Tracer Dispersion Studies for Hydraulic Characterization of Pipes

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Abstract
A series of experiments were conducted at the U. S. Environmental Protection Agency (EPA) Test & Evaluation (T&E) Facility in Cincinnati, Ohio, to quantify longitudinal dispersion of a sodium fluoride tracer in polyvinyl chloride (PVC) pipe and ductile iron pipe under laminar, transitional, and turbulent flow conditions. The tracer injection durations were varied at different flow conditions to study their impacts on the tracer transport characteristics. Pitot-tube type sampling ports were built into the pipe systems to study the in-pipe behavior of the tracer and identify the optimal sampling position. Preliminary tests confirmed the linear relationship between conductivity and fluoride, as published in previous EPA studies (Boccelli et al., 2004, Panguluri et al., 2005). Thereafter, conductivity (measured using online sensors) was used to characterize the dispersion and diffusion of the tracer material. The experiments indicate that the amount of tracer measured decreased with increase in flow rate regardless of pipe material. This observation supports the theory that there may be an increase in adsorption/reaction phenomena observed with increases in velocity. This result, if confirmed with the upcoming chlorine/chloramine disinfectant kinetic studies, may have an impact on how distribution systems are operated and modeled.

Disclaimer
This paper has been reviewed in accordance with the EPA's peer and administrative review policies and approved for presentation and publication. The mention of trade names or commercial products in this paper does not constitute endorsement or recommendation for use by the authors, or by their respective employers. The trade names have been included to accurately represent the equipment used for the purpose of testing and evaluation.

Overview and Background

EPA's Water Quality Management Branch (WQMB) has been conducting water quality research at the EPA T&E Facility for approximately 15 years to study flow and solute transport in drinking water distribution systems. Under contract to EPA, Shaw Environmental, Inc. has supported EPA on these studies. A pilot-scale distribution system simulator (DSS) was designed and fabricated at the T&E Facility for use in understanding the dynamics which influence water quality within water distribution systems. This DSS unit is designed to simulate continuous flow conditions observed in a typical water distribution system. The DSS comprises five individual 75 feet lengths of 6-inch diameter unlined ductile iron pipe and one 6-inch diameter PVC pipe arranged in "pipeloop" configurations to simulate a distribution system. The DSS is also equipped with two 1,500-gallon reservoir tanks to simulate a comprehensive simulated distribution infrastructure system. This unique engineering design permits operation of any of the six loops under various experimental operating parameters.

EPA is currently planning to conduct experimental studies focusing on the decay rates of chlorine and chloramine in unlined ductile iron and PVC pipeloops with simulated variations of water quality parameters and flow rates. Previous EPA tests at the T&E Facility and field locations have shown that chlorine and chloramine residual losses increase with increasing mass transfer in corroded metal pipes (Clark and Haught, 2005, and Clark et al., 2006). Other objectives of the proposed studies are to evaluate the rate of generation of disinfection byproducts (DBPs) such as triholomethanes (THMs) and haloacetic acids (HAAs) (Rossman et al., 1999).

As a precursor to the planned disinfectant decay rate studies, the tracer dispersion studies discussed in this paper were conducted at the T&E Facility using two pipeloops within the DSS (Loops #4 and #5) to quantify dispersion and diffusion of sodium fluoride tracer. Ductile iron pipeloop #4 and PVC pipeloop #5 were operated under laminar, transitional, and turbulent flow conditions during these studies. Test runs were conducted with two specific durations of pulse tracer injections lasting 30 seconds (short pulse) and 3 minutes (long pulse). The specific loop flow conditions were as follows:

1. Laminar flow testing: Q = 3 gallons per minute (gpm); Reynolds Number (Re) – 1,268
2. Transitional flow testing: Q = 6 gpm; Re – 2,536
3. Turbulent flow testing: Q = 10 gpm; Re – 4,226

Materials and Methods

Loop #4 (6-inch unlined ductile iron pipe) at the T&E Facility has been in service for over ten years and is impacted by both corrosion and tuberculation. To get a representative inner diameter (D) measurement, cut sections were used from a recently decommissioned unlined ductile iron pipeloop of similar age. These inner diameter measurements ranged between 5.69 and 5.80 inches, with the majority of the measurements between 5.72 and 5.75 inches. Loop #5 (6-inch PVC pipe) at the T&E Facility is a relatively new pipeloop system fabricated less than a year ago. The nominal inner diameter for a Schedule 80, 6-inch PVC pipe is 5.71 inches. To confirm this value, cut sections of the PVC pipe used to fabricate this loop were measured. The inner diameter measurements of the cut pieces ranged between 5.71 and 5.72 inches.

The tracer solution was prepared by mixing 66.8 grams of sodium fluoride in 10 liters of tap water. The resultant solution contained 400 milligrams per liter (mg/L) fluoride. The background fluoride concentration of Cincinnati tap water used for testing ranged between 0.9 and 1.1 mg/L. This concentrated tracer solution was injected at a rate of 500 ml/min in both the 30 second and 3 minute pulse test runs. The injection port for both loops was located downstream from the recirculation pump. A gear pump was used for tracer injection. To verify tracer injection volume during the operations, injection verification tests were performed which yielded a flow rate of 411 ± 31 milliliters per minute (mL/min) and 406 ± 27 mL/min for Loop #4 and #5, respectively.

The tracer tests were conducted under each of the 3 flow conditions (Re 1,268, 2,536, and 4,226) with the pipe loops operated in recirculation mode. Figure 1 shows the Process and Instrumentation Diagram (P&ID) for Loop #4. Each test run was considered complete after the detected tracer had completed three rounds within the loop. The water flow rate in the loop was recorded at the beginning and end of each test.

Sampling and Analysis

Both Loops #4 and #5 were sampled at two locations (Ports 1 and 2) during the test. The sampling ports for Loop #4 were located at 28.5 feet (Port 1) and 70.5 feet (Port 2) downstream from the injection port. The sampling ports for Loop #5 were located at 29 feet (Port 1) and 75.5 feet (Port 2) downstream from the injection port. Port 2 for both loops consisted of 3 "L"-shaped sampling pitot tubes which were positioned at 0.5D, 0.125D, and at the pipe wall. The "L" configuration allowed for water sampling along the flow lines and at different positions of a pipe cross-section. For the tracer tests, the samples were drawn only from the 0.5D location.

Preliminary testing was performed using grab sampling events where a sample was grabbed every 15 seconds from the aforementioned sampling locations. Both conductivity and fluoride measurements were performed to check for a linear relationship between fluoride and conductivity (Boccelli et al., 2004, Panguluri et al., 2005). Based on the results of the preliminary runs, conductivity measurements alone were considered to be sufficient to represent tracer concentrations. Furthermore, the grab sampling procedure was eliminated in favor of an online conductivity meter (YSI 6-series multi-parameter instrument) for continuous conductivity measurements and data acquisition. Typical accuracy of this YSI instrument is +/- 0.5 % of the reading. For example, the accuracy of a conductivity measurement of 400 microsiemens per centimeter (µS/cm) is 2 µS/cm (0.005 x 400). For the experimental setup, a flow-through cell was fabricated to immerse the YSI instrument and was connected to each sampling port during testing. Prior to testing on each day, the YSI instrument was checked in accordance to the manufacturer's recommendation by measuring its response to 1,000 and 447 µS/cm standard solutions to ensure its accuracy range of +/- 0.5 %. However, during the tests, the baseline conductivity levels for Ports 1 and 2 (for both Loops #4 and 5) were observed to be different. For the purpose of this analysis, the relative difference between baselines was removed so that the baseline conductivity levels at Port 1

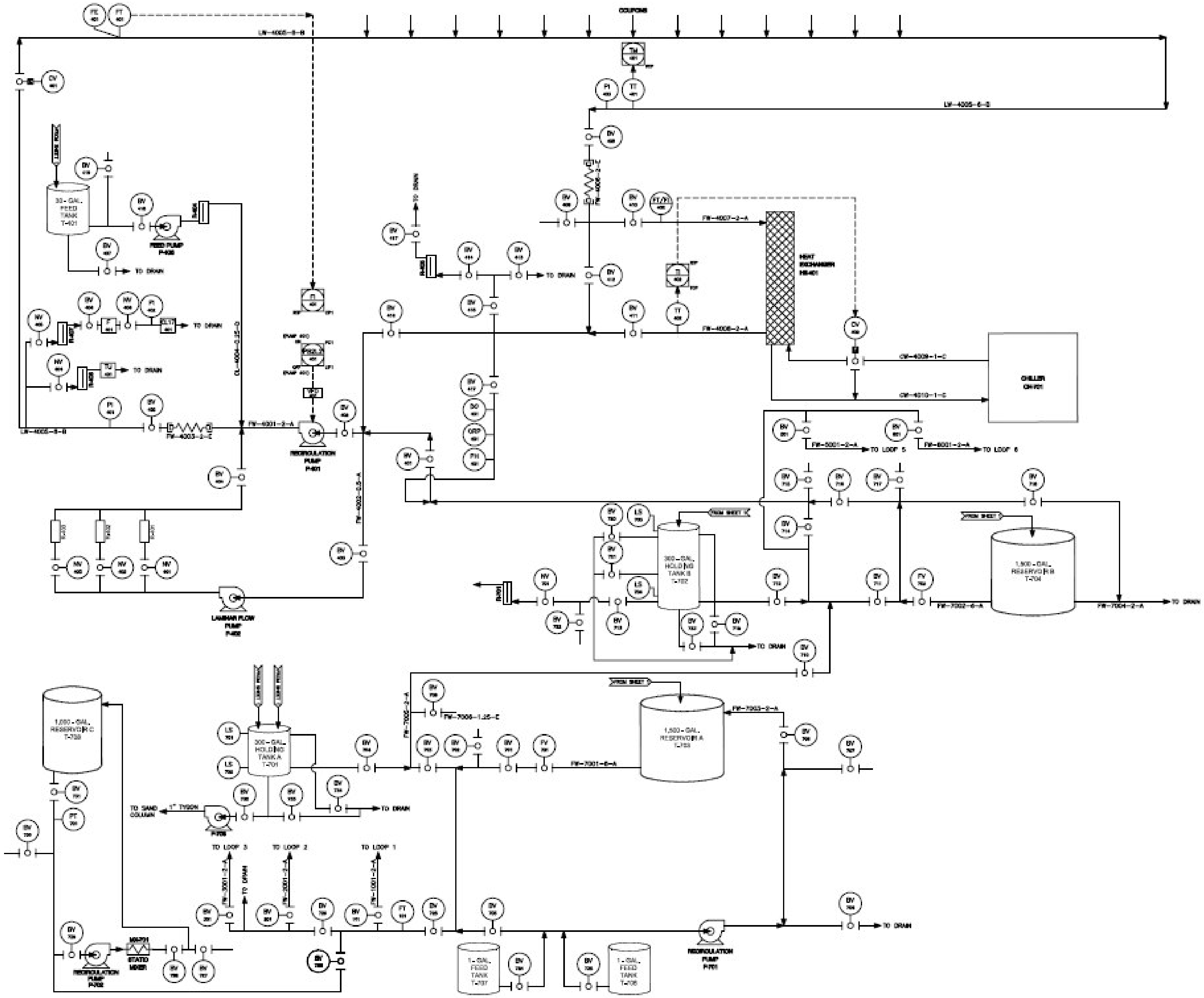

Figure 1. Process and Instrumentation Diagram (P&ID) for One of the Pipeloop Systems (Loop#4) Employed for the Tracer Tests.

and Port 2 were the same for individual injection tests. The tracer arrival at Port 1 for both loops was also matched to observe any relative variation in tracer dispersion. These adjustments are collectively referred to as "zeroed" in the figures included in the Data and Results section. The sampling cell flow rate was set to approximately 125 ml/min for each port.

The test data produced during these studies can be used to describe the hydraulic dispersion, tracer slug transport, and homogenization in the loop pipes, elbows, and pump.

Data and Results

Figures 2 through 4 show the results for the 30 second tracer injection tests at flow rates of 3, 6, and 10 gpm, respectively, for both Loops #4 and #5. Figures 5 through 7 show the results for the 3 minute tracer injection tests at flow rates of 3, 6, and 10 gpm, respectively, for both Loops #4 and #5.

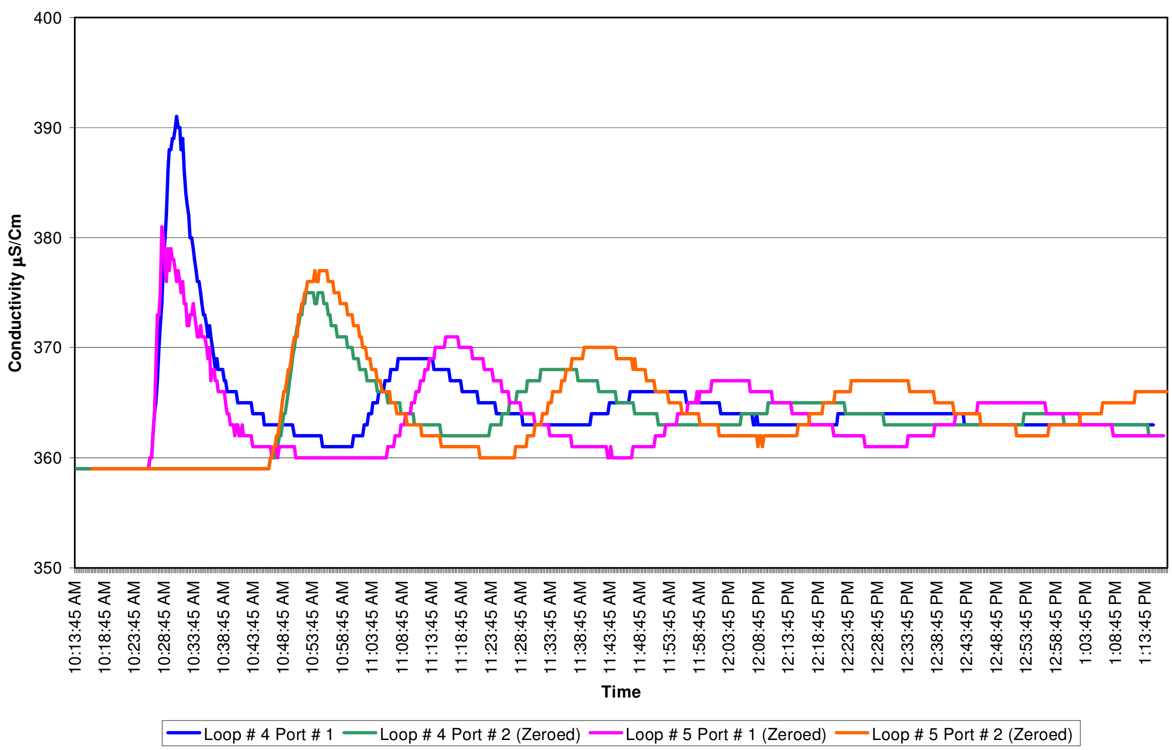

Figure 2. 3 gpm Tracer Run - 30 Sec Injection

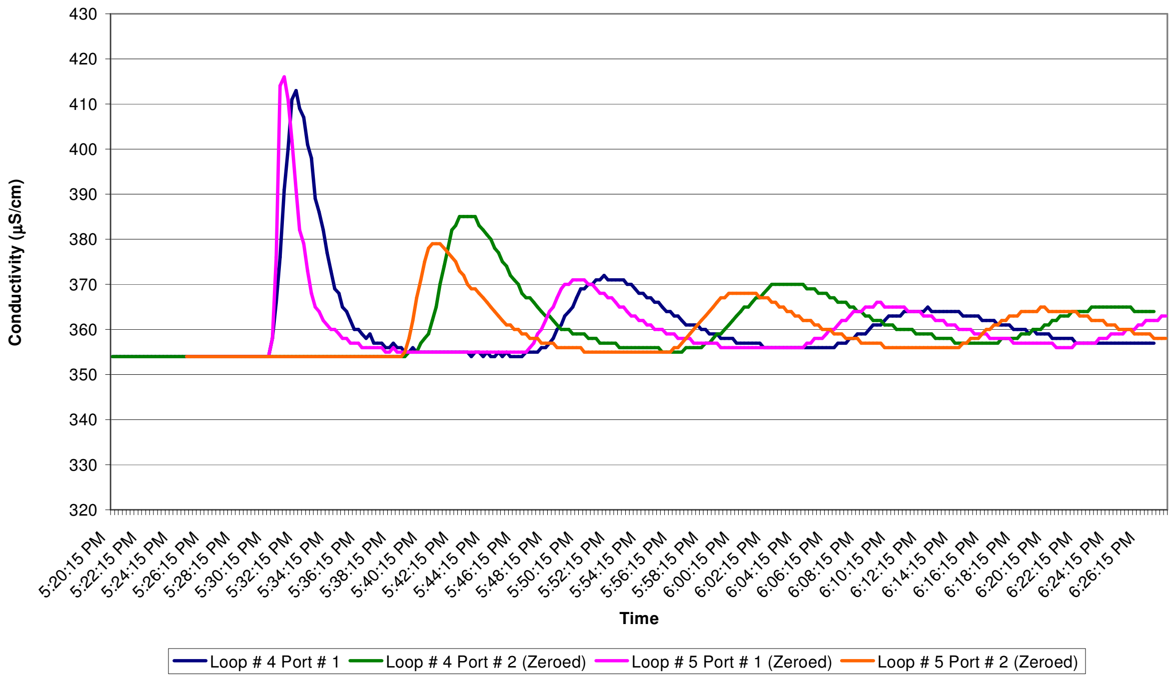

Figure 3. 6 gpm Tracer Run - 30 Sec Injection

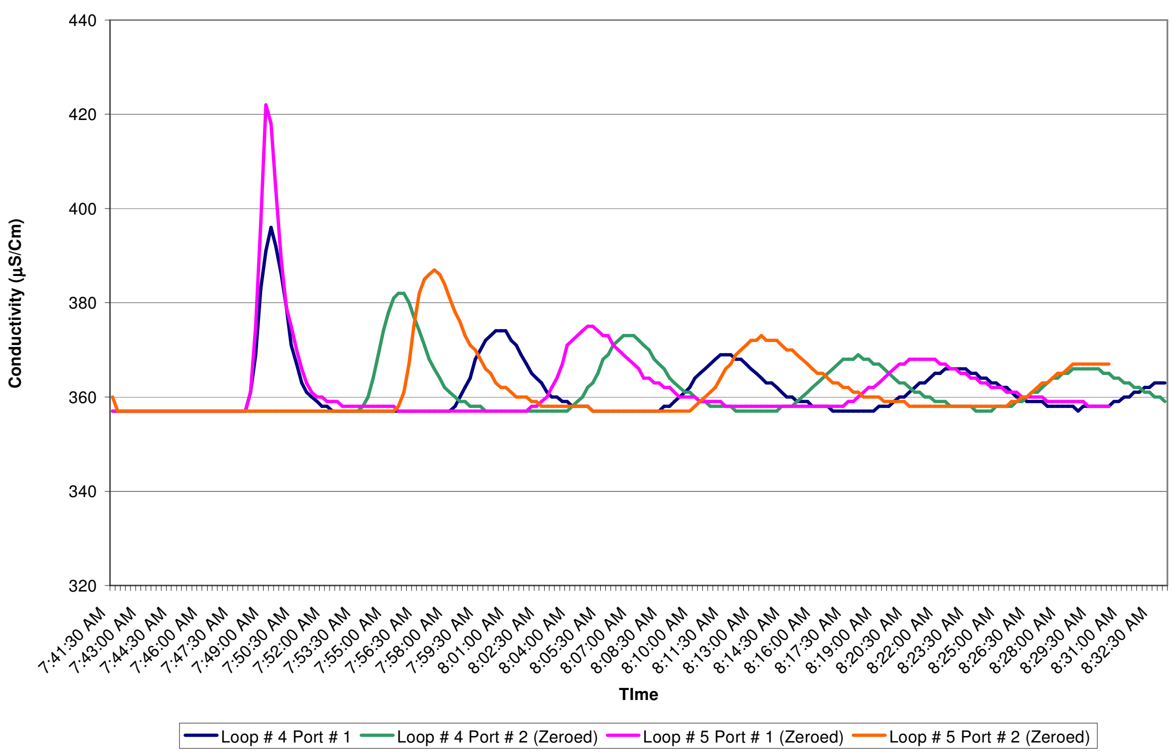

Figure 4. 10 gpm Tracer Run - 30 Sec Injection

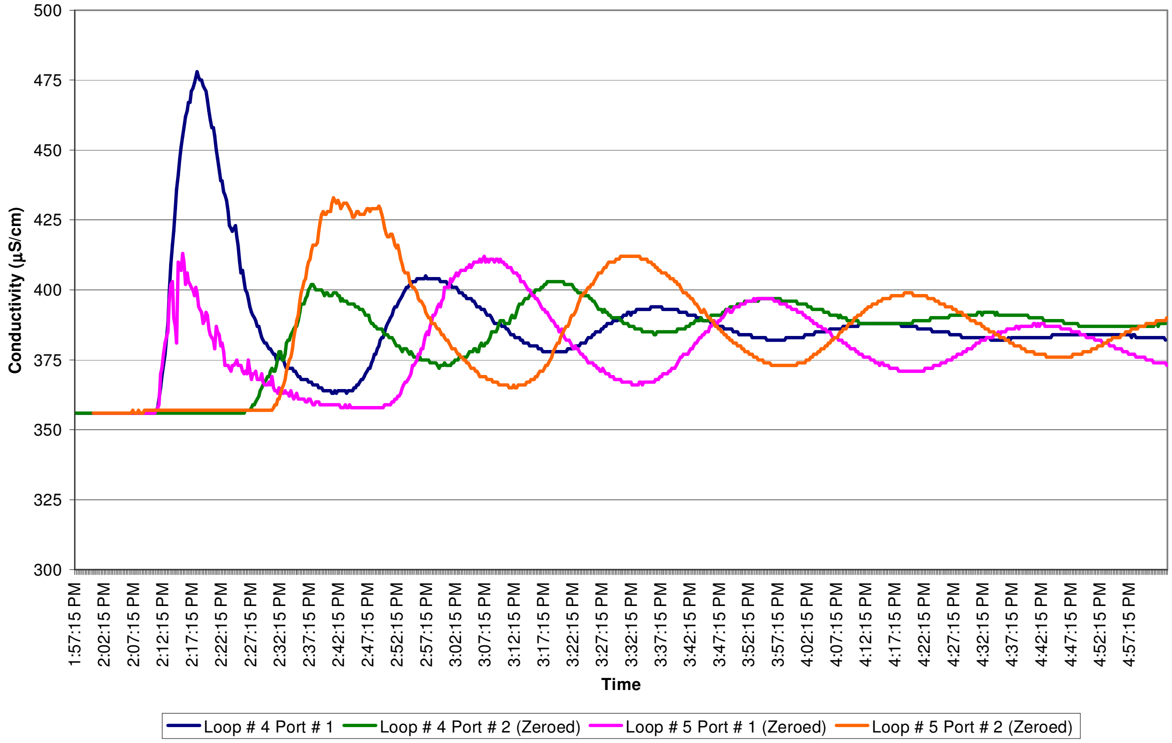

Figure 5. **3 gpm Tracer Run - 3 Min Injection**

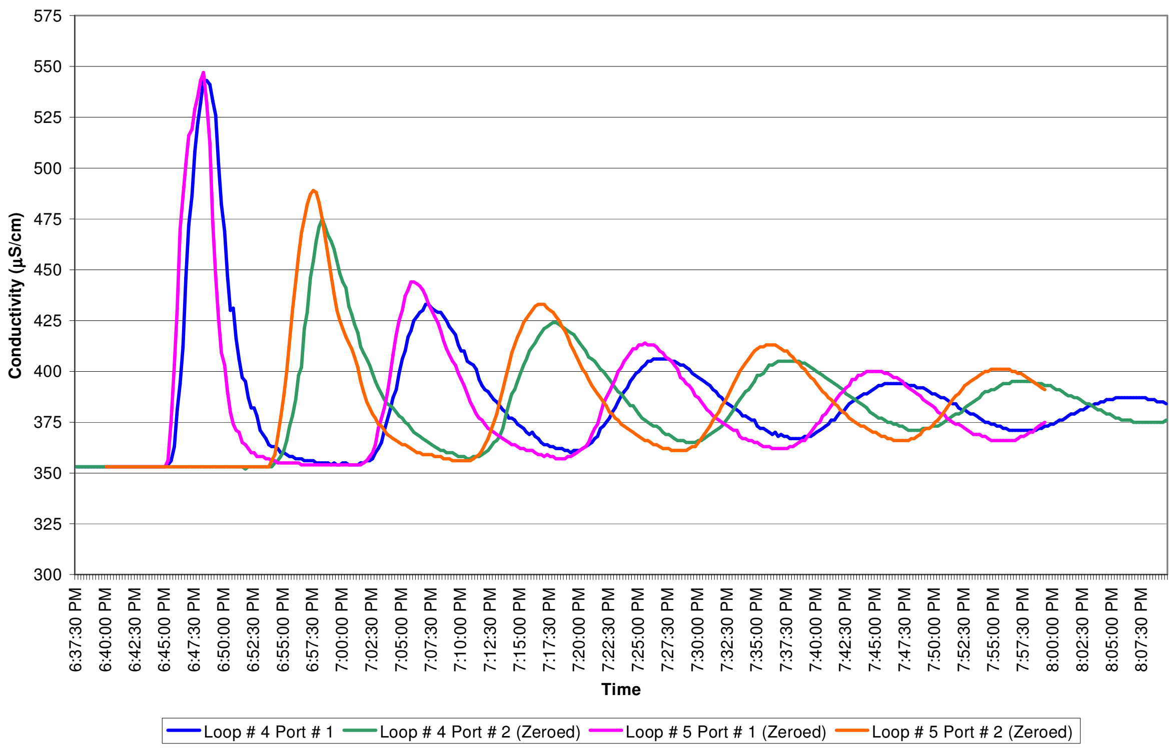

Figure 6. **6 gpm Tracer Run - 3 Min Injection**

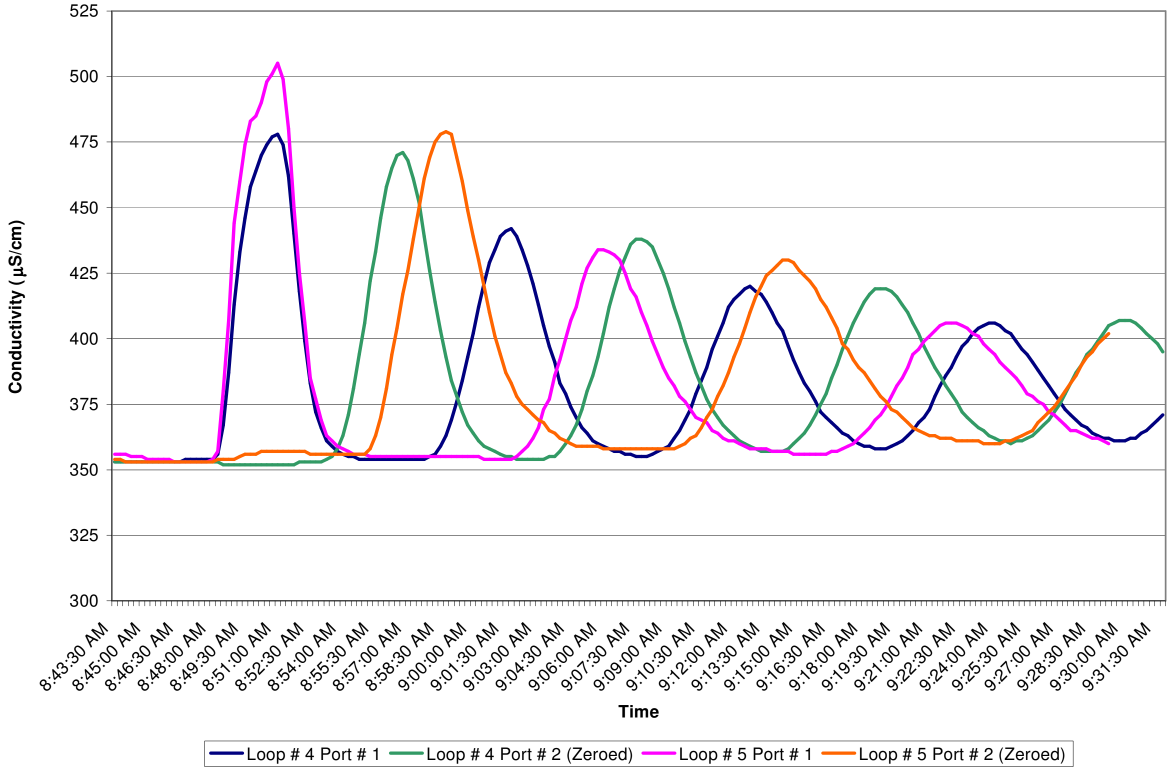

Figure 7. 10 gpm Tracer Run - 3 Min Injection

Results and Findings

The tracer testing has led to an accurate hydraulic characterization of the DSS Loops # 4 and #5. Scaling and tuberculation may have contributed to the buildups inside the ductile iron Loop #4 as evidenced in pipe diameter measurements. The scaling and tuberculation changes the hydraulic properties of the pipe and consequently affects chlorine and solute transport. Preliminary observations are as follows:

- Figures 2 through 7 show similar trends – the peak conductivity for each port decreases with each additional pass through the loop. Also, the baseline for the graphs gradually increases with each additional pass through the loop. These two trends are consistent with the fact that the tracer becomes more dispersed throughout the loop with time.

- When comparing 30 second tracer injections to 3 minute tracer injections, the peak conductivity is slightly higher with the longer injection time. Also, as expected, the peak separation between passes decreases with the longer injection time. Similarly, the peak separation at lower flow rates is lower than at the higher flow rates.

- The area under each curve was calculated for each pass through the loop. The area under the curve provided an estimate of the total tracer quantity in the loop. While calculating the area under the curves, a constant horizontal baseline was used, and it was estimated that the curves from consecutive passes did not overlap. No peak separation software was utilized, and the peaks were not extrapolated while estimating the area. Tracer loss through the sampling ports was calculated to be minimal (approximately 1% per pass in each loop), based on flow ratios in the main pipe and through the YSI sensor.

The areas under the curves for the first pass were examined closely. Minimal differences in tracer quantity were noted between Loops #4 and #5, and Ports 1 and 2. It was found that the area under the curves decreased with increasing flow rate regardless of the pipe material. Also, the ratio of the area under the curve for a 3 minute injection to the area under the curve for a 30 second injection increased with increasing flow rate. Both of these observations support the theory that there may be an increase in adsorption/reaction with increase in velocity.

Future Research

The increase in adsorption/reaction with increase in velocity is theorized to be a consequence of mass transport towards pipe-wall. This observation will be further verified and analyzed in planned data analysis. This result, if confirmed with the upcoming chlorine/chloramine disinfectant decay rate studies, may have an impact on how distribution systems are operated and modeled.

Conclusions

Based on the results from this research, the use of tracer techniques can be used to hydraulically characterize a distribution system. It appears from these studies that the tracers behave according to the established flow pattern dispersion theory. The finding during the studies that the tracer seems to be absorbed to the pipe walls in both the ductile iron and PVC pipe would indicate that there is a mass transfer of tracer from the bulk phase to the pipe wall. This phenomenon will be examined in more detail in future studies.

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