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Experimental testing and modeling analysis of solute mixing at water distribution pipe junctions

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ABSTRACT

Flow dynamics at a pipe junction controls particle trajectories, solute mixing and concentrations in downstream pipes. The effect can lead to different outcomes of water quality modeling and, hence, drinking water management in a distribution network. Here we have investigated solute mixing behavior in pipe junctions of five hydraulic types, for which flow distribution factors and analytical equations for network modeling are proposed. First, based on experiments, the degree of mixing at a cross is found to be a function of flow momentum ratio that defines a junction flow distribution pattern and the degree of departure from complete mixing. Corresponding analytical solutions are also validated using computational-fluid-dynamics (CFD) simulations. Second, the analytical mixing model is further extended to double-Tee junctions. Correspondingly the flow distribution factor is modified to account for hydraulic departure from a cross configuration. For a double-Tee(A) junction, CFD simulations show that the solute mixing depends on flow momentum ratio and connection pipe length, whereas the mixing at double-Tee(B) is well represented by two independent single-Tee junctions with a potential water stagnation zone in between. Notably, double-Tee junctions differ significantly from a cross in solute mixing and transport. However, it is noted that these pipe connections are widely, but incorrectly, simplified as cross junctions of assumed complete solute mixing in network skeletonization and water quality modeling. For the studied pipe junction types, analytical solutions are proposed to characterize the incomplete mixing and hence may allow better water quality simulation in a distribution network.

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1. Introduction

Solute mixing and transport at pipe junctions is complicated due to the secondary currents at the junctions and the flow instabilities at the interface of inflow streams. Both enhance turbulence and mixing between the water inflows of different composition. In a distribution network of normal flow velocities, however, short mixing time at the junction makes complete mixing to be unrealistic. How to account for and

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calculate the degree of mixing is essential for network simulations and system operations in drinking water supplies, particularly for water quality management.

EPANET (Rossman, 2000), widely used for hydraulic and water quality modeling of a water distribution system, assumes complete mixing of a solute such as free chlorine at a pipe junction. The assumed complete mixing was first studied by Flower and Jones (1991) and subsequently evaluated by others in EPANET applications. Van Bloemen Waanders et al. (2005) pointed out that the flows in cross junctions tend to bifurcate and reflect off one another, rather than to mix completely. O'Rear et al. (2005) concluded that the relative flow rates entering and leaving the junction can significantly affect the degree of mixing. Several others (Ho and O'Rear, 2009; Ho et al., 2006; Romero-Gomez et al., 2008) showed the usefulness of computational fluid dynamics (CFD) in describing the mixing behavior at the flow impinging interface when the fluid turbulence model and parameters are carefully selected. Experimental investigations (Austin, 2008; Ho, 2008; Ho and O'Rear, 2009) further showed that mixing is far from "complete" at the cross junctions and the outlet concentrations depend on junction geometry and the flow rates of inlets and outlets.

Various attempts have been made to improve the applicability of EPANET-based water quality models for pipe junctions that are numerous in a water distribution network. Ho and Khalsa (2008) described a bulk-advective mixing (BAM) model and the corresponding EPANET software extension, EPANET-BAM. It employs a mixing parameter for users to select linearly scaled results between the bulk mixing and the complete mixing. Ho and O'Rear (2009) also introduced a bulk-advective mixing wrap (BAM-WRAP) model in the EPANET-BAM extension for pipes of unequal size, assuming the flow can be divided into "core" and "wraparound" regions. It is noted, however, both EPANET-BAM and BAM-WRAP require a predetermination of the mixing parameter by linear interpolation between the two mixing end members. This required modeling input varies non-linearly, as shown in later sections, and consequently a precise determination of solute concentrations at outlets remains a challenge. Other CFD-based numerical solutions with experimental verification to calculate solute concentration at all types of pipe junctions have been reported in literature (e.g., Choi et al., 2008; Romero-Gomez, 2010; Romero-Gomez et al., 2008).

This study is focused on developing analytical solutions, rather than numerical simulations, to determine incomplete solute mixing at the cross junction and double-Tee pipe joints. The challenge to this attempt comes from a wide range of cross and double-Tee pipe joint configurations in a real-world distribution network and consequently solute transport. Here we describe the experimental and CFD simulation results and corresponding analytical solutions for the cross junction and double-Tee pipe joints under turbulent flow regime. Results for laminar and transitional flows will be reported elsewhere. Other pipe configurations such as WYE pipe branching have been reported previously (e.g., Choi et al., 2008; Song et al., 2009), for which analytical solutions await to emerge.

In describing the investigation results, we first define the common flow hydraulic configurations in pipe junctions for analysis and quantify the cross junction mixing using experimental results. Second, the developed cross junction mixing model is extended for double-Tee junctions by using experimental verified CFD simulations and experimental validation. The objective is to develop simple mixing models for these pipe junctions in water quality simulation.

2. Methodology: model and experiments

The investigation consists of experimental testing and CDF simulation of solute mixing at cross and double-Tee pipe junction configurations (Fig. 1). The modeling and experiments are focused on the flow distribution factor, a proposed variable to describe the solute concentration changes at the cross and double-Tee pipe junctions.

2.1. *Investigated pipe junction configurations*

A wide range of pipe cross and double-Tee configurations can be found in design and field engineering of a distribution system. They are all treated in network skeletonization as a cross connection of assumed complete mixing, for which the water quality simulation is prone to errors (Choi et al., 2008; Ho, 2008). In this investigation, experimental testing and CFD analysis are focused on five types of flow hydraulics configurations (Fig. 2): double-Tee(A), double-Tee(B), double-Tee(C), Cross(D) and Cross(E) junctions. For a pipe cross, two inflows can be in adjacent or opposite positions as shown in Fig. 2d and e, respectively. Complete mixing is plausible for Cross(E). Notably, a pipe cross is a special case of a double-Tee junction when the connecting pipe length $l = 0$ or pipe length and diameter (D) ratio $l/D \rightarrow 0$. Three general double-Tee junctions are: (1) double-Tee(A) defined for two inlet streams approaching the junction from adjacent directions, or at 90°; (2) double-Tee(B) having two inlet streams from opposite directions (i.e., at 180°); and (3) double-Tee(C) is equivalent to Cross(D) at $l/D = 0$ and a variance of Double-Tee(B) when $l/D > 0$. Thus only three pipe junction types – Cross(D), double-Tee(A) and double-Tee(B) (Fig. 2) are unique in flow configurations and are selected for the focus of this study. Pipe U and WYE junctions can be seen as the variations of the 90° double-Tee junction at different angles.

For the Cross, single-Tee and double-Tee junctions, two other flow configurations may exist: (1) single inlet flow

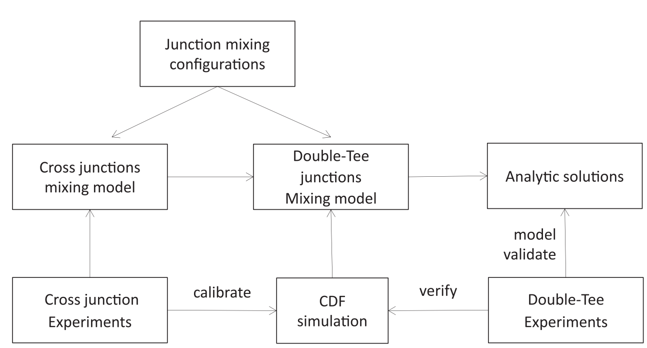

Fig. 1 – Flow chart of the experimental and CDF investigation to develop junction mixing analytical models.