Measurement and Modeling of Turbulent Flow in Water Supply Systems and Its Effect on Contaminant Transport

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Abstract

This paper describes the results of a measurement and modeling research project investigating the transport, accumulation and removal of contaminants from within water supply systems, including piping, fittings and fixtures. The traditional approach for decontaminating plumbing systems is to flush with water at high flow rates, primarily because this methodology is most easily implemented, and there are few simple alternatives. However, the effectiveness of this approach has not been demonstrated, and in fact, for several reasons this may not be the best way to remove contaminants. High velocity water flows in piping systems are in the turbulent regime, and the eddies that are generated may inhibit the transport and removal of entrained contaminants. This affects both the initial distribution and removal of contaminants.

In the modeling component of this project, we investigated the movement of contaminants in pipe flows with obstructions representative of typical plumbing system fittings. This entails solutions of the equations for fluid flow, the solution of an advection-diffusion equation for the motion of the contaminants, and a boundary condition for the advection-diffusion model. The modeling results are compared to measurements conducted using real-world piping systems. The effect of turbulent flows on contaminant distribution and removal is evaluated and described.

Introduction

The mechanisms responsible for the transport, accumulation and removal of contaminants in building water supply systems are the subject of increasing interest as related to the requirements to provide safe drinking water. The U.S. Environmental Protection Agency (EPA) has instituted a broad research program to investigate this subject. As part of this research program, the National Institute of Standards and Technology (NIST) has commenced an interdisciplinary project to evaluate contamination and decontamination issues associated with building plumbing systems. The goal of this NIST project is to develop the technical basis for guidelines, methodologies and procedures for responding to water contamination events involving building plumbing systems. This research project includes a detailed analysis of the interactions between various potential contaminants and the materials encountered in building plumbing systems, measurements of the accumulation of contaminants under different operating scenarios, evaluation of different decontamination procedures, and the development of analytical and computer models of contaminant accumulation and removal [Treado, 2006].

One of the interesting technical issues associated with this project is the transport, accumulation and removal of contaminants from within water supply systems, including piping, fittings and fixtures. The traditional approach for decontaminating plumbing systems is to flush with water at high flow rates, primarily because this methodology is most easily implemented, and there are few simple alternatives. However, the effectiveness of this approach has not been demonstrated, and in fact, for several reasons, this may not be the best way to remove contaminants. The following describes a modeling and measurement investigation of the effect of flow regime on the effectiveness of water flushing of water piping systems.

Turbulent Flow in Water Supply Systems

If a contaminant were to be introduced to the water supply system, the transport and eventual distribution of the contaminant throughout the system would depend on the water flow conditions, and the characteristics of the contaminant. In turn, the removal of the contaminant by flushing would depend on the interaction of the contaminant with the flush water and substrates, the water flow rates and water velocities [Treado, 2005]. When fittings such as valves or faucets are fully opened in water supply systems, flow rates meet or exceed one gallon per minute (gpm), and flows are typically in the turbulent range, even in the straight pipe sections. When consideration is given to the fact that there are many flow restrictions, obstructions and redirections in typical plumbing systems, turbulence and associated eddies and swirls are unavoidable. Water flows are also typically intermittent, with short periods of usage followed by long periods of static conditions.

Flushing Water Systems to Remove Contaminants

The question of how much water flushing is required to remove all of the contaminated water, and what flow rates or velocities are most effective, is an interesting one. In order to understand this better, we can consider two idealized cases: plug flow and perfectly mixed flow. Plug flow represents the case where, as the name implies, water flows in bulk and does not mix. Under this condition, a unit volume of water would be completely replaced by flushing with an equal volume. This can be considered a best case scenario, not likely encountered in practice. For the case of a 50 gallon water tank, the assumption of plug flow would imply that a flush volume of 50 gallons would completely eliminate the contaminated water. The second idealized case, perfectly mixed flow, represents the case where the flush water mixes with the contaminated water in a continuous, fully-mixed dilution process. If the incoming water is free of the contaminant, the concentration of contaminant in the outgoing water will decay exponentially. Mathematically, the contaminant concentration never reaches zero, but as a practical point, the contaminated water will be flushed out in a finite time period that is substantially longer than plug flow. This relation is given by equation 1.

$$C / C_O = \exp(-\alpha t) \quad (1)$$

where: C = contaminant concentration at time t
C_o = initial contaminant concentration
α = decay constant
and τ = time constant = $1/\alpha$

In actuality, the effectiveness of the flushing at removing the contaminated water could be less than the perfectly mixed case if there is poor mixing and bypass flow. In this condition, the clean flush water flows through the plumbing system and does not mix well with the contaminated water, thus requiring longer flushing times and volume of clean water to replace the contaminated water. The flushing could also be faster than the perfectly mixed condition, if the contaminant does not mix well or is not equally distributed, and can be flushed out more quickly. In order to try to quantify the effectiveness of flushing at removing contaminated water, we can define flushing efficiency (FE) as the ratio of the time constant for perfect mixing to the actual time constant determined from measurement or modeling, expressed as a percentage. The value of FE will be greater than one if the removal of the contaminated water by flushing is faster than the rate for perfect mixing, and less than one if it is slower.

$$FE = \tau_{PM} / \tau_a \quad (2)$$

where: τ_{PM} = time constant for perfect mixing case
τ_a = actual time constant

Measurement Results

A series of tests were conducted using a fluorescent tracer (fluorescein) as a surrogate contaminant. Fluorescein can be detected at very low concentrations, so is very useful for dilution measurements that cover a wide range of concentrations. The tracer was mixed with tap water to achieve a concentration in the range of 250-500 μg/L (ppb), and then circulated through a water supply line or a hot water heater using a pump, and allowed to equilibrate under static conditions. This allowed the tracer to diffuse throughout the system. At the end of the wait period, clean tap water was flushed through the supply line or water heater, and water samples were collected at periodic intervals. The flushing was done on a once-through basis. Water samples were collected at the faucet outlets for the water supply line, and from the drain valve on the water heater.

The test water line was approximately 33 feet in total length, and consisted primarily of one inch or ¾ inch copper pipe, and culminated with connections to three faucets using flexible plastic hoses and individual shutoff valves. The volume of the water line was approximately 1.13 gallons, with a total vertical rise of approximately 13 feet. The water line included typical elbows, tees and valves as might be found in residential or commercial construction.

The test water heater was a used unit that had been recovered from previous energy performance testing. Its nominal tank volume was 50 gal, which was verified by measurement. Tests were conducted without the heating elements activated.

The water samples were analyzed by measuring their fluorescence intensity using a fluorometer, which provides a relative measure of tracer concentration. Initial concentrations were determined using volumetric techniques, and the decay in tracer concentration with time was used to indicate flushing efficiency. Since the measurement is based on relative concentration, the results are not dependent on any uncertainty in the absolute concentration.

Figure 1 shows the measurement results for a typical test of a water line serving three sinks being flushed at a water flow rate of 1.2 gpm. The ratio of tracer concentration sampled at the faucet outlets to original tracer concentration is plotted as a function of time. It is notable that measurable amounts of tracer are still being detected after 15 min of continuous flushing, which corresponds to 15 volume changes. The computed flushing efficiency for this test was 43 %, indicating that the contaminant removal rate was less than one half as fast as the rate that would have occurred with perfect mixing. The conclusion to be drawn from this is that at least some of the contaminant was not able to be effectively carried out of the system by the flush water, probably due to stagnant regions and eddies caused by obstructions in the flow, such as tees and valves.

Figure 2 shows similar measurement results for a 50 gallon hot water tank being flushed at 0.94 gpm. Obviously, more time is required to flush a large volume water tank, as approximately 40 % of the contaminant still remains after one hour of flushing, which corresponds to one tank volume. The flushing efficiency for this test was 98 %, indicating that the flush water was mixing well with the water in the tank.

In order to try to understand the effect of flushing water flow rates and velocities on flushing efficiency, tests were conducted over a range of flow rates. Figure 3 shows the measured flushing efficiencies as a function of Reynolds number for a series of tests using the piping system and sinks. This figure also shows the measured and calculated (perfect mixing) time constants. Since Reynolds number is an indicator of flow turbulence, it was hypothesized that certain flow regimes might provide better flushing, and higher flow rates might provide less effective flushing due to turbulent eddies. The limited data in Figure 3 suggests that this might be the case, as flushing efficiency is higher at a Reynolds number of 4000 than at higher flow rates. There is considerable scatter in the data however, so additional measurements would help to confirm this effect.

Flow Modeling Results

A parallel modeling effort was conducted to try to gain insight into contaminant flushing performance, and to investigate the effects of flow rate and obstructions on contaminant migration in a piping system. The approach used to model fluid flow for this project is based on a hybrid Lattice Boltzmann/Navier-Stokes scheme developed by Martys [Martys, 2001]. This scheme is designed to be equivalent to solving the continuity equation and the Navier-Stokes equations to second order accuracy within a single framework. It has been found that with this approach there is an improved accuracy of flow fields near boundaries and that there is greater a stability with higher Reynolds number than that found with the standard Lattice Boltzmann methods. This simulation approach recovers simple Poiseuille flow in parallel plate geometries, the correct scaling of boundary layer flow, and qualitatively recovers features of higher Reynolds number flow such as the Karman or vortex street in flow past an obstruction. The code developed at NIST is set up to describe flow in three dimensional digital microstructures such as square pipes or digitized images, or even filter systems and with suitable modification should be able to describe flow in circular tube geometries.

The following two figures show the flow fields for the case of fluid flow between two slightly modified parallel plates, an idealization of a straight pipe. The modification is the inclusion of two small “bumps” on the plate surface and near the inlet to perturb the flow. A constant velocity is imposed at the inlet and outlet and there are no-slip boundary conditions at the walls. The first case, Figure 4, is for Reynolds number ~100 and the second, Figure 5, corresponds to Reynolds number of around 10,000. Note the dramatic difference in flow pattern. In the lower Reynolds number case, the flow is laminar and the wall perturbation has little effect on the flow fields. On the other hand, the higher Reynolds number flow is strongly affected by the perturbation, as vortices develop and the flow pattern is dramatically different. The consequence of such variation of flow fields on the transport of contaminants will be illustrated later in the following section.

Modeling the transport of contaminants

The transport of contaminants in the fluid phase is described by the advection-diffusion equation $\frac{dC(t)}{dt} = -\vec{\nabla} \cdot C\vec{V} + D\nabla^2 C$ where D is the molecular diffusion coefficient of the contaminant in the fluid. The following will illustrate some examples where the hydrodynamics dominate, which may be the case when flushing a pipe system. A dimensionless number, the Peclet number, $Pe = Vl / D$ where l is a typical length scale, characterizes the relative importance of flow vs. diffusion in transport phenomena. Hence, we consider the case where $Pe >> 1$ for the two flow fields given in the previous section. Figure 6 is a time sequence of images where a contaminant (magenta color) is flushed from the system for the lower Reynolds number case. Because the Peclet number is low, the contaminant moves very close to the wall surface. That is, in the time it takes to flow across the system, the contaminant is unable to diffuse very far towards the center. Further, in this laminar regime, the flow fields are nearly parallel to the wall; hence there is no hydrodynamic drive to move away from the wall.

Now consider the higher Reynolds number case, as shown in Figure 7. On the bottom side where the flow is greater the contaminant is quickly depleted, however on the top side, due to the greater vorticity, the contaminant remains much longer and, indeed, experiences some back flow, moving contrary to the average flow, without diffusion being a factor.

Summary

Measurements and modeling of contaminant transport and removal from water supply systems by flushing with water indicate that turbulent flows and flow obstructions can inhibit the elimination of water-borne contaminants from the system. The presence of flow obstructions normally present in plumbing systems, such as fittings and valves, creates turbulent eddies and recirculation that tend to trap the contaminants rather than moving them out of the system by advection. In order to effectively and efficiently eliminate contaminants from water supply systems, it will be necessary to carefully select appropriate flushing procedures, and perhaps use supplementary methods, such as variable flow rates, pulsations or additives to enhance contaminant removal.

References

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Treado, S., Kedzierski, M., Watson, S., Bentz, D., Martys, N., Cole, K., Report of Phase One Measurement and Analysis of Building Water System Contamination and Decontamination, NISTIR 7351, National Institute of Standards and Technology, Gaithersburg, MD, 20899, 9/2006

Martys, N., Int. J. Mod. Phys. C, Vol. 12, No. 8, 1169-1178 (2001).

Disclaimer

Use of Non-SI Units in a NIST Publication
The policy of the National Institute of Standards and Technology is to use the International System of Units (metric units) in all its publications. However, in North America in the construction and building materials industry, certain non-SI units are so widely used instead of SI units that it is more practical and less confusing to include measurement values for customary units. Thus, this document relies on gallons to describe fluid volumes, and gallons per minute for volume flow rates.

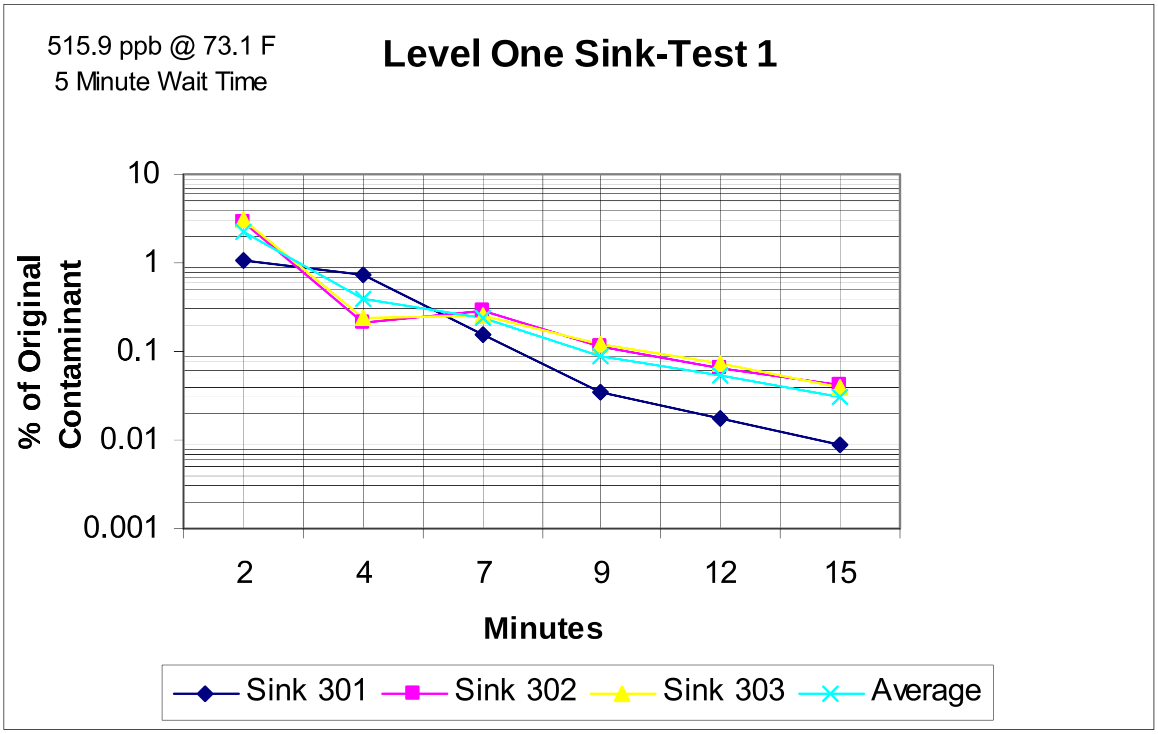

Figure 1. Typical flushing test results for piping/sink system

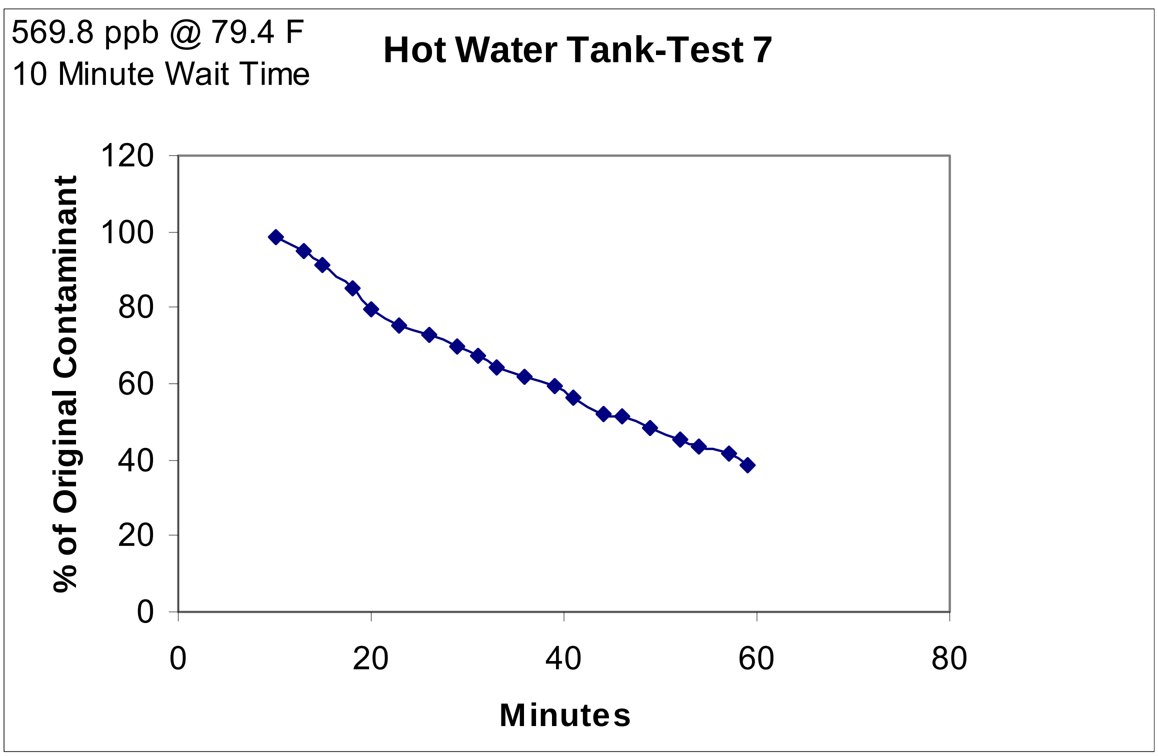

Figure 2. Typical flushing test results for hot water tank

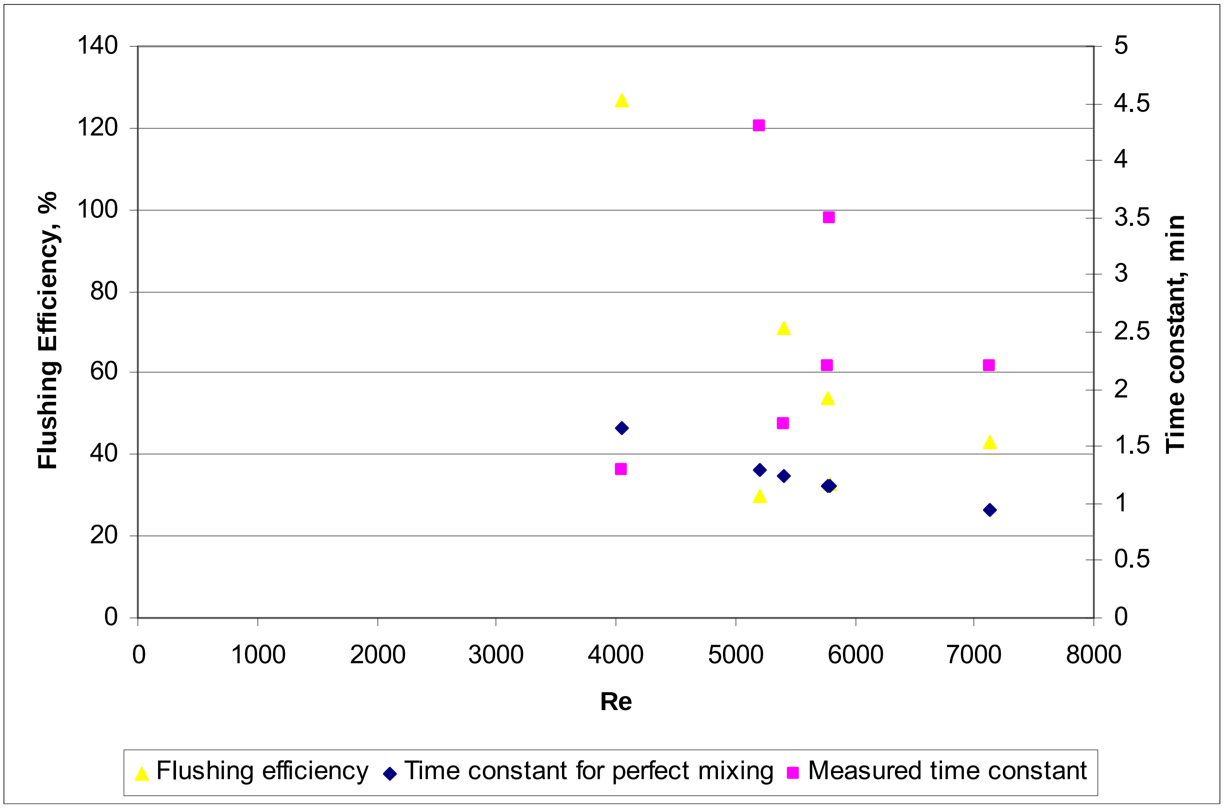

Figure 3. Measured flushing efficiency and time constant as a function of Reynolds number for water line tests

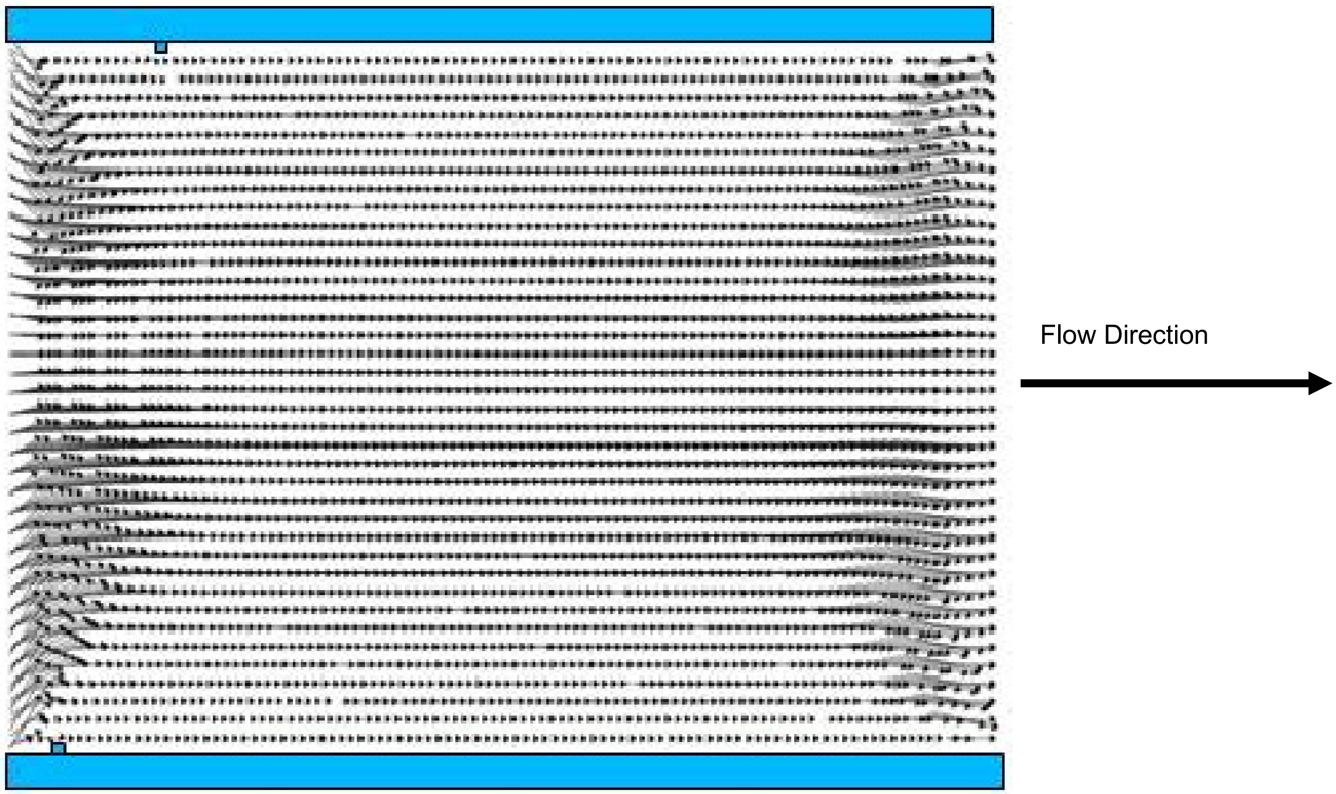

Figure 4. Simulation for low Reynolds number, Re = 100

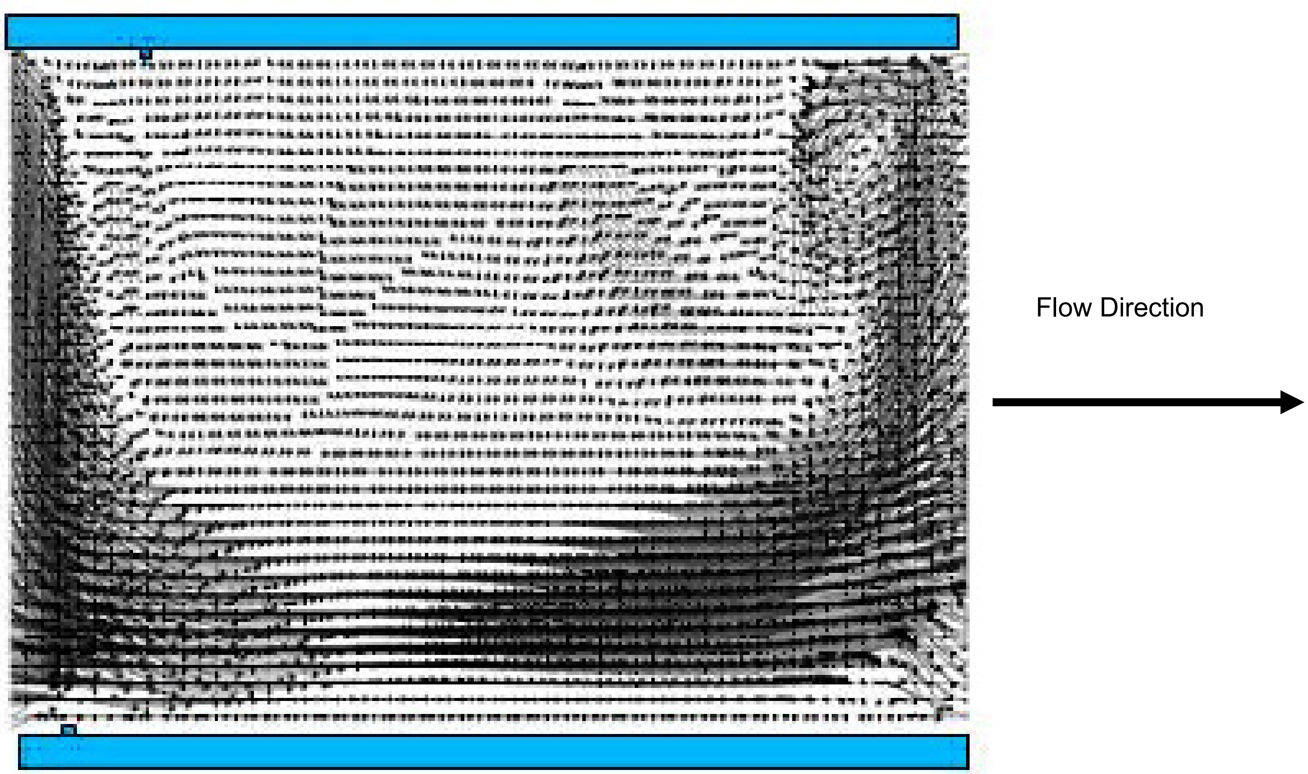

Figure 5. Simulation for high Reynolds number, Re = 10,000

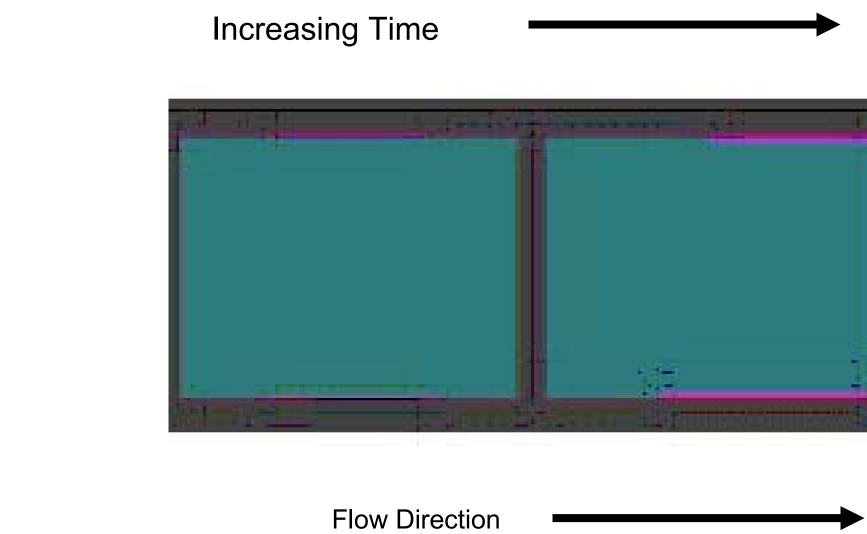

Figure 6. Contaminant transport at low Reynolds number, Re = 100

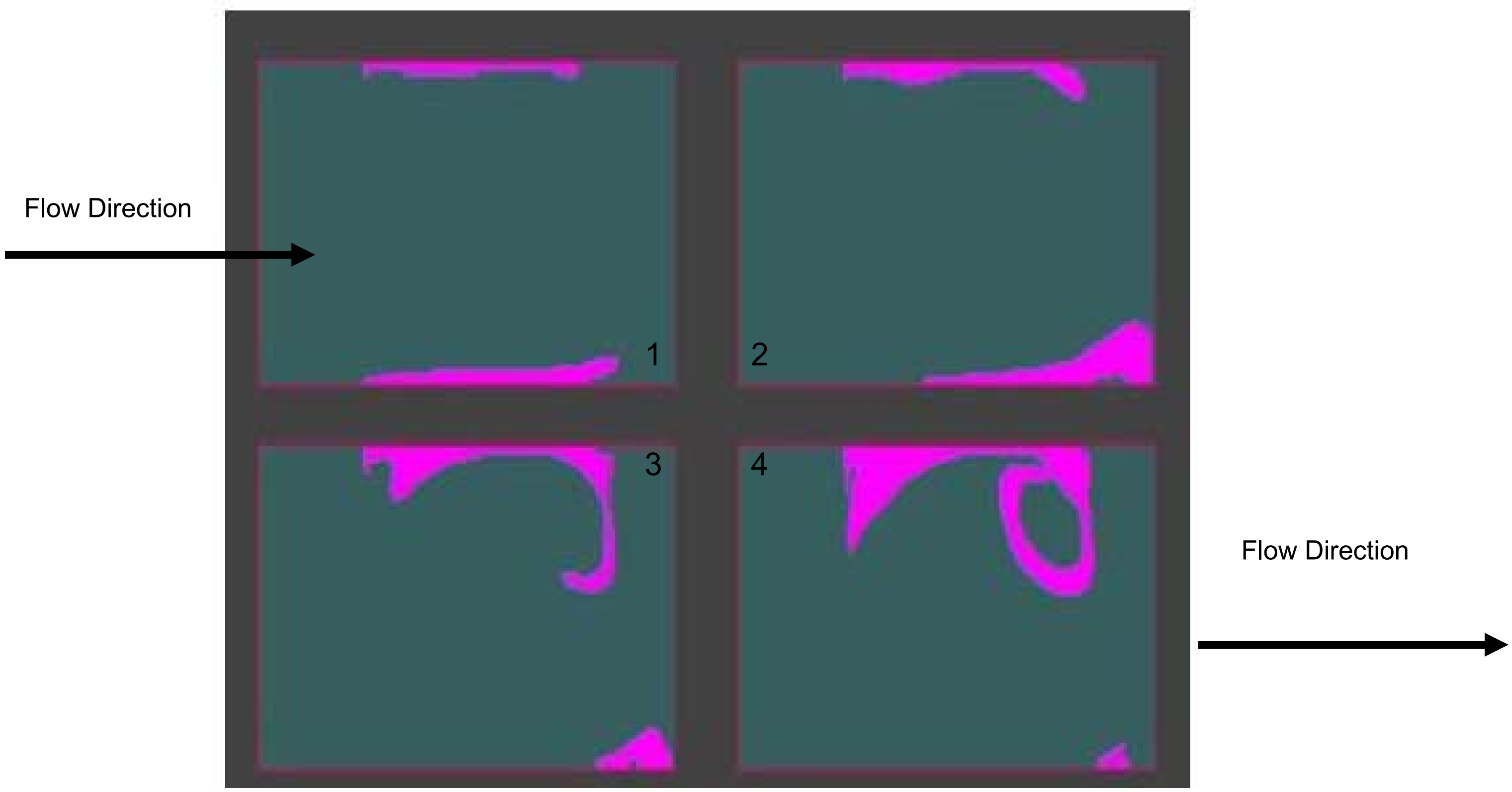

Figure 7. Contaminant transport at high Reynolds number, Re = 10,000