Mixing at double-Tee junctions with unequal pipe sizes in water distribution systems

Tingchao Yu, Hongying Qiu, Jeffrey Yang, Yu Shao and Liang Tao

ABSTRACT

Pipe flow mixing with various solute concentrations and flow rates at pipe junctions is investigated. The degree of mixing affects contaminant spread in a water distribution system, and many studies have focused on mixing at the cross junctions; however, only a few have focused on double-Tee junctions of unequal pipe diameters. To investigate the solute mixing at such junctions, a series of experiments was conducted in a turbulent regime (Re = 12,500–50,000) with different Reynolds number ratios and connecting pipe lengths. Dimensionless outlet concentrations were found to depend on mixing mechanism at the impinging interface of junctions, where junctions with a larger pipe diameter ratio were associated with more complete mixing. Further, the inlet Reynolds number ratio affected mixing more strongly than the outlet Reynolds number ratio. Finally, the dimensionless connecting pipe length in a double-Tee played an important and complicated role in the flow mixing. The results were used to develop two-dimensional isopleth maps for the calculation of normalized north outlet concentrations.

Key words | double-Tee junctions, solute mixing, unequal pipe sizes, water distribution systems

Tingchao Yu
Hongying Qiu
Yu Shao (corresponding author)
Liang Tao
Department of Civil Engineering,
Zhejiang University and Key Laboratory of Drinking Water Safety and Distribution Technology of Zhejiang Province,
Hangzhou 310058,
China
E-mail: *shaoyu1979@zju.edu.cn*

Jeffrey Yang
U.S. EPA, Office of Research and Development,
National Risk Management Research Laboratory,
Cincinnati,
Ohio 45268,
USA

INTRODUCTION

Contaminant transport in water distribution systems (WDSs) is a growing concern because of the potential occurrence of accidental or intentional contamination events that threaten the safety of WDSs (Ho 2008). Therefore, understanding the transport and mixing of either chemical or biological contaminants within WDSs is crucial to develop corresponding mitigation plans for contamination events (Romero-Gomez *et al.* 2011). EPANET software (Rossman 2000) is widely used to model the hydraulic and water quality variations in WDSs; however, it considers only cross-junctions, where it assumes that the mixing of solutes is complete and instantaneous. In contrast, recent research has shown incomplete mixing is widespread at pipe junctions (Fowler & Jones 1991; Ashgriz *et al.* 2001; Webb & van Bloemen Waanders 2006; Austin *et al.* 2008; Yu *et al.* 2014a), and thus the complete-mixing assumption is often a significant source of discrepancy between model predictions and field measurements of solute concentrations.

The assumption of instantaneous and complete mixing is unrealistic because of the limited interaction time between the two inlet flows at the cross junctions. Orear *et al.* (2005) concluded that transient instabilities at the impinging interface significantly affected the mixing at joints. Van Bloemen Waanders *et al.* (2005) found incomplete mixing as a result of the reflection of equal inlet flows at a cross junction. However, if the incoming flow rates are unequal, the degree of mixing increases but is still incomplete (Romero-Gomez *et al.* 2006). Several recent studies (Ho *et al.* 2006; McKenna *et al.* 2007; Webb 2007; Ho 2008; Romero-Gomez *et al.* 2008) have presented experimental and numerical results of single cross-junctions, which show

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incomplete mixing because of transient instabilities at the impinging interface. Computational and experimental investigations by Romero-Gomez et al. (2008), Austin et al. (2008), and Choi et al. (2008) identified the Reynolds number ratios of inlets and outlets as the significant mixing variables. More recently, Yu et al. (2014a) found that the Reynolds number ratio of inlets was the most important factor, followed by the pipe diameter ratio and the Reynolds number ratio of outlets.

For the Tee junctions that are common in a WDS, flow mixing has been investigated for decades – see for example Breidenthal (1981) and Holdeman (1993). More recently, Plesniak & Cusano (2005) found that flow mixing increased with turbulence at the Tee junction interface, while Webb & Van Bloemen Waanders (2006) used computational fluid dynamics models to simulate mixing behaviors at double-Tee junctions with 2.5 times of the diameter of the connecting-length pipe. They found dimensionless concentrations for the two outlets of 0.59 and 0.41, respectively. Such results differed considerably from the experimental findings of Yu et al. (2014b). In Shao et al. (2014), the flow and solute mixing for double-Tee junctions were reasonably described by an analytical solution. Flow mixing for the unequal pipe diameters was not discussed.

The present study further extends the work of Yu et al. (2014b) to the mixing behaviors at double-Tee junctions of unequal pipe sizes. The aim is to examine the governing mechanisms that determine flow-mixing behavior under variable flow conditions, leading to the development of a generalized model for pipe junction mixing.

MATERIALS AND METHODS

Mixing parameters

The Tee-junction joint configuration used in the experiments below comprised two adjacent inlets, a connected pipe, and two outlets, as shown in Figure 1. Pipes were labelled using geographic notations as W (west inlet, tracer water with high concentration C_W), S (south inlet, clean water with low concentration C_S), E (east outlet, concentration C_E), and N (north outlet, concentration C_N). Sodium chloride (NaCl) was used as the tracer. The main pipe had a diameter of $D = D_S = D_N$ and the branches had a diameter of $D_W = D_E$. To describe the degree of mixing, the dimensionless concentration (C_N^*) for the north outlet was introduced (Ho 2008) as:

$$C_N^* = \frac{C_N - C_S}{C_W - C_S}. \tag{1}$$

Experimental method

Branch pipes are usually smaller than the main pipe, with a minimum of half the diameter of the main pipe at most

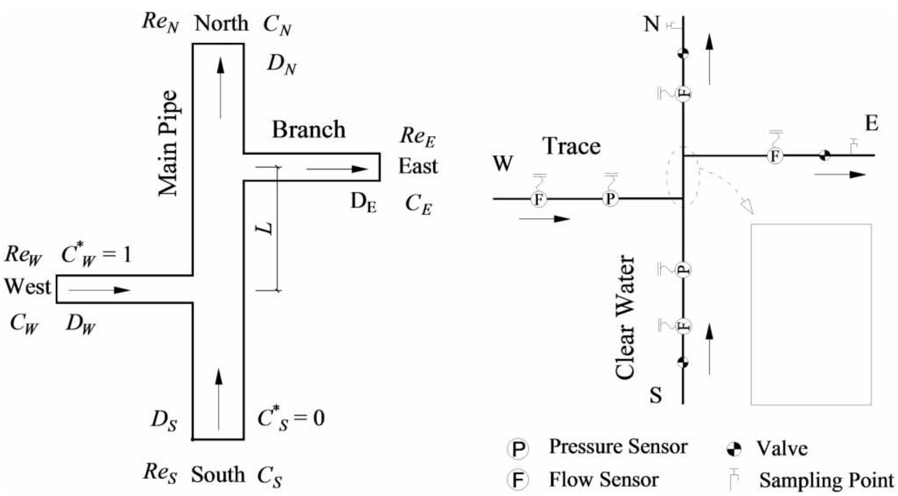

Figure 1 | Double-Tee junction configuration and the mixing picture of colored water.

junctions. Initially, three potential diameter ratios ($D_W/D =$ 25:25, 25:32 and 25:50) were considered for an investigation of the effect of pipe diameters on mixing, and because equal pipe diameters were studied in Yu *et al.* (2014b), two unequal diameter ratios ($D_W/D = 25$:32 and 25:50) were ultimately selected. In terms of pipe length, the minimum of the dimensionless connecting pipe length (L/D) is 2.5 to allow sufficient space between the two branch pipes for the installing operation. Further, because a dimensionless connecting pipe length (L/D) greater than 10.0 should produce complete mixing (Shao *et al.* 2014), four dimensionless connecting pipe lengths ($L/D = 2.5$, 5.0, 7.5, and 10.0) were included in the study. Finally, the hydraulic parameters $Re_{W/S}$ and $Re_{N/E}$ were chosen. All experimental cases are listed in Table 1. Note that the experimental setup and approach were based on the work of Yu *et al.* (2014b), and every experiment was repeated three times to obtain average results. The percent mass fraction error, as defined by McKenna *et al.* (2007), ranged from −1.0 to 3.0% for most experimental runs, indicating well-controlled experimental conditions and measuring apparatuses.

RESULTS AND DISCUSSION

The experimental results at double-Tee junctions with different L/D and D_W/D were used to determine dimensionless concentrations, C_N^*, under varying flow conditions. $C_N^* = 1$ indicates equal concentrations at the west inlet and at the north outlet for a perfect flow bifurcation, while $C_N^* = 0$ means that the concentrations at the south inlet and north outlet are equal.

Effect of flows on mixing

The experimental results show the significant effect of relative flow rates on solute mixing at pipe junctions. The C_N^* values were significantly affected by $Re_{W/S}$ when $Re_{N/E} = 1$ (Figure 2(a) and 2(b)). As $\mathrm{Re}_{W/S} \rightarrow 0$, the C_N^* value at double-Tee junctions tended toward that of cross junctions: specifically, a small to insignificant flow from the west inlet was able to penetrate and mix with the large flow from the south inlet. Conversely, the C_N^* value indicated complete mixing because the west inlet flow increased relative to south inlet flow under an increasing $Re_{W/S}$. When the flow velocity at the west inlet was twice as large as the velocity at the south inlet (i.e., $Re_{W/S} \geq 1.50$ for $D_W/D = 25/32$ or $Re_{W/S} \geq 1.0$ for $D_W/D = 25/50$), the C_N^* value coincided with that of complete mixing for double-Tee junctions with $L/D \geq 5.0$.

Flow mixing at double-Tee junctions with equal pipe diameters is a special condition, with C_N^* values larger than that of complete mixing, but smaller than that of cross-mixing (Yu *et al.* 2014b). In such a configuration, connecting pipe segments offer more space and time for flow mixing than the cross junctions. However, Figure 2(b) shows that the C_N^* value at double-Tee junctions with $D_W/D = 25/50$ exceeded that of cross mixing, when $Re_{W/S} = 2.0$ and $L/D \geq 5.0$, or $Re_{W/S} = 4.0$ and $L/D \geq 2.5$, where the high-speed flow from the west inlet penetrated the main pipe

Table 1 | List of the experimental conditions

Group	D_W/D	L/D	$Re_{W/S}$	$Re_{N/E}$
1	25/32	2.5	0.25,0.5,0.67,1.0,1.5, 2.0,4.0	0.25,0.5,0.67,1.0,1.5, 2.0, 4.0
2		5.0	0.25,0.5,0.67,1.0,1.5, 2.0,4.0	0.25,0.5,0.67,1.0,1.5, 2.0, 4.0
3		7.5	0.25,0.5,0.67,1.0,1.5, 2.0,4.0	0.25,0.5,0.67,1.0,1.5, 2.0, 4.0
4		10.0	0.25,0.5,0.67,1.0,1.5, 2.0,4.0	0.25,0.5,0.67,1.0,1.5, 2.0, 4.0
5	25/50	2.5	0.25,0.5,0.67,1.0,1.5, 2.0,4.0	0.25,0.5,0.67,1.0,1.5, 2.0, 4.0
6		5.0	0.25,0.5,0.67,1.0,1.5, 2.0,4.0	0.25,0.5,0.67,1.0,1.5, 2.0, 4.0
7		7.5	0.25,0.5,0.67,1.0,1.5, 2.0,4.0	0.25,0.5,0.67,1.0,1.5, 2.0, 4.0
8		10.0	0.25,0.5,0.67,1.0,1.5, 2.0,4.0	0.25,0.5,0.67,1.0,1.5, 2.0, 4.0

Note: Diameters of main pipes are 32 mm and 50 mm, diameter of the branch pipe size is 25 mm.

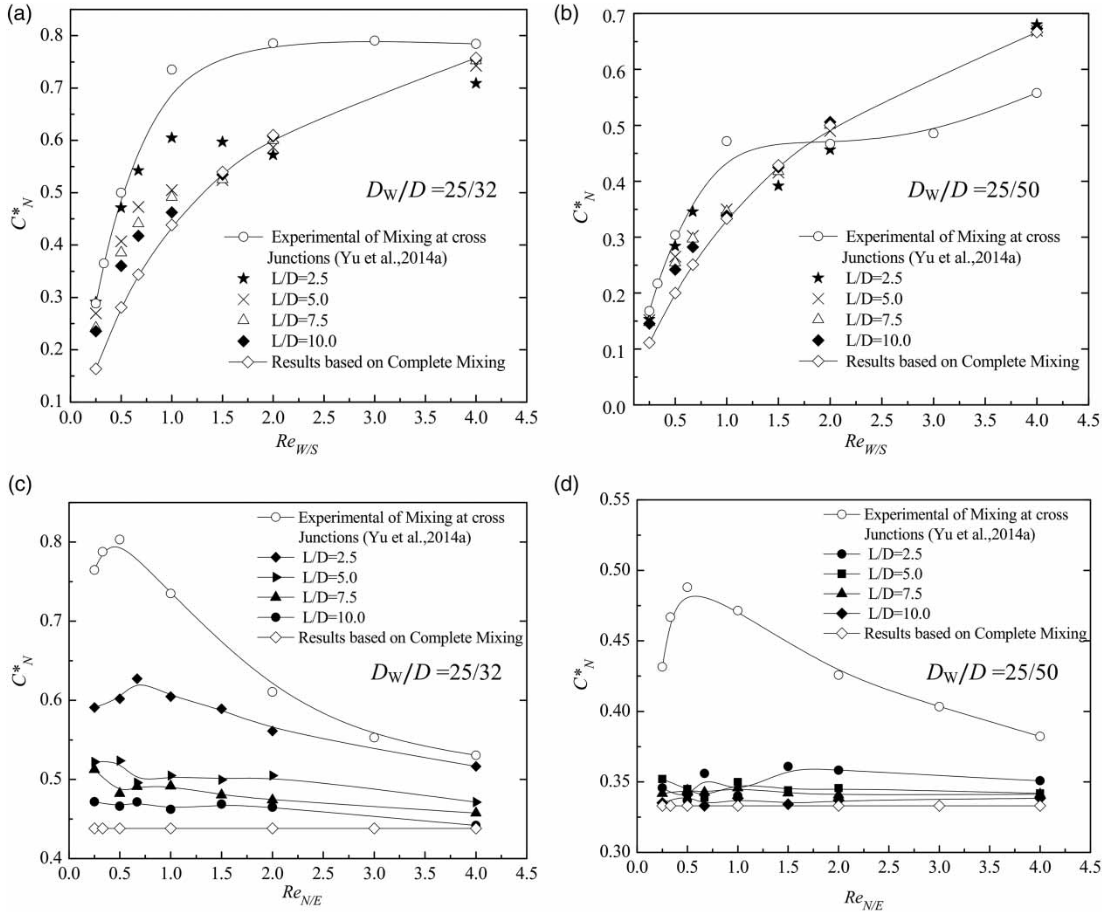

Figure 2 | Normalized north outlet concentration with $D_W/D = 25/32$ and 25/50: (a) and (b) $Re_{W/S} \neq 1$ and $Re_{N/E} = 1$; (c) and (d) $Re_{W/S} = 1$ and $Re_{N/E} \neq 1$.

flow. For the cross junctions, the flow may directly enter the opposite east outlet. However, for double-Tee junctions with certain connecting pipe segments (i.e., $L/D \geq 5.0$), the flow may be impeded from opposite pipe wall, allowing more mixing in the collection pipe segment (Shao *et al.* 2014); as a result, less tracer water flows into the east outlet as compared with the cross-mixing conditions.

Where the C_N^* values lay between complete mixing and cross mixing (Figures 2(c) and 2(d)), the general C_N^* variations showed little change with varying $Re_{N/E}$, which indicates that mixing at double-Tee junctions is insensitive to the Reynolds number ratio of the outlets. For the junction of $D_W/D = 25/32$, the mixing was closer to cross mixing than complete mixing for $L/D = 2.5$, while complete mixing was approached when $L/D \geq 5.0$. For the junction of $D_W/D = 25/50$, the C_N^* value matched that for complete mixing.

Effect of pipe sizes on mixing

The pipe diameter ratio (D_W/D) can affect the degree of mixing at double-Tee junctions because it changes the junction geometry. Figure 3 shows normalized north outlet concentrations for $L/D = 5.0$ and $D_W/D = 25/25$, 25/32, and 25/50, when $Re_{W/S}$ is made to equal $Re_{E/N}$ through adjustment of the flow rates. Note that the $D_W/D = 25/25$ results are from Yu *et al.* (2014b). The different pipe diameters resulted in different flow velocities for a given Reynolds number or flow rate, and these velocity differences then caused intense turbulence during mixing. In addition, inlet flows from smaller pipes were encircled by the flow in the large pipe (e.g., Choi *et al.* 2008), which increased the contact surface of the two flows. Therefore, larger diameter differences between the branch and main pipes led to improved mixing at the double-Tee junctions

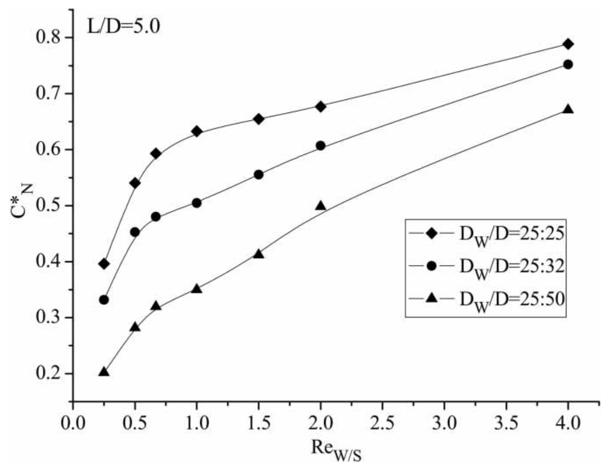

Figure 3 | Normalized north outlet concentration with $D_W/D = 25/25$, 25/32, and 25/50 when $Re_{W/S} = Re_{N/E}$.

(Figure 3). The pipe-diameter ratio had a similar effect on mixing for other dimensionless connecting pipe lengths of $L/D = 2.5$, 7.5, and 10.0.

Contour graphs of C_N^* and its usage

For $D_W/D = 25/32$ and 25/50, mixing experiments were conducted under 196 ($7 \times 7 \times 4$) flow conditions (Table 1), with each condition tested three times. The experimentally-determined C_N^* values are shown in logarithmic plots of $Re_{S/W}$ and $Re_{N/E}$. The C_N^* contour graphs for each dimensionless connecting pipe length are shown in Figures 4 and 5, while the C_N^* values for equal pipe diameters ($D_W/D = 25/25$) can be found in Shao *et al.* (2014) and Yu

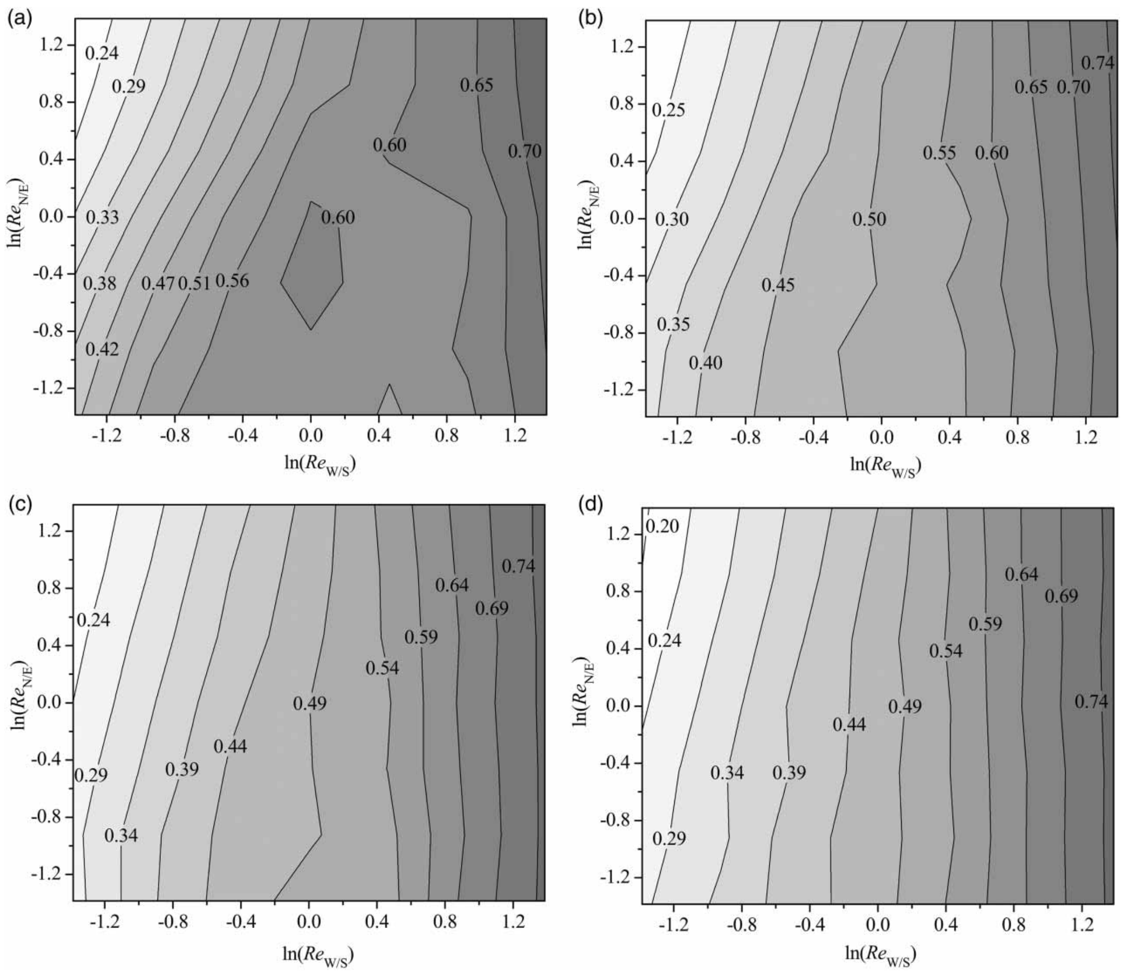

Figure 4 | Contour graphs of C_N^* with $D_W/D = 25/32$: (a) $L/D = 2.5$; (b) $L/D = 5.0$; (c) $L/D = 7.5$; and (d) $L/D = 10.0$.

et al. (2014b). For junctions of pipe diameters that satisfy the following flow conditions, $-1.0 \geq D_W/D \geq 0.5$, $10 \geq L/D \geq 0$, $4.0 \geq Re_{W/S} \geq 0.25$, and $4.0 \geq Re_{N/E} \geq 0.25$, linear interpolation can be used to obtain the predicted C^*_N value from the available contour graphs.

Figures 4 and 5 show clearly that C^*_N values decrease with an increase in L/D, for given $Re_{S/W}$ and $Re_{N/E}$, which demonstrates that the connecting pipe segments promoted mixing at the junctions. Further, the C^*_N value increased as $Re_{W/S}$ increased, but changed only slightly with $Re_{N/E}$ – and nearly paralleled the $Re_{N/E}$ axes – especially when $L/D = 7.5$ and 10.0.

The top-left corner of the contour map shows an extreme case of a very small inlet Reynolds number ratio ($Re_{W/S}$<0.25) coupled with a large outlet Reynolds number ratio ($Re_{N/E}$>1). This situation indicates that momentum in the main pipe was much larger than for the branch pipe, which caused nearly all of the tracer water to flow directly north and resulted in a bulk mixing. The bottom right corner of the contour map also shows an extreme case of a large inlet Reynolds number ratio ($Re_{W/S}$>1) and an extremely small outlet Reynolds number ratio ($Re_{N/E}$<0.25). Here, the momentum in the main pipe was smaller than that in the branch pipe, and the tracer water penetrated through the water in the main pipe and resulted in complete mixing. Under general conditions when $0.25 \leq Re_{W/S} \leq 1$ and $0.25 \leq Re_{N/E} \leq 1$, the hydraulic conditions and the geometric characteristics of junctions (D_W/D and L/D) had a more complicated effect on mixing. Additional experiments and computational studies were necessary to determine the mixing characteristics at double-Tee junctions of flows ranging from laminar to transitional flows.

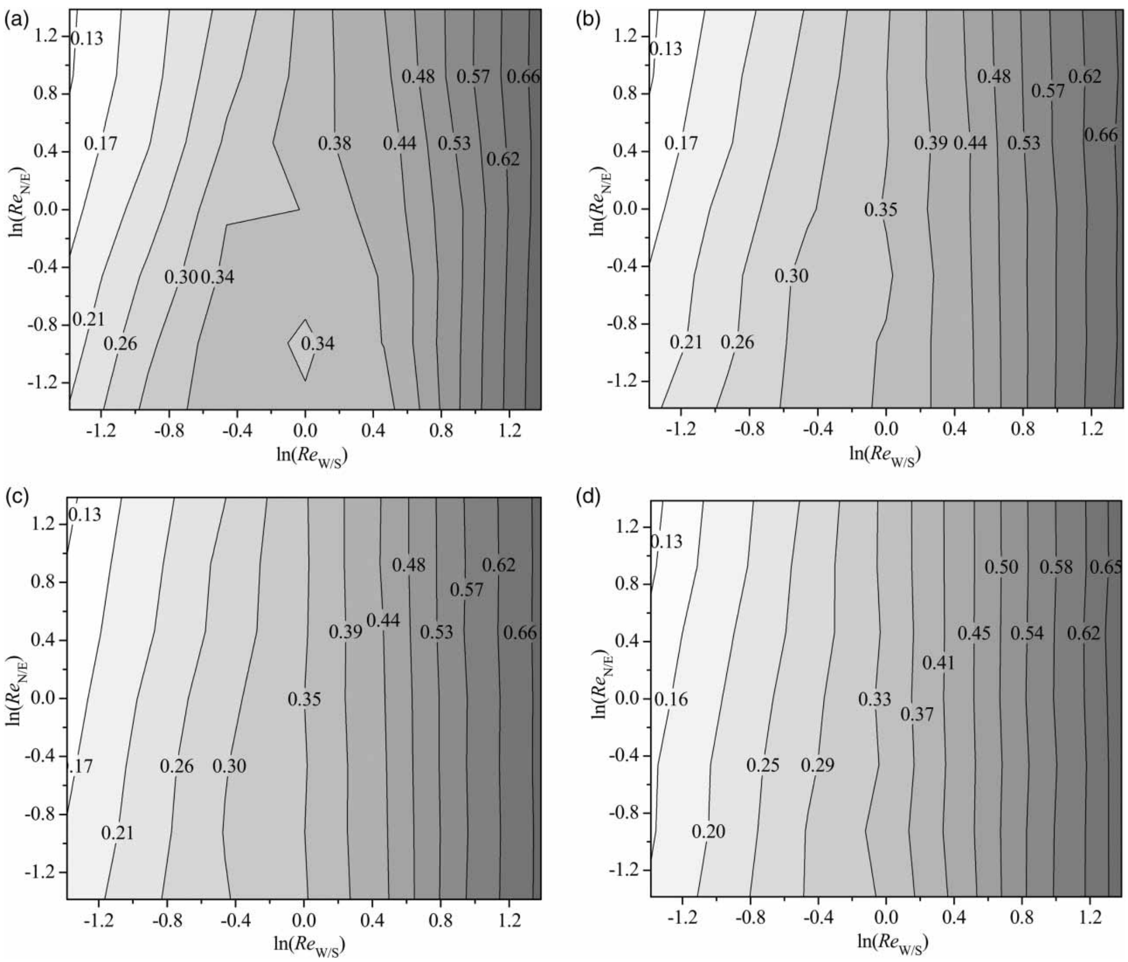

Figure 5 | Contour graphs of C^*_N with $D_W/D = 25/50$: (a) $L/D = 2.5$; (b) $L/D = 5.0$; (c) $L/D = 7.5$; and (d) $L/D = 10.0$.

CONCLUSIONS

Solute mixing phenomena at double-Tee junctions with unequal pipe diameters were investigated. The results should aid in predicting solute concentrations and quantifying water quality variations in a distribution pipe. The effect of the inlet and outlet Reynolds number ratios and the connecting pipe length on mixing were found to increase in complexity when unequal pipe diameters were considered. The larger the difference in the pipe diameters, the more complete the mixing. In addition, the inlet Reynolds number ratio exerted a greater impact on mixing than the outlet Reynolds number ratio, while the connecting pipe also promoted mixing at the connecting segments. These observations were generalized using two-dimensional contour graphs for a normalized north outlet concentration, based on which linear interpolation can be used to obtain predicted outlet solute concentrations for other flow and junction conditions.

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REFERENCES

Ashgriz, N., Brocklehurst, W. & Talley, D. 2001 Mixing mechanisms in a pair of impinging jets. *Journal of Propulsion and Power* **17** (3), 736–749.

Austin, R. G., Waanders, B. V. B., McKenna, S. & Choi, C. Y. 2008 Mixing at cross junctions in water distribution systems. II: experimental study. *Journal of Water Resources Planning and Management* **134** (3), 295–302.

Breidenthal, R. 1981 Structure in turbulent mixing layers and wakes using a chemical reaction. *Journal of Fluid Mechanics* **109**, 1–24.

Choi, C. Y., Shen, J. Y. & Austin, R. G. 2008 Development of a comprehensive solute mixing model (AZRED) for double-tee, cross, and wye junctions. In: *10th Annual Water Distribution Systems Analysis Symposium*, 17–20 August, Kruger National Park, South Africa.

Fowler, A. G. & Jones, P. 1991 Simulation of water quality in water distribution systems. In: *Proc. Water Quality Modeling in Distribution Systems*, 4–5 February, Cincinnati, OH, USA.

Ho, C. K. 2008 Solute mixing models for water-distribution pipe networks. *Journal of Hydraulic Engineering* **134** (9), 1236–1244.

Ho, C. K., Orear, L., Wright, J. L. & McKenna, S. A. 2006 Contaminant mixing at pipe joints: comparison between laboratory flow experiments and computational fluid dynamics models. In: *Proc., 8th Annual Water Distribution System Analysis Symposium*, 27–30 August, Cincinnati, OH, USA.

Holdeman, J. D. 1993 Mixing of multiple jets with a confined subsonic cross flow. *Progress in Energy and Combustion Science* **19** (1), 31–70.

McKenna, S. A., Orear, L. & Wright, J. 2007 Experimental determination of solute mixing in pipe joints. In: *Proceedings of the ASCE 2007 World Environmental and Water Resources Congress*, Tampa, FL, USA.

Orear, L., Hammond, G., McKenna, S. A., Molina, P., Johnson, R., O'Hern, T. & van Bloemen Waanders, B. G. 2005 Physical modeling of scaled water distribution systems networks. SAND2005-6776, Sandia National Laboratories, Albuquerque, NM, USA.

Plesniak, M. W. & Cusano, D. M. 2005 Scalar mixing in a confined rectangular jet in crossflow. *Journal of Fluid Mechanics* **524**, 1–45.

Romero-Gomez, P., Choi, C. Y., van Bloemen Waanders, B. & McKenna, S. A. 2006 Transport phenomena at intersections of pressurized pipe systems. In: *Proc., 8th Annual Water Distribution System Analysis Symposium*, 27–30 August, Cincinnati, OH, USA.

Romero-Gomez, P., Ho, C. K. & Choi, C. Y. 2008 Mixing at cross junctions in water distribution systems. I: numerical study. *Journal of Water Resources Planning and Management* **134** (3), 285–294.

Romero-Gomez, P., Lansey, K. E. & Choi, C. Y. 2011 Impact of an incomplete solute mixing model on sensor network design. *Journal of Hydroinformatics* **13** (4), 642–651.

Rossman, L. 2000 *EPANET User's Manual*. U.S.E.P. Agency (USEPA), Cincinnati, OH, USA.

Shao, Y., Jeffrey Yang, Y., Jiang, L., Yu, T. & Shen, C. 2014 Experimental testing and modeling analysis of solute mixing at water distribution pipe junctions. *Water Research* **56**, 133–147.

Van Bloemen Waanders, B., Hammond, G., Shadid, J., Collis, S. & Murray, R. 2005 A comparison of Navier-Stokes and network models to predict chemical transport in municipal water distribution systems. In: *Proc., World Water and Environmental Resources Congress*. ASCE/EWRI, 15–19 May, Anchorage, Alaska, USA.

Webb, S. W. 2007 High-fidelity simulation of the influence of local geometry on mixing in crosses in water distribution systems. In: *9th Annual Water Distribution Systems Analysis Symposium, ASCE/EWRI*, Tampa, Florida, USA.

Webb, S. W. & Van Bloemen Waanders, B. G. 2006 High fidelity computational fluid dynamics for mixing in water distribution systems. In: *8th Annual Water Distribution System Analysis Symposium*, 27–30 August, Cincinnati, Ohio, USA.

Yu, T. C., Shao, Y. & Shen, C. 2014a Mixing at cross joints with different pipe sizes in water distribution systems. *Journal of Water Resources Planning and Management* **140** (5), 658–665.

Yu, T. C., Tao, L., Shao, Y. & Zhang, T. Q. 2014b Experimental study of solute mixing at double-Tee junctions in water distribution systems. *Water Science & Technology: Water Supply* **15** (3), 474–482.

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