Experimental Verification of Incomplete Solute Mixing in a Pressurized Pipe Network with Multiple Cross Junctions

Inhong Song[1]; Pedro Romero-Gomez[2]; and Christopher Y. Choi[3]

Abstract: Water quality models based on accurate mixing data at cross junctions are important for estimating concentrations of chemical species in municipal water distribution systems. Recent studies indicate that the instantaneous complete (thus "perfect") mixing assumption potentially can result in an erroneous prediction of water quality. The present study examines the updated "incomplete" solute mixing model at cross junctions in a network having multiple cross junctions. The model performance in predicting solute transport was evaluated through a series of tracer experiments in a pressurized 5×5 network with 9 cross junctions. The perfect mixing model consistently overestimated solute dilution at cross junctions and predicted evenly distributed solute concentration throughout the network. In contrast, the incomplete mixing model demonstrated uneven distribution patterns with a distinct solute plume, and the corresponding results were significantly more accurate than those based on the perfect mixing assumption. Average prediction errors in tracer concentrations were 15 and 66% using the updated and perfect mixing models, respectively, and the difference was statistically significant (P-value <0.001). Therefore, this study concludes that the incomplete mixing model can drastically improve the prediction of solute transport in pressurized pipe systems that have multiple cross junctions.

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CE Database subject headings: Water quality; Mixing; Verification; Pressure pipes; Water pipelines; Water quality; Water distribution systems.

Introduction

It is important to predict accurately the transport of chemical species, such as chlorine and fluoride, in pressurized water distribution systems. Therefore, water quality models for water distribution systems have been developed in order to simulate hydraulic behavior coupled with solute transport, and they have been widely used for designing, simulating, and analyzing water networks. These models also have been used to simulate the spatiotemporal dispersion of chemical and microbial agents during accidental or intentional contamination events. The inability to predict accurate water quality in water distribution systems may potentially lead to overdesigning monitoring systems and overdeploying real-time sensors to compensate for inaccuracies in modeling tools coupled with intrinsic uncertainties in real-world systems. Certainly, for the safety and security of water supply infrastructures, it is important to improve prediction accuracy.

In water distribution networks, grid, loop, and tree/branch pipe networks are basic skeletonized configurations. Grid and loop configurations are commonly found at large urban centers. A real-world municipal system likely consists of multiple grid/loop networks along with branch/tree configurations employed as the network extends toward suburban and rural areas. These municipal networks inevitably contain numerous cross- and tee-junction connectors. In particular, cross junctions are ubiquitous in many cities of the United States, although two closely located tee connectors also can be used for the same purpose. The flow and solute transport mechanisms through two tees may be substantially different from those at cross junctions. Modelers therefore should be careful when specifying snap functions in pipe network design or CAD tools, as two tees can potentially merge and misrepresent two closely located tees as a cross junction. In general, cross junctions have four legs with equal pipe diameters, although various geometries exist which connect unequal diameter pipes.

At cross junctions, the current water quality model in water distribution systems is based on the assumption of instantaneous, complete mixing of biological or chemical species (Grayman et al. 1999). Fowler and Jones (1991) previously noted possible errors caused by the simple assumption. A series of recent studies focused on improving solute transport modeling at cross junctions in water distribution systems (van Bloemen Waanders et al. 2005; Romero-Gomez et al. 2006; McKenna et al. 2007). These studies consistently reported that mixing at pipe cross junctions is far from perfect. Comprehensive computational and experimental investigations followed, and the results were reported by Romero-Gomez et al. (2008a), Austin et al. (2008), and Choi et al. (2008).

Austin et al. (2008) and Choi et al. (2008) showed that solute mixing at a cross junction was incomplete due to the incoming flow bifurcation, and was in fact greatly dependent on incoming and outgoing flow ratios. Computational flow and concentration visualization results were presented by Romero-Gomez et al. (2008a). These studies characterized mixing phenomena computationally and experimentally at a pipe cross junction with various

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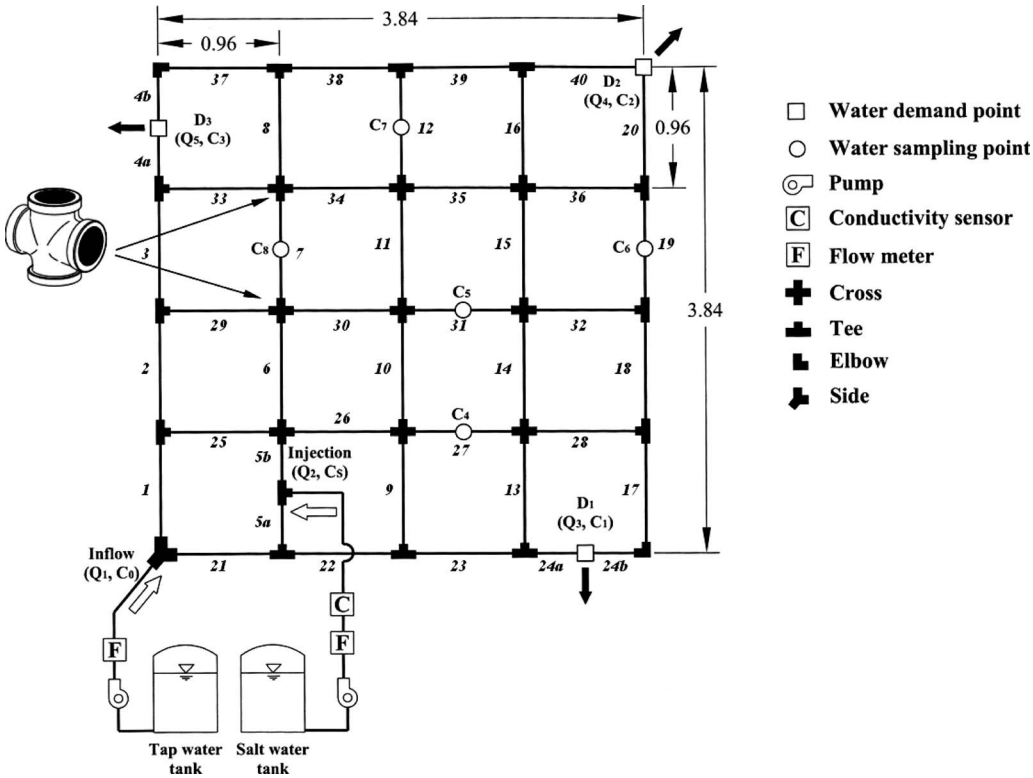

Fig. 1. Schematic of the 5×5 pipe network for the salt tracer experiment (Configuration 3 as an example). Q represents incoming (1 and 2) or outgoing flow rates (3, 4, and 5) of the network. The points labeled by C and D indicate conductivity measurement and water demand points, respectively and each pipe segment was identified by an italic number nearby. Water demand points (□, i.e., D1, D2, D3 in order) were placed at pipe segment 14, 24, and 38 for configuration 1, and 13, 36, and 8 for configuration 2, respectively. PVC pipes used in this network were 1.6 cm in diameter. Units in m.

flow conditions including laminar, transitional, and turbulent regimes. They provided important data for the modification of the perfect mixing assumption.

Additionally, there have been several computational studies to elucidate mixing phenomena at cross junctions. A paper by van Bloemen Waanders et al. (2005) investigated the accuracy of chemical transport for small cross configurations using a Navier-Stokes model combined with a convection-diffusion formulation. The study predicted only a small fraction of the tracer inflow mixing with the other incoming water. Romero-Gomez et al. (2008a) applied a computational fluid dynamics (CFD) approach using the Reynolds averaged Navier-Stokes turbulence model under steady state conditions to study detailed mixing mechanisms at cross junctions. These studies described the bifurcation behavior of those incoming flows at the impinging interface that resulted in incomplete mixing at a cross junction. Webb and van Bloemen Waanders (2006) used the large eddy simulation (LES) turbulence model to resolve the spatial and temporal mixing behavior and found that the fluid interfacial mixing behavior was highly transient due to the turbulent velocity fluctuations of incoming flows. Webb (2007) also applied the LES approach to a case of highly unequal flows entering into a cross junction, showing that the mixing interface formed near the wall of the fitting rather than at the flow centerline because of a large difference in the momentum of the fluid streams.

In short, recent computational and experimental investigations consistently showed that the assumption of complete and instantaneous mixing at pipe cross junctions may generate considerable errors, and therefore, to achieve an accurate prediction of the solute introduced in water distribution systems, the assumption should be modified based on adequate characterization of solute transport.

Austin et al. (2008) further characterized the detailed mixing behavior at a cross junction for various hydraulic conditions in the turbulent regime. They have correlated the solute mass split between two adjacent outlets with the ratios of the Reynolds numbers of the two incoming and two outgoing flows at a cross junction and quantitatively incorporated into the network water quality model; i.e., the flow rates within the pipe network were first determined using a network hydraulic model to calculate the flow ratios of two adjacent inlets and outlets of a cross junction and the subsequent solute mass split ratio. The solute concentrations at the junction outlets were determined by using inlet and outlet flow rate ratios. Choi et al. (2008) described a summary of the code development (named AZRED) with the incomplete mixing assumption at various junctions and flow regimes and its application for a large-scale water distribution system. Additionally, Romero-Gomez et al. (2008b) indicated the possibility of using (instead of the plug flow assumption) an integration of axial dispersion in the water quality model based on CFD and experimental data. Using a 4×5 network, Austin et al. (2008) demonstrated the significant errors caused by the perfect mixing assumption.

Computer-generated results have never been experimentally evaluated in a pressurized network with multiple cross junctions. The primary purpose of the present study is, therefore, to conduct a series of tracer experiments in a network with multiple cross junctions in an effort to verify the modified water quality model. As shown in Fig. 1, the 5×5 pipe network is a representative

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grid/loop with nine cross junctions. Similar 5×5 and 4×4 grid networks were recently used for contaminant source determination by Laird et al. (2005,2006) and Lansey et al. (2007). The simulation results generated by the perfect and incomplete mixing models were compared in order to evaluate the performance of the updated water quality model with respect to the prediction of solute transport in a water network.

Experimental Setup and Procedure

A 5×5 pressurized pipe network was designed and constructed in the Water Village at the Environmental Research Laboratory of the University of Arizona, Tucson, Ariz. Schedule 40 PVC pipes were used to build the pipe network consisting of 32 pipe links and 25 pipe junctions with eight tees, four elbows and nine crosses. Three network configurations were chosen carefully after a series of computer simulations. Fig. 1 presents a schematic of one of three configurations used in this study. Flow rates were converted into the following Reynolds number, $R=UD/\nu$, where U, D, and ν represent the average flow velocity, pipe diameter, and kinematic viscosity, respectively. Pipe segments are numbered to describe all configurations, and corresponding Reynolds numbers (R) are listed in Table 1. All the network flow and solute transport results were presented in dimensionless forms.

The fittings used for the pipe connections were manufactured by NIBCO Inc. (Elkhart, Ind.). Each pipe segment of the network was 96 cm in length and 1.6 cm in diameter. Each section represents an 18-m section with a 30-cm equivalent pipe diameter, which is found in many distribution water mains. Accordingly, the same results are expected for both sizes for the same inlet and outlet Reynolds numbers and geometry, following the dimensional analysis and similitude. This fact was readily proven to be justified after a few runs using CFD with 1.6–30 cm diameter pipes at any given Re, thus precluding the need for expensive and time-consuming field experiments. The CFD runs followed the same preparation and procedure described by Romero-Gomez et al. (2008a), and for brevity the results are omitted.

The entire experimental system is modular, and any part of the network can be connected to any type of sensor so that various geometric configurations can be readily designed and constructed. Additionally, the system can be multilayered, branched out, and expanded in lengths that simulate intermediate and large-scale water distribution networks. The present single-layered 5×5 network is designed for the purpose of demonstrating mixing patterns through multiple cross junctions.

Two plastic tanks of 240 L in volume served as reservoirs to supply water to the system. Both tanks were filled with tap water, and a measured amount of NaCl (No. 7647–14-5, Cargill, Minneapolis, Minn.) was added as a solute tracer only into the salt water tank. The tap water tank was connected to the lower left corner of the network, while the salt water tank was connected to the injection point (shown in Fig. 1). Two 1/2 hp centrifugal pumps (MCS Goulds pumps, Seneca Falls, N.Y.) were used to supply water to the networks from each of the two water tanks. A solenoid valve was installed at each of three water demand points, and these served as the system's water outlets. To extract water samples for salinity measurements, a 0.08-cm diameter hole was drilled in the middle of the pipe segment at each conductivity measurement location (C_4–C_8 in Fig. 1), The two incoming flows from both tanks were measured using paddle wheel sensors (FP-5600, the Omega Corporation, Stamford, Conn.). In addition, to allow for the continuous measurement of salt concentration, a conductivity probe (CDE-1201, CDTX-1203, the Omega Corporation, Stamford, Conn.) was installed in the injection pipe. These sensors were connected to a datalogger (CR3000, Campbell Scientific Corp., Logan, Utah) that recorded the sensor readings every second.

Table 1. Estimated Reynolds Number in the Pipe Networks for the Three Experimental Configurations

	Reynolds number (R) for each pipe link		
Pipe number	Configuration 1	Configuration 2	Configuration 3
1	36,526	37,574	36,077
2	23,153	23,652	23,153
3	15,419	16,067	16,666
4 or (4a, 4b)[a]	8,932	8,633	(14,421, 17,415)[a]
5a, 5b	(7,285, 26,846)[a]	(7,335, 27,145)[a]	(6,786, 26,596)[a]
6	20,309	20,409	20,109
7	14,820	15,968	15,469
8	10,928	(18,163, 11,377)[a]	12,425
9	9,880	8,433	8,483
10	13,822	11,776	12,225
11	12,075	11,477	11,876
12	12,525	7,585	9,780
13 or (13a, 13b)[a]	9,181	(16,267, 15,369)[a]	3,144
14 or (14a, 14b)[a]	(20,708, 10,080)[a]	259	6,237
15	5,938	7,834	7,984
16	7,784	150	7,834
17	7,185	2,744	17,115
18	11,577	4,441	4,541
19	10,379	9,181	5,189
20 (20a, 20b)[a]	(18,612, 10,728)[a]	4,690	12,774
21	33,482	34,780	32,933
22	26,197	27,444	26,147
23	16,367	19,011	17,664
24 or (24a, 24b)[a]	7,185	2,744	(14,521, 17,115)[a]
25	13,373	13,922	12,924
26	19,910	20,608	19,411
27	15,918	17,265	15,668
28	4,391	1,697	12,575
29	7,734	7,585	6,437
30	13,223	12,076	11,127
31	14,820	12,375	11,477
32	1,198	4,790	9,730
33	6,487	7,385	2,295
34	10,329	5,189	5,339
35	10,080	9,082	7,435
36 or (36a, 36b)[a]	8,233	(17,115, 13,872)[a]	7,585
37	8,932	8,633	17,415
38 or (38a, 38b)[a]	(19,860, 9,581)[a]	2,744	5,040
39	2,944	4,840	4,740
40	10,728	4,690	12,575

[a]Two Reynolds numbers are presented when incoming or outgoing flows exist in a pipe segment. For the Experimental Configuration 1, as an example, "a" represents the east or south side of the pipe while "b" does the west or north side as shown for the pipe numbers 4, 5, and 24 in Fig. 1.

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Two separate approaches were used in this study to investigate hydraulics and solute transport in the networks. A series of preliminary experiments indicated that installations of built-in-pipe flow and conductivity sensors within the pipe networks could disturb the network flows and generate hydraulic resistances. Because of the scale of the pipe networks used in this study, it was determined that not just small flow disturbances could impact downstream solute transport phenomena considerably, but also, due to these measurement devices, hydraulic resistance could be significant enough to change network flow rates. Therefore, network flow experiments were conducted separately from the salt tracer experiments conducted to verify the model performance in simulating network hydraulics. Neither flow meters nor conductivity sensors were placed within the pipe networks during the salt tracer experiments. Conductivity readings were taken at the sampling and demand points, as extracted water passed through the conductivity sensor at each location. Three different network configurations were defined based on the locations of the water outlets, *i.e.*, water demand points as shown in Fig. 1, and each configuration experiment was carried out independently with three replications.

Each configuration involved three water demand points and eight sampling points. Both flow and tracer mass balances were monitored to ensure that all the measurements were correctly taken. The mismatches in flow and solute mass were assessed with $(\Sigma Q_I - \Sigma Q_O)/\Sigma Q_I$ and $(\Sigma C_I Q_I - \Sigma C_O Q_O)/\Sigma C_I Q_I$, where Q and C indicate flow rate and salt concentration, while the subscripts I and O represent incoming and outgoing, respectively.

For the network hydraulic model verification, outflow at each water demand point was measured manually by recording its volume with a graduated cylinder to calculate the flow rate. The readings from the flow meters also were retrieved from the datalogger. The waters in both tanks were pumped into the network, and the system reached a steady state within a minute, based on sensor readings. For these hydraulic measurements, two pipe segments within the pipe network were replaced with two flow meters to measure network flow rates. Flow measurements were repeated three times independently by shutting the entire system down after each run. The sensors were then relocated and flow measurements were repeated. This was done three times for each demand configuration: to measure network flow rates for three configurations, a total of eighteen pipe segments were selected; i.e., six flow measurement locations for each configuration. These network flow data were compared with the results of hydraulic model simulations.

Network hydraulics was simulated with the measured inflow and outflow data ($Q_1 - Q_5$ in Fig. 1) as input data using EPANET (Rossman 2000). To consider the hydraulic resistance factor from the flow sensor installation into the network, the pressure drop through a flow sensor was characterized at the range of flow rate within the network. Two pressure transducers (MSP 600, Measurement Specialties Inc., Hampton, Va.) were installed before and after each flow sensor, and the pressure differences were measured. The pressure drops were converted into hydraulic head loss with respect to the flow rate and a corresponding characteristic curve was developed to calculate the hydraulic energy loss for each sensor. The flow sensors installed within the network were represented as general purpose valves in the EPANET model. The characteristic curve was assigned to each general purpose valve in order to generate hydraulic resistance for a given flow rate.

For solute transport experiments, approximately 120 g of salt was dissolved into 200 L of water in the salt tank and thoroughly mixed for 5 min using a submerged pump before injection. To minimize any disturbance in mixing patterns at cross junctions, no sensors were installed within the pipe network during the salt tracer runs. Only outflow rates at water demand points were measured and used for calculating the flow balance. Similar to the hydraulic experiments, after both tap water and salt injection pumps were turned on, the system was allowed one minute to reach a steady-state condition.

To determine salt concentration, a water sample of approximately 300 ml was collected from each water demand point as well as from each of the five conductivity measurement locations. Tap and salt water pumping rates were measured in the pipes entering the system, and the conductivity of the injection water was measured in the injection pipe. The sensor readings of the steady state flow rate and the conductivity of injection water were retrieved from the datalogger. When each experimental run was completed, the system's operation was entirely stopped and restarted for the next trial. Three replicate experimental trials were processed for each network configuration.

Since the injected salt concentrations varied slightly from one configuration to another, all the salt concentrations were normalized with respect to each injection salt concentration using $C'_J = (C_M \text{ or } C_S)/C_I$, where C'_J, C_M, C_S, and C_I represent normalized, measured, simulated, and injected salt concentrations, respectively. The subscript J in C'_J is either measured (M) or simulated (S).

The differences between the measured and the simulated salt concentrations were calculated for each of the perfect and incomplete mixing model simulations. The absolute error and prediction error percentage were defined by $(C'_M - C'_S)$ and $(C'_M - C'_S)/C'_M$, respectively. A statistical analysis using ANOVA in terms of prediction errors was conducted between two models to determine the significance of the updated mixing model in improving network salt transport prediction.

Results and Discussion

Prior to solute transport experiments, a total of six network pipe flow rates was measured for each configuration and compared with the computed flow rates using EPANET. The overall hydraulic simulation error was 15.1% on average, varying from 13.5–16.2% for different configurations. The differences between the measured and predicted flow rates are likely due to cumulative minor losses at ells, tees, and crosses. Since the connectors are densely populated within the experimental setup, the cumulative effect of minor losses could be exaggerated when compared to a real pipe network. Thus, the minor loss effect should be drastically reduced in a full scale system. Overall, the hydraulic simulation results were in good agreement with experimental measurements, where the coefficient of determination is 0.82.

Table 1 summarizes the simulated network flow rates in terms of the Reynolds numbers (R) and details the flow distributions of all three configurations. Most flows within the networks were beyond the laminar flow regime ($R > 2,100$), while laminar flow also appeared in a few pipes. For configuration 2, in particular, quasistagnant flows ($R < 300$) occurred in two pipe segments (see pipes 14 and 16 in Table 1). These configurations that exhibited a wide range of the Reynolds number were carefully chosen based on a series of preliminary hydraulic simulations.

All the measured values of flow rates and salt concentrations were presented in Table 2. Water and salt mass balance for each experimental run also was calculated. Total inflow was 1.12 l/sec, combining 0.87 l/sec from the tap water inflow and 0.25 l/sec

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Table 2. Experimental Result of Normalized Flow Rates and Salt Concentrations (See Fig. 1 for the Measurement Locations)

		Flow rate					Salt concentration					Mass balance error	
		Q_1	Q_2	Q_3	Q_4	Q_5	C_0	C_I	C_1	C_2	C_3	Water	Salt
Configuration	Repetition	$Q_i/(Q_1+Q_2)$ [a]					C_i/C_I [b]					%	%
1	1	0.78	0.22	0.35	0.34	0.33	0.00	1.00	0.30	0.25	0.06	1.8	5.3
	2	0.78	0.22	0.35	0.34	0.34	0.00	1.00	0.30	0.26	0.05	2.6	4.2
	3	0.78	0.22	0.35	0.33	0.33	0.00	1.00	0.30	0.26	0.06	1.3	4.4
2	1	0.78	0.22	0.35	0.35	0.32	0.00	1.00	0.21	0.35	0.05	1.9	4.4
	2	0.78	0.22	0.37	0.35	0.33	0.00	1.00	0.21	0.35	0.05	4.3	3.3
	3	0.78	0.22	0.36	0.35	0.33	0.00	1.00	0.21	0.34	0.05	4.5	4.7
3	1	0.78	0.22	0.36	0.29	0.36	0.00	1.00	0.13	0.52	0.07	1.0	1.0
	2	0.78	0.22	0.36	0.29	0.37	0.00	1.00	0.12	0.50	0.07	1.3	3.4
	3	0.78	0.22	0.36	0.29	0.36	0.00	1.00	0.13	0.51	0.07	0.7	2.1

[a]Flow rates were normalized by the total inflow (Q_1+Q_2) which maintained at 1.12 l/sec (0.87 and 0.25 l/sec for tap water inflow and salt injection, respectively).

[b]Salt concentration was normalized by the injected salt concentrations (C_I). Salt injection concentration was 542 mg/l on average varying from 524 to 573 mg/l depending on the network configuration.

from the salt water injection. The salt concentration of the injection water was 542 mg/l on average, varying from 524 to 573 mg/l depending on the network configuration. All of the tracer experimental runs were carefully controlled, and water and salt mass balance errors were less than 5%, as shown in Table 2.

Fig. 2 schematically compares the solute transports in the network between the perfect mixing model and the incomplete mixing model. Each pipe segment maintains a uniform concentration in the EPANET. Accordingly, isoconcentration contour lines were generated, although they might not accurately present detailed concentration contours within each pipe segment. The assumption of perfect mixing at cross junctions rendered the injected solute equally mixed at each cross junction in the network and resulted in more evenly dispersed patterns of salt in the network [Fig. 2(a)] as compared to those produced by the incomplete junction mixing assumption. On the other hand, the incomplete mixing case showed a high salt concentration plume, spread diagonally in the network [Fig. 2(b)].

An ANOVA test using the absolute prediction errors in salt concentration was conducted between the two mixing models (Table 3). The average prediction error in normalized salt concentration was 0.04 when using the incomplete mixing model, which was significantly smaller than the 0.13 obtained with the perfect mixing model (P-value <0.001). These absolute prediction error values correspond to the average percentage errors of 15 and 66%, respectively.

The hydraulic simulation error and its propagation through the network was likely a major source of errors in predicting tracer concentration values since the ratio of flow rates at each cross junction is the primary parameter affecting the tracer transport in the network. As indicated earlier, the hydraulic prediction error was 15.1% on average. Another uncertainty arises from the difference of the network flow regime. It should be noted that the solute transport characterization at a cross junction as indicated by Austin et al. (2008) was obtained in the turbulent flow regime, and the updated incomplete model was solely based on those data

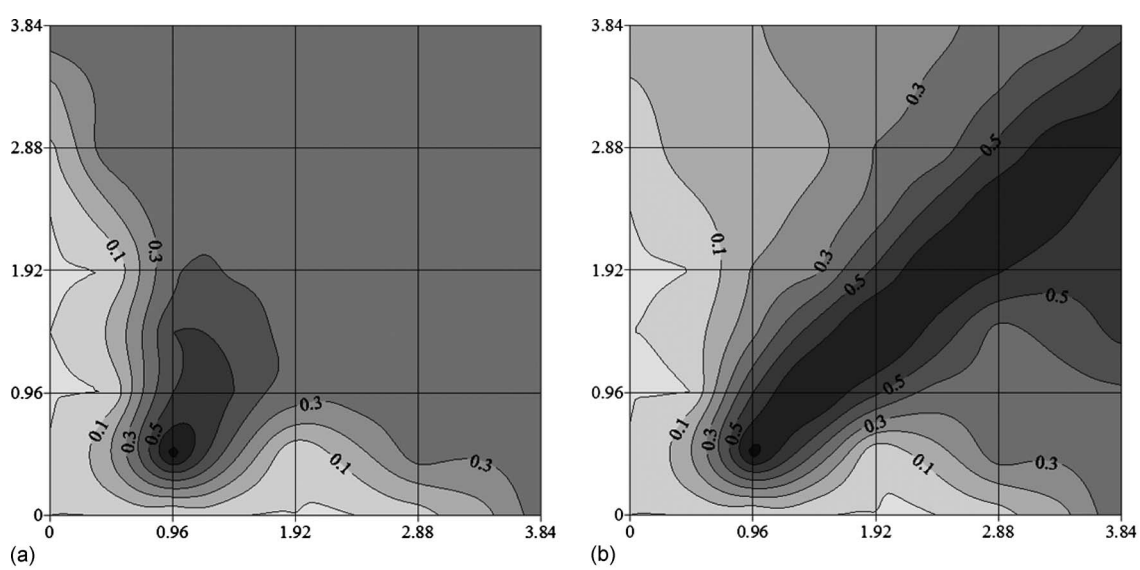

Fig. 2. Solute dispersion patterns in the 5×5 pipe network for Configuration 3: (a) simulation results based on the perfect mixing assumption; (b) simulation results based on the incomplete mixing assumption. The contours represent isoconcentration lines of salt normalized by injection concentrations (C_i/C_I). Values in the axes are distances from the lower left corner of the grid in m.

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Table 3. ANOVA Results Using Absolute Prediction Errors in Normalized Salt Concentration between the Complete and Incomplete Mixing Model

		Prediction errors in normalized salt concentration			
Data summary	Number of data	Average	Variance		
Complete mixing model	72	0.127	0.011		
Incomplete mixing model	72	0.036	0.001		
ANOVA					
Source of variation	Sum of square error	Degree of freedom	Mean square error	F	P-value
Between models	0.299	1	0.299	46.762	0.000
Within models	0.907	142	0.006		
Total	1.206	143			

sets. For the present study, however, the flow regime in the network ranges from quasi stagnant to laminar to transitional to turbulent flows. According to Choi et al. (2008), the junction mixing patterns in laminar and transitional regimes were slightly different from those in the turbulent regime. They concluded that a generalized and simplified model based on turbulent flows should be sufficient to improve the mixing model for all practical cases. Nevertheless, they also noted that a model tailored to each flow regime could further improve the prediction of solute transport in grid/loop pipe networks.

Fig. 3 shows the overall comparison of simulated and measured tracer concentrations of all three configurations. Clearly, the incomplete mixing model demonstrates a performance that is superior to the perfect mixing model in salt concentration simulation. The perfect mixing model significantly underestimated salt concentrations in the higher range and overestimated concentrations in the lower range, reflecting evenly dispersed solute in the network. The normalized simulated concentrations calculated by the perfect mixing model were generally in the range of 0.2–0.4. In contrast, the simulation results based on the incomplete mixing model are in excellent agreement with the experimental results over the entire salt concentration range with R square value of 0.935. The slope of the trend line was 0.936 for the incomplete mixing case, which is close to 1, indicating accurate prediction.

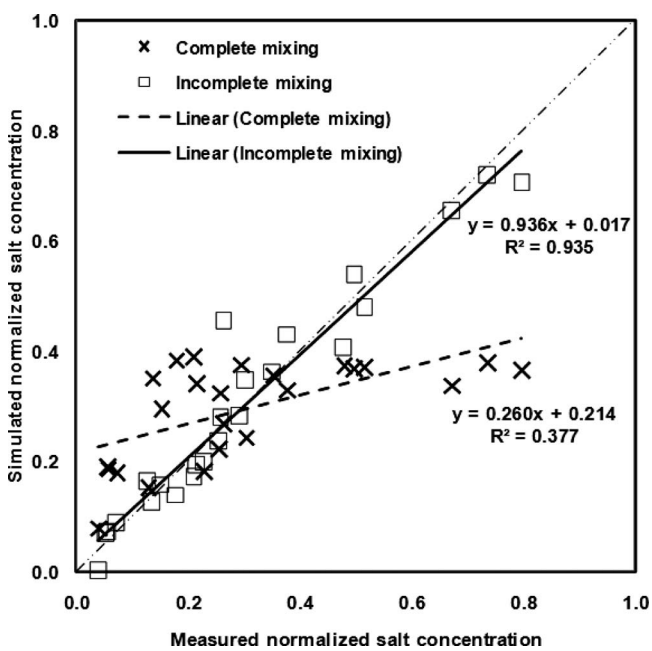

Fig. 3. Comparison of salt concentration values between the measured and the simulated runs (complete mixing versus incomplete mixing at cross junctions). The dash-dotted line denotes perfect agreement.

Conclusions

In the present study, a series of steady-state experiments in a pipe network successfully provided experimental data with which to evaluate the model performance in predicting solute transport in a pressurized pipe grid network. An averaged hydraulic error was 15%. The perfect mixing model tends to overestimate dilution at cross junctions and thus results in more even solute spreading throughout the network. In contrast, the incomplete mixing model predicted a narrow diagonal solute plume along the downstream region. Overall, the prediction error for salt concentration produced by the incomplete mixing model was 15% for the given 5×5 network. This error factor is significantly smaller than the 66% produced by the complete mixing model (P-value <0.001). In conclusion, the updated incomplete mixing model can convincingly improve the prediction of solute transport in pressurized pipe systems with multiple cross junctions. A full-scale field experiment is desired for future studies.

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References

Austin, R., van Bloemen Waanders, B., McKenna, S., and Choi, C. Y. (2008). "Mixing at cross junctions in water distribution systems—Part II. An experimental study." *J. Water Resour. Plan. Manage.*, 134(3), 295–302.

Choi, C. Y., Shen, J. Y., and Austin, R. (2008). "Development of a comprehensive solute mixing model (AZRED) for double-tee, cross, and wye junctions." *Proc., 10th Annual Water Distribution Systems Analysis Symp.*, ASCE, South Africa, 1004–1013.

Fowler, A. G., and Jones, P. (1991). "Simulation of water quality in water distribution systems." *Proc., Water Quality Modeling in Distribution Systems*, AWWA/EPA, Cincinnati.

Grayman, W. M., Rossman, L. A., and Geldreich, E. E. (1999). "Water

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quality." *Water distribution systems handbook*, L. W. Mays, ed., McGraw-Hill, New York.

Laird, C. D., Biegler, L. T., and van Bloemen Waanders, B. (2006). "Mixed-integer approach for obtaining unique solutions in source inversion of water networks." *J. Water Resour. Plann. Manage.*, 132(4), 242–251.

Laird, C. D., Biegler, L. T., van Bloemen Waanders, B., and Bartlett, R. A. (2005). "Contamination source determination for water networks." *J. Water Resour. Plann. Manage.*, 131(2), 125–135.

Lansey, K. E., Delgado, D., and Banihani, Q. (2007). "Discussion of Mixed-integer approach for obtaining unique solutions in source inversion of water networks by C. D. Laird, L. T. Biegler, B. van Bloemen Waanders." *J. Water Resour. Plann. Manage.*, 133(6), 573–575.

McKenna, S. A., O'Rear, L., and Wright, J. L. (2007). "Experimental determination of solute mixing in pipe joints." *Proc., World Water and Environmental Resources Congress*, ASCE/EWRI, Tampa, Fla.

Romero-Gomez, P., Choi, C. Y., van Bloemen Waanders, B., and McKenna, S. A. (2006). "Transport phenomena at intersections of pressurized pipe systems." *Proc., 8th Annual Water Distribution Systems Analysis Symp.*, ASCE, Cincinnati.

Romero-Gomez, P., Ho, C. K., and Choi, C. Y. (2008a). "Mixing at cross junctions in water distribution systems – Part I. A numerical study." *J. Water Resour. Plann. Manage.*, 134(3), 285–294.

Romero-Gomez, P., Li, Z., Choi, C. Y., Buchberger, S. G., Lansey, K. E., and Tzatchkov, V. T. (2008b). "Axial dispersion in pressurized pipe under various flow conditions." *Proc., 10th Annual Water Distribution Systems Analysis Symp.*, ASCE, South Africa, 1015–1024.

Rossman, L. (2000). *EPANET—User's manual*, United States Environmental Protection Agency (USEPA), Cincinnati, Ohio.

van Bloemen Waanders, B., Hammond, G., Shadid, J., Collis, S., and Murray, R. (2005). "A comparison of Navier-Stokes and network models to predict chemical transport in municipal water distribution systems." *Proc., World Water and Environmental Resources Congress*, ASCE/EWRI, Anchorage, Alaska.

Webb, S. W. (2007). "High-fidelity simulation of the influence of local geometry on mixing in crosses in water distribution systems." *Proc., 9th Annual Water Distribution System Analysis Symp.*, ASCE/EWRI, Tampa, Fla.

Webb, S. W., and van Bloemen Waanders, B. (2006). "High fidelity computational fluid dynamics for mixing in water distribution systems." *Proc., 8th Annual Water Distribution System Analysis Symp.*, ASCE, Cincinnati.

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