe diameter and pressure on mixing phenomenon.

2 EXPERIMENTAL SETUP AND PREPARATION

The experiments were carried out in the Mini Water Distribution Network Laboratory of Institut National de la Recherche Scientifique (INRS) in Quebec City, Canada. This laboratory has been built in a hall with dimensions of 15 m x 9 m to hold a 12x5 pipes grid network. All connections in this network are flanged in order to make changing the pipe diameters easy. The network was equipped with two pumps which are a 3 hp (Xylem-AquaBoost) and a 75 hp (Berkeley-B4EPBMS) pumps, and also several pressure probes (Ashcroft-G2) to be able to apply a variety of high and low pressures. In addition, 12 flow control valves with electric actuators (Assured Automation-P2R4 with S4 actuator) and several electromagnetic flow meters (ModMAG-M2000) were installed in this network so that any specific flow can be adjusted in the pipes (Figure 1). In this study, sodium chloride ($NaCl$) was used as a soluble tracer for the experiments, and 4 conductivity meters (Teledyne-LXT220) were installed in each leg of the cross junction to measure the conductivity (related to the concentration of salts) in each inlet and outlet. All the settings of pumps and valves were set through a central computer (Honeywell-EBI R430 and Honeywell-Controller HC900) to increase the accuracy of applied conditions in experiments. The flow, pressure and conductivity results were also measured and recorded every 5 s by a data logger to the central computer. These data were averaged over a 60 s interval to collect repeatable data by reducing the signal noise of the sensors.

Figure 1. Mini water distribution network Laboratory of INRS

In order to add salt to the flow and network, an injection pump was employed. This injection pump can work under different frequencies, making it possible to have different salt concentrations.

Two cross junctions with the pipe size of 100 and 150 mm were considered. These two cross junctions have the same pipe size in all of their four legs, as shown in Figure 2 for the 150 mm configuration.

Figure 2. 150-mm cross junction used in mini water distribution network laboratory of INRS

3 DEFINITIONS AND SCENARIOS

In this study, tap water was used in the whole network and salt (NaCl) was injected. The distance between the salt injection point and the cross junction was about 3 m to ensure that the longitudinal mixing occurred entirely in the water before reaching the cross junction. In all the experiments, the salt was injected into the southern pipe (red arrow in Figure 3), tap water was coming from the western pipe (blue arrow in Figure 3), and northern and eastern pipes were the outlets (orange arrows in Figure 3).

Figure 3. Schematic picture of the experiments to obtain dimensionless concentrations

A statistical analysis was carried out in Quebec City WDN to find the most common real characteristics and conditions of WDNs. In this network, the two pipe sizes of 100 and 150 mm are the most often used pipe size, and flow rates between 1.50 and 3.00 LPS are the most common. Therefore, based on this result, 25 different flow rate scenarios were tested for each cross junction size (Table 1). In each scenario, two pressures, of 320 and 430 kPa, were applied. Ten different concentrations of salt were injected into the southern pipe. In total, 500 experiments were carried out in this phase to find the effect of pressure and pipe diameter on the mixing phenomenon in junctions.

Table 1. Flow rate scenarios for the experiments to consider the effect of pressure and pipe diameter on mixing

South inlet (Salty Water) (LPS)	West Inlet (Tap Water) (LPS)	North Outlet (LPS)	East Outlet (LPS)
1.50	3.00	3.00	1.50
1.50	3.00	2.50	2.00
1.50	3.00	2.25	2.25
1.50	3.00	2.00	2.50
1.50	3.00	1.50	3.00
2.00	2.50	3.00	1.50
2.00	2.50	2.50	2.00
2.00	2.50	2.25	2.25
2.00	2.50	2.00	2.50
2.00	2.50	1.50	3.00
2.25	2.25	3.00	1.50
2.25	2.25	2.50	2.00
2.25	2.25	2.25	2.25
2.25	2.25	2.00	2.50
2.25	2.25	1.50	3.00
2.50	2.00	3.00	1.50
2.50	2.00	2.50	2.00
2.50	2.00	2.25	2.25
2.50	2.00	2.00	2.50
2.50	2.00	1.50	3.00
3.00	1.50	3.00	1.50
3.00	1.50	2.50	2.00
3.00	1.50	2.25	2.25
3.00	1.50	2.00	2.50
3.00	1.50	1.50	3.00

The dimensionless concentration of injected salt in each outlet, which is obtained from equation (1), was chosen to present the level of mixing:

$$C^* = \frac{C - C_w}{C_s - C_w} \quad (1)$$

where C^* is dimensionless concentration of injected salt in the studied outlet (north or east), C is the concentration of salt in the studied outlet, and C_s and C_w are concentrations of salt in the southern (salty water) and western (tap water) inlets, respectively. Finally, since for each flow scenario, 10 different quantities of salt were injected, the dimensionless concentration of injected salt for each scenario was obtained through taking the average of dimensionless concentration for 10 quantities of injected salt:

$$C^* = \frac{\sum_{i=1}^{10} C_i^*}{10} \quad (2)$$

where C_i^* is the dimensionless concentration in any outlet for the i^{th} of 10 experiments carried out in each flow rate scenario.

3.1 Uncertainty of dimensionless concentration in outlets

The accuracy of conductivity meters is ±0.1% of full scale. Based on our calibration data, we selected a conductivity range of [0, 1.41] mS/cm. Therefore, ±0.1% of the maximal conductivity (1.41 ms/cm) would be ±0.00141 ms/cm. Then, to find the dimensionless concentration of salt in each outlet, the following equations of absolute error propagation were used.

For addition and subtraction ($Z = X + Y$ or $Z = X - Y$):

$$\Delta Z = |\Delta X| + |\Delta Y| \quad (3)$$

and for multiplication and division ($Z = X \times Y$ or $Z = X/Y$):

$$\frac{\Delta Z}{Z} = |\frac{\Delta X}{X}| + |\frac{\Delta Y}{Y}| \quad (4)$$

where X and Y are measurements with absolute uncertainty of $|\Delta X|$ and $|\Delta Y|$, respectively. Finally, the uncertainty of the dimensionless concentration of injected salt in each outlet was estimated to be about $|\pm 0.05|$.

4 RESULTS

4.2 Pressure impact on mixing phenomenon

To study the effect of pressure on the mixing phenomenon, 25 different flow scenarios (see Table 1) within two pipe sizes cross junctions were studied. Detailed results will be presented here for three of these cases. In the first case, the simplest flow scenario, i.e. with equal flow rate (2.25 LPS) in all cross junction legs, was investigated. In this case, the cross junction with pipe diameters of 100 mm was used, and three different pressures were applied: 5, 140, and 320 kPa. Different flow rates in inlets and outlets were then considered, in Case 2, to study the effect of pressure within a more complicated flow rate scenario. The same cross junction and pressures as in Case 1 were used for this experiment. In the last experiment, Case 3, the same flow scenario as in Case 2 was applied but this time in a 150-mm cross junction. For this experiment, four pressures were considered. More details about each case are presented in Table 2 and the results of these 3 cases are shown in Figure 4 and 5.

Table 2. Specifications of some of the experiments conducted to study the pressure impact

		South	West	North	East
Case 1	Pipe Diameter	100 mm	100 mm	100 mm	100 mm
	Flow Rate	2.25 LPS	2.25 LPS	2.25 LPS	2.25 LPS
Case 2	Pipe Diameter	100 mm	100 mm	100 mm	100 mm
	Flow Rate	1.50 LPS	3.00 LPS	1.50 LPS	3.00 LPS
Case 3	Pipe Diameter	150 mm	150 mm	150 mm	150 mm
	Flow Rate	1.50 LPS	3.00 LPS	1.50 LPS	3.00 LPS

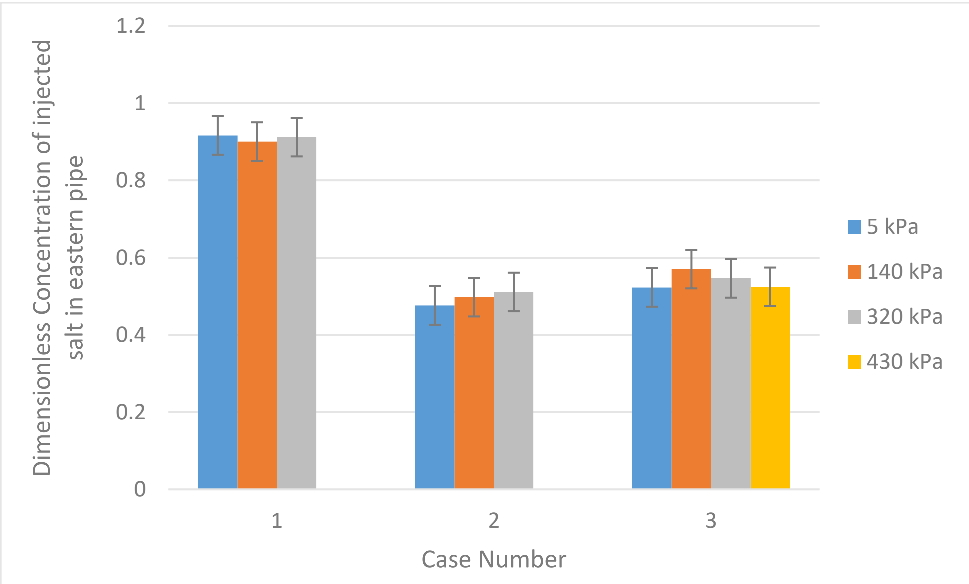

Figure 4. Dimensionless concentration of injected salt in the eastern pipe for the experiments conducted to study the pressure impact

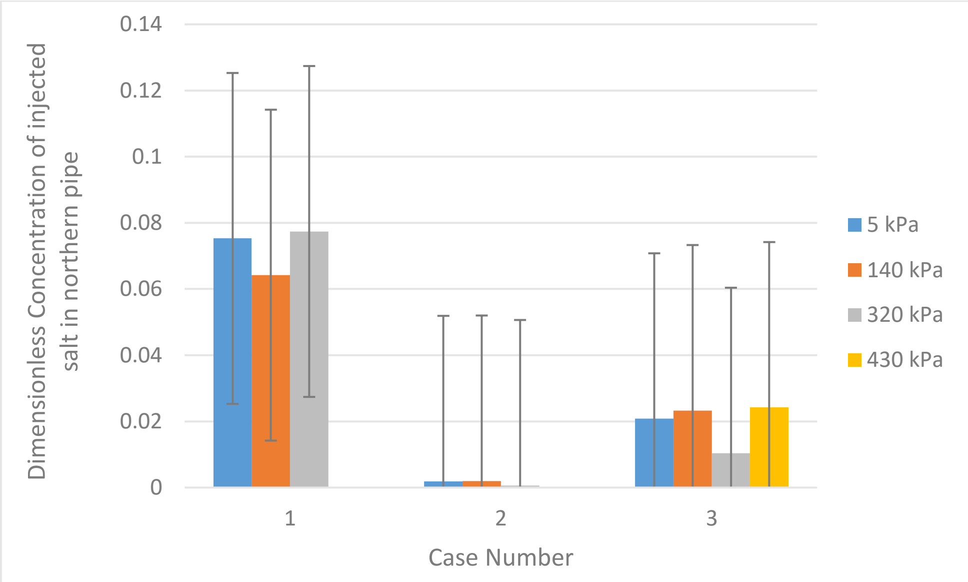

Figure 5. Dimensionless concentration of injected salt in the northern pipe for the experiments conducted to study the pressure impact

In general, pressure can affect the intensity of flow turbulence and molecular diffusion. However, as shown in Figure 4, when the flow rates or Reynolds numbers are equal in all cross junction legs (Case 1), the effect of pressure results in a maximal difference of about 0.016 in dimensionless concentrations in the eastern pipe, which happens between 5 and 140 kPa. In comparison, this difference decreases to about 0.011 in dimensionless concentration in the eastern pipe for the pressures of 140 and 320 kPa. When considering the uncertainty (shown by error bars in each figure), it can be concluded that for this flow scenario (Case 1), the pressure has a negligible impact on mixing. For Case 2, with different flow rates or Reynolds numbers in the four cross junction legs, the difference between the dimensionless concentration of eastern pipe with 5 and 320 kPa is about 0.035. However, this difference decreases to 0.013 when the pressures of 140 and 320 kPa are considered. For the last experiment, Case 3, also, the difference in dimensionless concentration in the eastern pipe is about 0.047 between 5 and 140 kPa. However, when pressures greater than 140 kPa are compared to each other, the difference in dimensionless concentration in the eastern pipe is about 0.024. Therefore, it can be concluded that when the flow rates are different in the cross junction legs, the pressure can change the dimensionless concentration up to 0.047 in the eastern pipe when a low pressure like 5 kPa (which was previously used to develop the existing empirical models) is considered; however, this difference is lower than the uncertainty related to the measurements. For pressures greater than 140 kPa, the pressure can change the dimensionless concentration in the eastern pipe by about 0.02. Since such low pressures do not usually happen in real WDNs and since for pressures greater than 140 kPa the impact of pressure in comparison with the uncertainty of experiments is insignificant, it can be concluded that the impact of pressure on mixing phenomenon can be neglected. It should be added that this conclusion was also obtained from the results of experiments carried out under the 25 flow scenarios (see Table 1) and the pressures of 320 and 430 kPa in both 100 and 150 mm cross junctions.

4.3 Pipe diameter impact on mixing phenomenon

To find the impact of pipe diameter on mixing in cross junctions, all 25 flow scenarios (see Table 1) were tested in both cross junctions (100 and 150 mm); the results of three of those scenarios are presented here as examples. The following table (Table 5) shows the specifications of these scenarios, while the results are shown in Figures 7 and 8.

Table 3. Specifications of the experiments to study the pipe diameter impact

	South	West	North	East
Case 4-Flow Rates	2.25 LPS	2.25 LPS	2.25 LPS	2.25 LPS
Case 5-Flow Rates	3.00 LPS	1.50 LPS	3.00 LPS	1.50 LPS
Case 6-Flow Rates	1.50 LPS	3.00 LPS	1.50 LPS	3.00 LPS

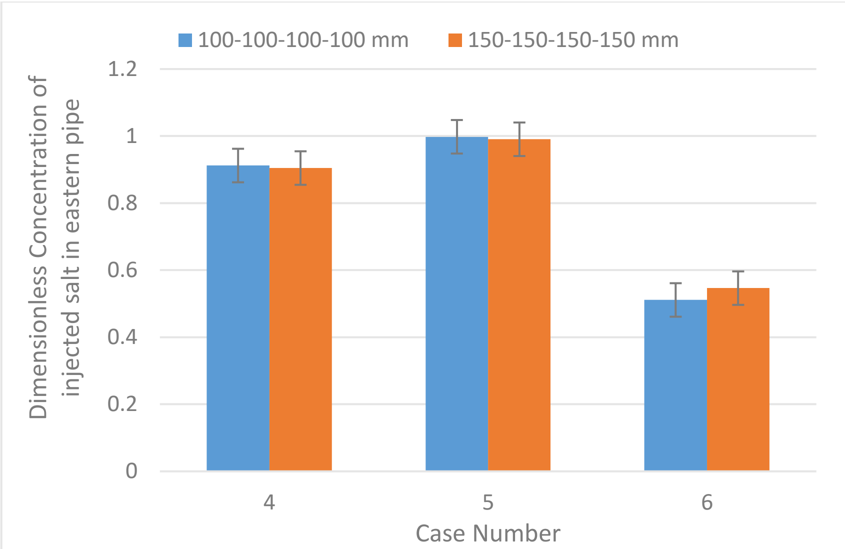

Figure 6. Dimensionless concentration of injected salt in the eastern pipe for the experiments conducted to study the pipe diameter impact

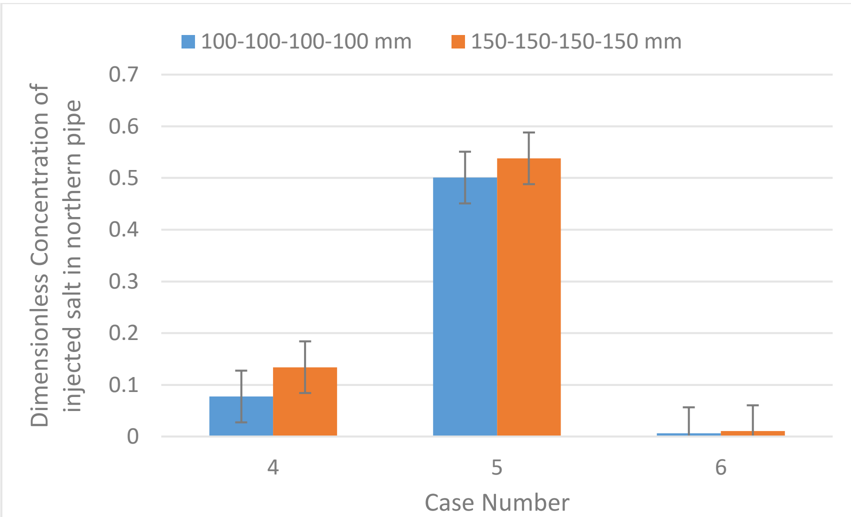

Figure 7. Dimensionless concentration of injected salt in the northern pipe for the experiments conducted to study the pipe diameter impact

As shown in Figure 6, the difference in dimensionless concentration in the eastern pipe for the two pipe diameters, when the flow rates are equal in all four legs of the cross junction (Case 4), is less than 0.01. This difference was also observed in the Case 5, where the flow rates were different in the cross junction legs. However, for the last case (Case 6), in which the flow rate in the inlet with salty water was less than the flow rate in the inlet with tap water, this difference increases to about 0.035. Considering the uncertainty, which is shown by error bars in all charts, it can be concluded that when the flow rates are equal in all four cross junction legs (Case 4) or when the flow rate of salty water is different from the one of tap water (Case 5 and Case 6), the mixing is the same in the cross junctions with 100 and 150 mm diameter, for the conditions that were simulated in the laboratory. This was also observed for all other 22 scenarios in both 100 and 150 mm cross junctions.

5 CONCLUSIONS

In this research, the effects of pressure and pipe size on mixing phenomenon in the cross junctions of WDNs were studied. For this purpose, two cross junctions with 100 and 150 mm pipe diameters were used. For each size, 25 flow rate scenarios were tested under two different pressures in the mini WDN laboratory of INRS, Canada. In all experiments, the salty water was injected into the southern inlet and tap water was coming from western inlet and two northern and eastern pipes were outlets. Each experiment was repeated ten times with varying concentrations of salt. By comparing the results of these 500 experiments, the following conclusions were acquired:

1. When the flow rates are the same in all four legs of cross junctions, the pressure does not impact the mixing phenomenon.
2. When the flow rates are different in the legs of the cross junction, the pressure can change the mixing or dimensionless concentration in the eastern pipe by about 0.05, which is of the same order as the uncertainty related to measurements, if low pressures like 5 kPa, which are not encountered in real word conditions, are considered.
3. For pressures greater than 140 kPa, the effect of pressure can change the dimensionless concentration of injected salt in the eastern pipe by about 0.02, which considered as non-significant since the uncertainty related to measurements is about 0.05.
4. Since low pressure like 5 kPa do not happen in real WDNs and since the effect of high pressure is lower than the uncertainty of the experiments, it is concluded that in real WDNs, the pressure does not have a significant impact on the mixing phenomenon and can be neglected.
5. The impact of pipe diameter (100 and 150 mm) on mixing within different flow rate scenarios (Table 1) can change the dimensionless concentration by 0.035, which is considered to be negligible since it is lower than the uncertainty of the laboratory measurements,

Since in real WDNs, the pressures are mostly above 140 kPa and since the effect of pipe size for 100 and 150 mm on the dimensionless concentration in the eastern pipe in our experiments was found to be less than the uncertainty related to measurements (±0.05), it leads to the conclusion that in real WDNs, the mixing for cross junctions with four equal pipe sizes is the same for different pressures and for pipe sizes of 100 and 150 mm. However, cross junctions with different pipe sizes (e.g. 100-150-100-150 mm) still needs to be studied in the future.

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