NUMERICAL MODELING OF PREMISE PLUMBING SYSTEM CONSIDERING DISPERSION EFFECT

Hyoungmin Woo¹, Jonathan Burkhardt², Lewis Rossman³, James Mason⁴, Regan Murray⁵

¹Oak Ridge Institute for Science and Education
²,⁵USEPA, National Risk Management Research Laboratory
³USEPA, Emeritus
⁴Oak Ridge Associated Universities
Outline

• Introduction to Premise Plumbing System
• Dispersion Modeling
• Modeling Methods
• Results
• Conclusions

Disclaimer. The information in this presentation has been reviewed and approved for public dissemination by the U.S. Environmental Protection Agency (EPA). The views expressed in this presentation are those of the authors and do not necessarily represent the views or policies of the Agency. Any mention of trade names or commercial products does not constitute EPA endorsement or recommendation for use.
Introduction

• Water quality in premise plumbing systems (PPS)
  • Increase in public awareness of the importance of safe drinking water in homes and buildings
  • Risk of exposure to contaminants (e.g., lead or legionella) from water in homes or buildings

• Quality of water and potential exposure at the end use is affected by numerous factors:
  • Plumbing materials, dimensions and layout
  • Water chemistry
  • Number of residents and their usage patterns
  • System hydraulics
Introduction

• Premise plumbing has several unique characteristics

Hydraulic Aspects
• High Water Age
• Variable Velocities

Water Quality Aspects
• High Surface Area to Volume Ratio
• Different Materials
• Extreme Temperatures
• Low Residual Disinfectant
• Multiple Exposure Pathways (contact, ingestion, aerosols)

Sources
• Surface
• Ground

Water Distribution System

Drinking Water Treatment Plant
Premise Plumbing
Reservoirs Residences

Physical-chemical Filtration Disinfection Reservoir

Intermittent Uses

https://www.nap.edu/read/11728/chapter/10
 Dispersion Modeling

• Burkhardt et. al (2018), demonstrated the limitations of using EPANET to simulate the water quality of PPS by comparing to real data
  • EPANET does not accurately model the water quality of PPS (time alignment, peak)
  • EPANET assumes uniform flow in the pipe, solves advection and reaction equations

• Dispersion plays an important role in water quality prediction
  • Dead end, laminar flow, transition flow, chlorine decay

• Modeling of PPS also needs to consider dispersion due to the change of velocity in the pipe, specially in the laminar flow regimes

![Diagram showing uniform and non-uniform flow](image.png)
Modeling Methods

• General transport equation: Advection - Reaction - Dispersion (ARD)
  • Governing partial differential equation (PDE)
  \[
  \frac{\partial C}{\partial t} = -u \frac{\partial C}{\partial x} + D \frac{\partial^2 C}{\partial x^2} - KC
  \]
  where \( u \) = velocity, \( D \) = diffusion and dispersion coefficients, \( K \) = reaction coefficients

• Analytical solutions are available for special or simplified cases only.
  Ex) Stagnant or steady-state flow with special condition (continuous injection or instantaneous injection)

• Numerical solutions are available for certain conditions.
  • Transport equation is combined with two different types of PDEs
    (Advection – hyperbolic PDE, Dispersion – parabolic PDE)
Model Parameters

- Lead dissolution reaction model
  - $1^{st}$ order saturation model for stagnant condition (Van Der Leer, 2002)

- Dimensionless dispersion coefficients
  - Dimensionless dispersion coefficients in premise plumbing system (Woo et al., 2018)

\[
\frac{dc}{dt} = \frac{AM}{V} \left( \frac{E - c}{E} \right)
\]

where

- $A =$ internal area, $V =$ volume of pipe,
- $M =$ mass transfer rate,
- $E =$ plumbosolvency (a measure of the extent of lead dissolution)

Fig 1. Stagnation curve for a lead propensity

Fig 2. Comparison of the dimensionless dispersion coefficients
Numerical Implementation

- Hydraulic simulation - used the EPANET 2.2 toolkit
- Quality simulation - used the operator splitting technique
  - Eulerian - Lagrangian splitting method: decompose unwieldy (systems of) PDEs into simpler subproblems and treat them individually using specialized numerical algorithms (Divide-and-conquer strategy)
  - Advection - Method of Characteristics (MOC)
  - Reaction – 1st order saturation growth model
  - Dispersion - Backward Time Central Space (BTCS) Finite Difference Method
- Using C++ for calculation and Python for graphical representation
Example of Dispersion effect

Simple Example

- Lead dissolution at lead service line

Contaminant transport in a pipe

Comparison results between EPANET and EPANET-ARD model at Node 4

- Arrival time difference
  - EPANET: 57 ug
  - ARD: 56.7 ug

- Peak difference (77 ug/L)
  - EPANET: 147.56 ug/L
  - ARD: 70.53 ug/L

- Total mass
  - EPANET: 57 ug
  - ARD: 56.7 ug

- Duration
  - EPANET: 6:04:02
  - ARD: 6:16:54
Verification of Model using Data from Home Plumbing System Simulator

- **Experimental setup**
  - Home Plumbing System Simulator

- **Sequential Sampling**

```
Inlet

Lead Service Line (D 5/8” – length)

Copper pipe (D 1/2” – Length)

Concentration

$C_C$ @ LSL

$u$ @ Faucet

Flow: 3000 ml/min, Sampling: 1000 ml/bottle

Lead Concentration (ppb)
```

Inlet sample

Outlet sample

Inlet

Faucet #1

Faucet #2

Toilet

Faucet #3

Shower

Faucet #4

Faucet #5

Valve

Sampling Port

Lead Service Line

Copper pipe

• EPANET 2.2
• Total Duration : 4 week (650 hrs)
• Hydraulic time step: 1 sec
• Quality time step: 1 sec
• Lead saturation conc: 140 ppb
HPSS Modeling Results

EPANET

EPA Test Home System

Node 2: LSL lead concentration after stagnation
F4C: closest to LSL
F2C
SHC: shower – highest usage

F1C: longest path from LSL
most prevailing number < 0.2 ppb
HPSS Modeling Results

EPANET-ARD

LSL

F1C: longest path

most prevailing value < 2-6 ppb

Node 2:

F4C: closest location - frequency

F2C

SHC: shower – highest usage
Comparison between EPANET and EPANET-ARD
Comparison to Samples

Comparison to 1st Draw Sample

- Sampling data details
  - Location: Faucet #3
  - Method: 1st draw sample with 1 Liter bottle
  - Frequency: Twice a week after 16 hours stagnation
  - Duration: 30 week periods

- EPANET-ARD has improved agreement with sampling data compared to EPANET
• Contaminant transport modeling of a PPS
  • PPS modeling needs to consider dispersion effects for realistic results (base concentration level, peak intensity, and duration).

• Demonstration of EPANET-ARD model
  • Lead dissolution reaction model and solute transport model were integrated with EPANET hydraulic simulation.
  • Proposed model was verified with sequential sampling data from HPSS.

• Comparison of simulation results to experimental data
  • HPSS operated to simulate a realistic usage pattern within a four-person residence.
  • EPANET-ARD model results compared favorably to HPSS sample data collected for 30 weeks of simulation.
Future Work

• Model integration to EPANET – full implementation in EPANET for PPS model
• Real home application – model application to water quality data from real home and buildings
• Further probabilistic lead exposure assessment study for public drinking water
• Application to different contaminants
Thank you!

For more information contact:

Jonathan Burkhardt: burkhardt.jonathan@epa.gov
Regan Murray: murray.regan@epa.gov
Literature Review

- Literature Review for numerical methods for solute transport
  - 1975 Holly – numerical diffusion remains a concern for all FDM for pure advective transport
  - 1984 Baptista – dispersion dominant and advection dominant
  - 1994 Chaudhry and Islam – two step Lax-Wendroff scheme
  - 1996 Barry et al. - the Runge-Kutta method
  - 1998 Islam and Chaudhry – Priessman four-point implicit scheme for water quality analysis to reduce numerical diffusion.
  - 2002 Tzatchkov et al. – numerical green function
  - 2005 Zhang et al. – split-operator technique
  - 2006 Li – introduce laminar dispersion into Tzatchkov model (ADRnet)
  - 2007 Basha and Malaeb - Eulerian - Lagrangian splitting method
• Explicit finite difference technique – forward–time centered-space (FTCS)

\[
\frac{\partial C}{\partial t} = -u \frac{\partial C}{\partial X} + D \frac{\partial^2 C}{\partial X^2} \quad \text{and} \quad \frac{C_{i}^{n+1} - C_{i}^{n}}{\Delta t} = -u \frac{C_{i+1}^{n} - C_{i-1}^{n}}{2\Delta t} + D \frac{C_{i}^{n+1} - 2C_{i}^{n} + C_{i-1}^{n}}{2(\Delta x)^2}
\]

• Operator Splitting Technique
  • Divide-and-conquer strategy: decompose unwieldy (systems of) PDEs into simpler subproblems and treat them individually using specialized numerical algorithms
  • Eulerian - Lagrangian splitting method (ELM)

\[
\frac{\partial C}{\partial t} = -u \frac{\partial C}{\partial X} + D \frac{\partial^2 C}{\partial X^2} \quad \Rightarrow \quad \mathcal{L}(C) = C_t + uC_x - DC_{xx} = 0 \quad \Rightarrow \quad \mathcal{L}(C) = \mathcal{L}_1(C) + \mathcal{L}_2(C)
\]

\[
\frac{1}{2} \frac{\partial C}{\partial t} = -u \frac{\partial C}{\partial x} \quad \mathcal{L}_1(C) = \frac{\partial C}{\partial t} + 2u \frac{\partial C}{\partial x} = 0
\]

\[
\frac{1}{2} \frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \quad \mathcal{L}_2(C) = \frac{\partial C}{\partial t} - 2D \frac{\partial^2 C}{\partial x^2} = 0
\]
Advection Step

\[ L_1(C) = \frac{\partial C}{\partial t} + 2u \frac{\partial C}{\partial x} = 0 \]

Dispersion Step

\[ L_2(C) = \frac{\partial C}{\partial t} - 2D \frac{\partial^2 C}{\partial x^2} = 0 \]

\[ \frac{\Delta t_q}{2} \]

\[ \Delta x \]

\[ u \Delta t_q \]

\[ \Delta x \]

\[ \Delta t_q \]

\[ \Delta x \]

\[ \frac{\Delta t_q}{2} \]

\[ \frac{\Delta t_q}{2} \]

Appling Interpolation method

\[ \frac{C_{i+1/2}^{n+1} - C_{i+1/2}^n}{\Delta t} = -u \rightarrow C_{i+1/2}^{n+1/2} = C_{i+1/2}^n - u \Delta t \]

Appling Crank-Nicolson method

\[ \frac{C_i^{n+1} - C_i^{n+1/2}}{\Delta t} = \frac{D}{2(\Delta x)^2} \left( (C_{i+1}^{n+1} - 2C_i^{n+1} + C_{i-1}^{n+1}) + (C_{i+1/2}^{n+1/2} - 2C_i^{n+1/2} + C_{i-1/2}^{n+1/2}) \right) \]

\[ u = \text{velocity} \]