Improving the hydraulics of drinking water contact tanks using random packing material

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This study investigated the use of industrial packing material for increasing the hydraulic efficiency of small-scale, chlorine contact tanks used in drinking water treatment. The packing material used in this study was spherical, with porosities between 0.9 and 0.95 and a density less than that of water. A total of 67 tracer studies, conducted on laboratory-scale chlorine contact tank systems, examined three sizes of packing material, two tank sizes, and two flow rates. Sodium chloride solution was injected as a continuous tracer at the inlet and was monitored in the tank outflow through electrical conductivity. Several studies were validated with the use and direct measurement of a lithium ion tracer. Hydraulic efficiency was measured by determining the baffling factor as outlined by the US Environmental Protection Agency. Results suggest that the use of packing material in small drinking water contact tanks can significantly increase the baffling factor, improving the disinfection efficiency obtained from existing tanks.

Keywords: *baffling factor, contact tank hydraulics, hydraulic efficiency, random packing material*

Packing material has long been used in vapor separation towers, but its use in drinking water contact tanks has received little, if any, attention. The goal of the current study was to fill this void and investigate the applicability of using packing material to increase the hydraulic efficiency of contact tanks. Column packing material has been used in aeration towers (Kavanaugh & Trussell, 1980) and trickling filters (Richards & Reinhart, 1986) and to improve the operating efficiency of distillation towers (US DOE, 2001). Packing material is designed so that it can be dumped into these towers (random packing) or installed in interlocking units (structured packing). Many types of packing material (both random and structured) are constructed with material that has met National Sanitation Foundation (NSF) Standard 61 criteria and as such are safe for drinking water applications.

A major area of research in packed column hydraulics is the phenomenon known as flooding, which occurs near the maximum operating capacity of the system. When a packed column undergoes flooding, the pressure drop throughout the system increases abruptly and the separation efficiency begins to decline (Hanley, 2011). However, flooding occurs only when the packing material is used in a system with two-phase (gas–liquid) flow, and this phenomenon did not present an issue in the current study. The complex hydraulics of packed columns have been modeled using computational fluid dynamics (CFD) by, among others, Owens et al (2013), Szulczewska et al (2003), and Petre et al (2003). CFD was not used as an investigative tool in the current study because of the complexities associated with flow through random packing material. Most CFD research into packed column hydraulics uses structured packing media, which are easier to model using CFD because of the symmetric nature of the material. CFD simulations were not performed because of the inherent difficulty in modeling the complex geometry of random packing material.

MEASURING HYDRAULIC (DISINFECTION) EFFICIENCY

Disinfection concentration times contact time. Chlorination is a primary method of drinking water disinfection throughout the United States (Taylor, 2012; Wang et al, 2003). Federal and state agencies regulate water disinfection on the basis of the concept of $C \times T$, in which C is the residual disinfection concentration and T is the contact time (USEPA, 2003). The assumption underlying this regulation is that the extent of disinfection is related to the disinfectant concentration multiplied by the time it is in contact with the water. T is often referred to as T_{10} and, according to the US Environmental Protection Agency (USEPA), "is an estimate of the detention time within a basin or treatment unit at which 90 percent of the water passing through the unit is retained within the basin or treatment unit" (USEPA, 2003). This means that T_{10} represents the time at which 10% of a disinfectant or injected tracer (which simulates the disinfectant in the experimental systems) has passed through the outlet of a given system.

Measuring the baffling factor. One of the principal aspects of hydraulic efficiency used in calculating $C \times T$ is the baffling factor, which is represented by T_{10} divided by the theoretical detention time of a system (TDT). Contact tanks undergoing perfect plug flow exhibit a baffling factor of 1.0, whereas other systems exhibit baffling factors of < 1.0. Plug flow describes a condition in which a tank contains no short-circuiting, dead zones, or areas of incomplete transport. Such a condition is ideal for both contact time and disinfection. In this project, hydraulic efficiency was measured by calculation of the baffling factor.

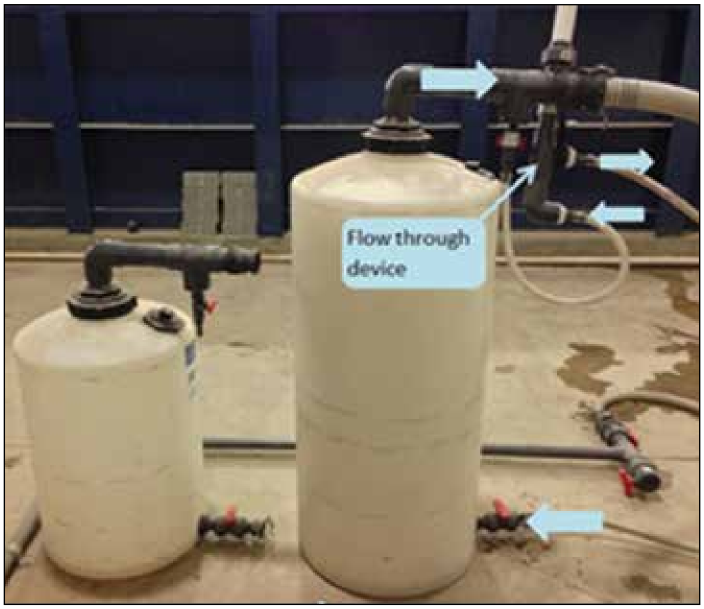
Residence time distribution curves. Residence time distribution (RTD) curves represent the variation in tracer concentration at the tank outlet over time, with continual injection of the tracer material. Injection begins after steady-state conditions for the background value of the tracer material have been reached and continues until the outlet concentration peaks and levels out. In this study, the outlet concentration C was normalized by subtracting a measured background value and dividing by the maximum outlet concentration C_{max}. The time at which $C/C_{max} = 0.1$ was taken to be T_{10}. The times plotted in the RTD curves for this study were normalized by dividing the measured time by the TDT of the contact tank for a given flow rate. This allowed direct calculation of the baffling factor and direct comparison of all graphed results.

METHODOLOGY

Materials and system setup. Three sizes of spherical polypropylene packing material were investigated to determine their efficacy for increasing the hydraulic efficiency of drinking water contact tanks. Because of practical concerns, such as cost and ease of installation, only random packing material was tested in laboratory-scale systems. Packing spheres with diameters of 1-, 2-, and 3.5-in. were tested in a 25-gal cylindrical tank at a flow rate of 5 gpm. These same materials were then tested in a 50-gal cylindrical tank at flow rates of 5 and 10 gpm. Water was fed to the tanks through a ¾-in. inlet at the bottom of the tank and drained through a 2-in. outlet located on top (see photograph below left). The photograph below right shows the three sizes of random packing material tested. Although this packing material is NSF 61–certified, it did float. To prevent the material from escaping with the tank's outflow, a mesh screen consisting of chicken wire with ¾-in. openings was installed at the outlet. The screen was installed before baseline testing of the tanks so that any effect it might have on the baffling factor would be accounted for. The amount of packing material used in the tanks was varied so that it constituted 0, 25, 50, or 100% of the tank volume. Because of the material's porosity (between 0.9 and 0.95), the volume lost to the packing material was very small compared with the tank's total volume and was greatly outweighed by the observed benefits. The maximum volume lost was approximately 5 gal for the 50-gal tank, leaving most of the tank's volume to act as a contact medium. This volume loss was computed using the volume of packing material and the material's porosity as specified by the manufacturer.

Testing procedure. The majority of the tests were conducted with a sodium chloride tracer. A total of 67 sodium chloride tracer studies were performed. To ensure that the results were accurate, each test was carried out a minimum of two times. Several tests were repeated with a lithium tracer in order to validate previously replicated results. Both the sodium chloride and lithium tracer studies were conducted using the methods outlined by Wilson and Venayagamoorthy (2010).

Sodium chloride tests. For the sodium chloride tests, the tracer solution was mixed so that it would raise the conductivity of the flow by 100 µS/cm. Typical background conductivity resulting from the presence of other ions in the raw water was 65–70 µS/cm. The sodium chloride solution was injected into the influent by means of a constant displacement pump and was integrated into the flow via a static mixing tube. As water left the tank, a portion of the flow was diverted into a flow-through device (see photograph below left). The effluent entered this chamber from the bottom plastic tube and exited through the top. This configuration allowed accurate conductivity measurements because no fluid could collect in the sampling area. Conductivity readings were collected by a conductivity meter,[1] calibrated using standard solu-



Tanks used for study with flow-direction arrows (25 gal left, 50 gal right)

1-, 2-, and 3.5-in. random packing polypropylene material used in study.

tions as specified by the manufacturer. Sampling times were determined on the basis of changes in effluent conductivity because RTD curves were unknown a priori from CFD results. Typical sampling intervals were between 30 s and 4 min, depending on how fast the effluent conductivity changed. Once the conductivity at the outlet varied by < 0.5 µS/cm over a 5-min period, the test was stopped as the system was assumed to have reached equilibrium. This criterion, however, led to each test ending between 4 and 6 TDTs. To ease comparisons between tests, all of the presented data has been truncated to 3 TDTs. This truncation had little effect on the measured baffling factor of each system.

Despite the precautions taken during the sodium chloride tracer studies, several anomalies occurred. Measurements were conducted at the Engineering Research Center (ERC) of Colorado State University (CSU). Because the hydraulics laboratory at the ERC uses raw water from Horsetooth Reservoir, the background conductivity could vary from day to day. This variation was sometimes severe enough to induce shifts in the measured RTD curves generated from the sodium chloride results. To eliminate any error this might have caused, additional safeguards were taken. First, each system was tested until a minimum of two RTD curves matched. This helped to identify which tests had been compromised by shifts in the background conductivity or other factors. After this, key tracer studies were repeated using a lithium solution.

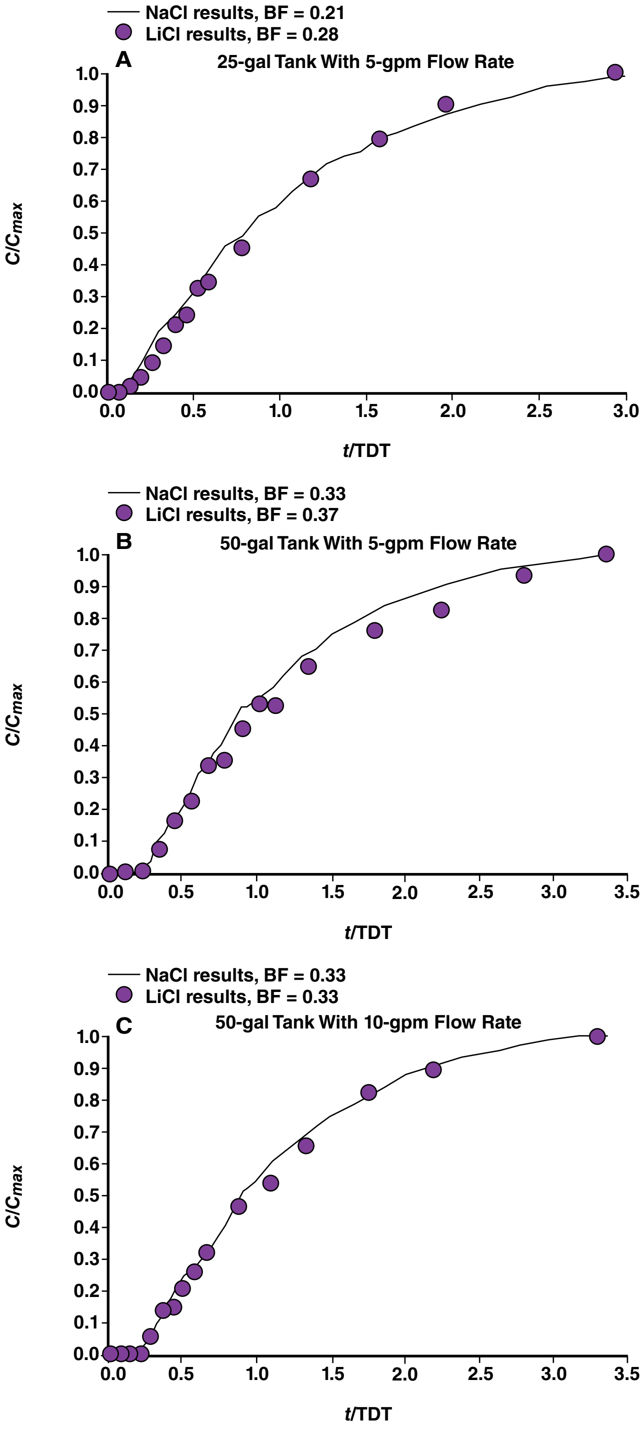
Lithium studies. Six lithium tests were conducted to validate the use of sodium chloride solution as a tracer and the use of conductivity as a measurement method. Lithium chloride was chosen as a validation tracer because little or no background concentration was found in the raw water. Although the lithium tracer studies were more accurate, they were also very costly and thus were used only to validate key results. The same equipment was used for the lithium studies as for the sodium chloride tests, but instead of changing the conductivity of the flow by 100 µS/cm, the lithium tracer solution was mixed so that the system effluent would contain a maximum concentration of 0.04 mg/L of lithium ion. Samples were taken at predetermined intervals from a diversion valve on the effluent and then analyzed in CSU's Soil, Water, and Plant Testing Laboratory by means of inductively coupled plasma atomic emission spectroscopy.

RESULTS

Lithium results. Figure 1 shows results for both the lithium and sodium chloride tracers under each tank's baseline conditions. These baseline studies, conducted on full tanks without any packing material, served as the project control. Results from tests using packing material were compared with results of the baseline studies in order to assess effects on hydraulic efficiency. As Figure 1 shows, the lithium results match very well with the sodium chloride data. These initial tracer studies confirmed that the two tanks originally had poor baffling factors, which ranged from 0.21 to 0.33, and that conductivity was a sufficient method for measuring the hydraulic efficiency of these tanks. Table 1 shows the results for each scenario tested and indicates that adding packing material to contact tanks can significantly increase the baffling factor.

Packing material volume. One of the variables investigated in this study was the volume of packing material versus tank volume

FIGURE 1 Baseline RTD curves for lithium and saline tracers



BF—baffling factor, *C/Cmax*—the measured background value of a tracer material at a given time (*t*) divided by the tracer's maximum concentration at the system outlet, LiCl—lithium chloride, NaCl—sodium chloride, RTD—residence time distribution, *t*/TDT—contact time divided by a system's theoretical detention time

TABLE 1 Baffling factors for all systems tested

Tank Size and Flow Rate	$V_{packing}/V_{tank}$	Baffling Factor Packing Material *1 in.*	 Packing Material *2 in.*	 Packing Material *3.5 in.*
25 gal, 5 gpm	0	0.21	0.21	0.21
	0.25	0.38	0.42	0.37
	0.5	0.53	0.6	0.51
	1	0.85	0.83	0.85
50 gal, 5 gpm	0	0.33	0.33	0.33
	0.25	0.44	0.46	0.42
	0.5	0.57	0.65	0.53
	1	0.95	0.94	0.85
50 gal, 10 gpm	0	0.33	0.33	0.33
	0.25	0.45	0.45	0.4
	0.5	0.59	0.63	0.58
	1	0.96	0.9	0.76

$V_{packing}/V_{tank}$—volume of the packing material divided by volume of the tank

($V_{Packing}/V_{Tank}$). For each tank size, flow rate, and packing material size, $V_{Packing}/V_{Tank}$ was tested at values of 0, 25, 50, and 100%. Each system that was tested showed a similar, incremental increase in baffling factor compared with the control system, which contained no packing material. This trend is illustrated in Figure 2, which shows four RTD curves generated from tests on the 25-gal tank containing 1-in. packing spheres. Changes in the shape of each RTD curve indicate that the flow became more uniform and closer to plug flow as more packing material was added. When the baffling factor of the system was plotted against $V_{Packing}/V_{Tank}$, a linear trend could be observed. This linear increase in the baffling factor, shown in Figure 3, was most likely caused by properties of the packing material itself. Because the packing material was less dense than water, it floated and became concentrated at the outlet of the tank. As more material was added to the tank, the interface between the packing material and the open tank volume moved closer to the inlet. This allowed the packing material to more quickly disperse any jets or eddies caused by the inlet, and this in turn increased the effective volume of the tank. Table 2 highlights how the packing material increased the effective tank volume (V_{eff}) in the 25-gal system. Effective tank volume was defined as

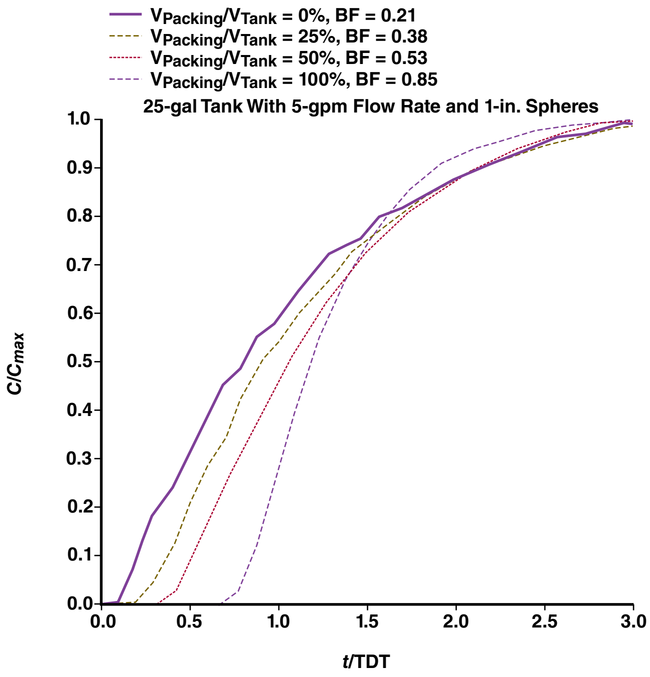
$$V_{eff} = \mathrm{BF}\left(V_{tank} - (1 - \mathrm{porosity}) \times \frac{V_{packing}}{V_{tank}} \times V_{tank}\right) \qquad (1)$$

in which BF is the baffling factor.

As Table 2 shows, the addition of random packing material increased the effective tank volume by more than 280%.

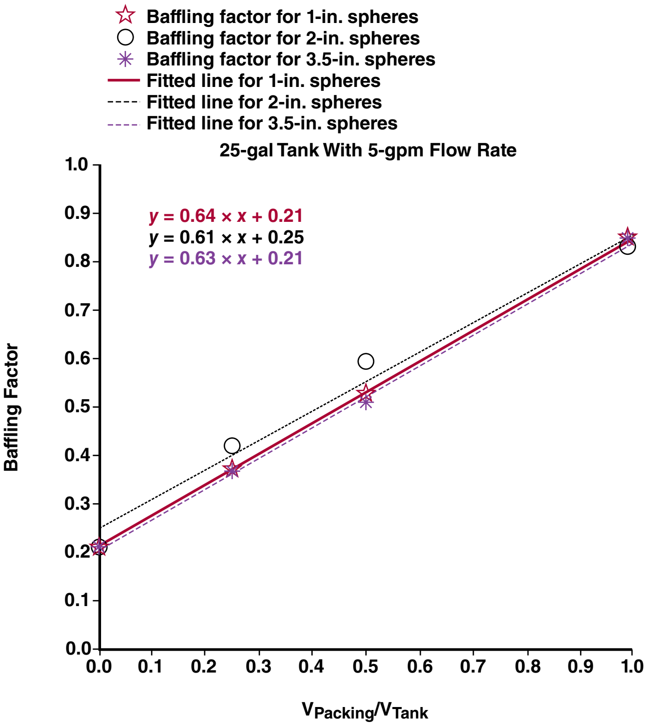
Packing material size. Tracer studies showed that the performance of each system was mildly dependent on packing material size. As determined from the data in Table 1, the average variation in baffling factor caused by a change in packing material size was only 12%. However, this was 5.6 times smaller than the change in baffling factor induced by the total volume of packing material within the tank. Figure 4 shows two sets of RTD curves indicating the effects of packing material size on hydraulic efficiency. The curves are very similar and appear to match each other considering experimental error. However, as the flow rate and size of the system were increased, the more systematic and exaggerated the effects of packing material size became. Multiple measurements suggested that as packing material size increased, hydraulic efficiency decreased because the 1- and 2-in. spheres consistently performed better than the 3.5-in. spheres. The RTD curves shown in Figure 4, part B, exemplify this trend. This phenomenon can be explained by the underlying physics. Although all three material sizes are designed to obtain similar porosities, the smaller material can be more intricately packed. In other words, when smaller material was used, the average space between spheres was slightly less than when larger material was used, making the flow path more tortuous. In effect, this results in a larger dissipation of kinetic energy, more effectively reducing the large-scale turbulent properties of the flow (e.g., short-circuiting, large eddies). Data from the 50-gal tank tested at a flow of 10 gpm show this trend most clearly, suggesting that as the flow momentum increases, the larger the effect the size of the packing material will have.

FIGURE 2 RTD curves for 1-in. packing material in a 25-gal tank



BF—baffling factor, C/C_{max}—the measured background value of a tracer material at a given time (*t*) divided by the tracer's maximum concentration at the system outlet, *t*/TDT—contact time divided by a system's theoretical detention time, $V_{Packing}/V_{Tank}$—volume of material packed into tank divided by volume of tank

FIGURE 3 Baffling factors for the three sizes of packing material with various $V_{Packing}/V_{Tank}$ values



$V_{Packing}/V_{Tank}$—volume of material packed into tank divided by volume of tank

Tank size and flow rate. Data collected in this study suggest that both tank size and flow rate have little effect on observed increases in hydraulic efficiency. However, minute trends indicate that these parameters may have greater influence on larger systems with higher flow rates. The data in Figures 5 and 6 can be used to explain these observations. Figure 5 shows RTD curves for each system when it was 50 and 100% full of 1-in. packing material. Each set of curves shows a negligible difference for the 50-gal tank within the T_{10} zone (considering two different flow rates). Although a similar observation can be made for the 2- and 3.5-in. packing materials, variations in the measured results for these two sets of curves were greater than those for the 1-in. set, suggesting increased turbulence. Therefore, flow rate exhibits a noticeable increasing effect when 2- and 3.5-in. materials are used. Higher flow rates may even affect the dispersing ability of the 1-in. material, but this is yet to be observed.

Similar to flow rate, the effects of tank size on the increase in hydraulic efficiency were very small. This is apparent from Figure 6, which shows the increase in baffling factor for each system using 1-, 2-, and 3.5-in. packing material. Figure 6, part A, shows the trend lines for the 1-in. spheres in the 25-gal tank with a flow of 5 gpm and the 50-gal tank with flows of 5 and 10 gpm, respectively. It is evident that there is no tail-off to the increase in baffling factor with the use of this material. The three lines have almost exactly the same slope, with the main difference being where they cross the y-intercept. Both trend lines for the 50-gal tank tested at flows of 5 and 10 gpm have a slope and y-intercept that are within 3.5% of each other. The primary difference between the trend lines for the 25- and 50-gal tanks was caused by the tank's baseline performance.

The similarity of the slopes of each fitted line in Figure 6, part A, provides what appears to be proof of the independence of flow rate and tank volume, but results for the 3.5-in. material suggest otherwise (Figure 6, part C). The effect of packing material size increased with flow rate and tank size. This can be seen through the increasing difference in slope in Figure 6, parts B and C. Even though this difference is small, it implies that larger systems with higher flow rates could be more adversely affected. In addition, although the RTD curves in Figure 5, part A, are almost identical, they begin to separate in Figure 5, part B. This divergence was most likely caused by flotation of the packing material. As more packing material was added to the tank, more of the material was forced closer to the inlet, and this allowed any jets caused by the inlet to be dispersed sooner.

CONCLUSIONS

The packing materials tested showed a pronounced potential to greatly increase the hydraulic efficiency of small chlorine contact tanks used in drinking water treatment. The results of this study suggest that the turbulent kinetic energy of the systems tested was effectively dissipated by all packing material sizes. Although the results show a relatively small dependence of baffling factor on packing material size, faint trends suggest that this parameter may exhibit exaggerated effects in larger tanks using higher flow rates.

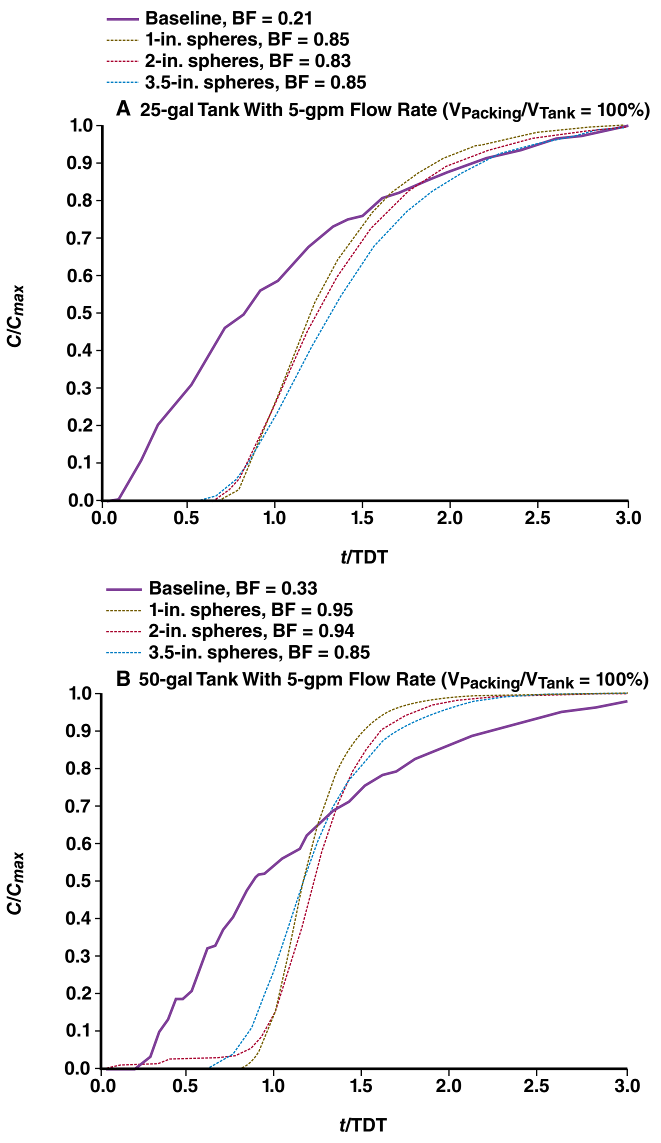
Drinking water contact tanks are typically plumbed so that the outlet is located near the bottom of the tank and the inlet is closer to the top. This inlet–outlet orientation allows the tank to be drained when maintenance is required or other issues arise. If the inlet–outlet design used in this study had been switched, this might have altered the results. The plunging jet caused by the typical inlet–outlet configuration might cause a hole to form in the floating layer of packing material if the contact tank has a $V_{Packing}/V_{Tank}$ value < 1. Such a hole would effectively cause a short circuit within the contact tank and allow the water to bypass most of the packing material.

TABLE 2 Effective volumes for the 25-gal system

$V_{packing}/V_{tank}$ %	Effective Volume—*gal*		
	Packing Material *1 in.*	Packing Material *2 in.*	Packing Material *3.5 in.*
0	5.25	5.25	5.25
25	9.26	10.33	9.13
50	12.59	14.51	12.43
100	19.13	19.40	20.19

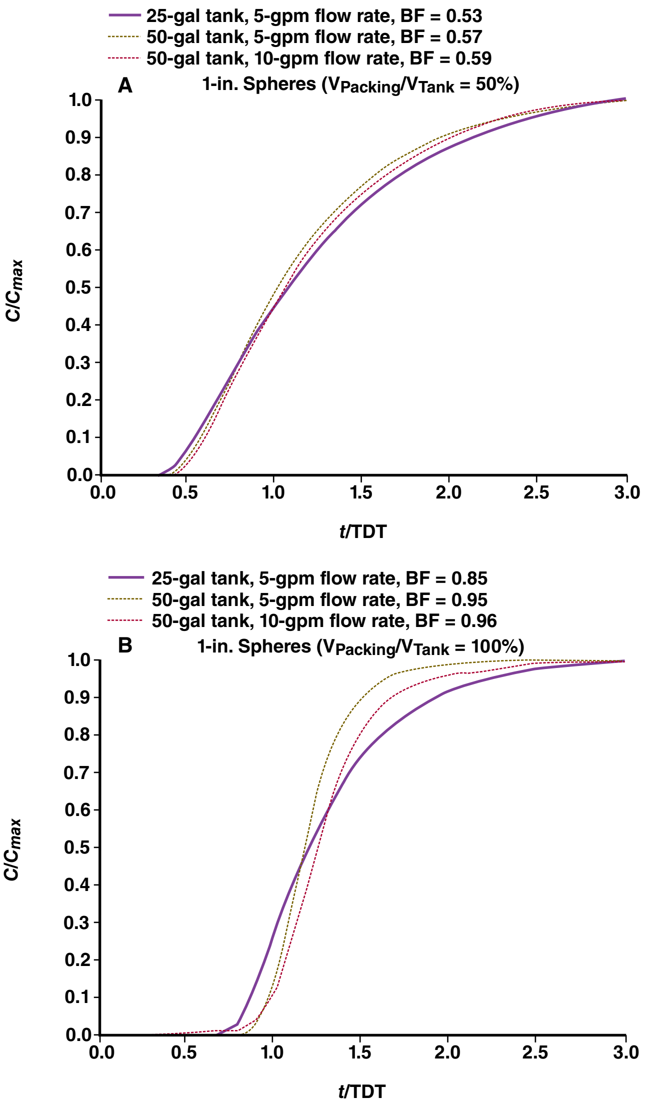
$V_{packing}/V_{tank}$—volume of the packing material divided by volume of the tank

FIGURE 4 RTD curves with a $V_{Packing}/V_{Tank}$ value of 100%



BF—baffling factor, *C/Cmax*—the measured background value of a tracer material at a given time (*t*) divided by the tracer's maximum concentration at the system outlet, *t*/TDT—contact time divided by a system's theoretical detention time, $V_{Packing}/V_{Tank}$—volume of material packed into tank divided by volume of tank

FIGURE 5 RTD curves for 1-in. packing material

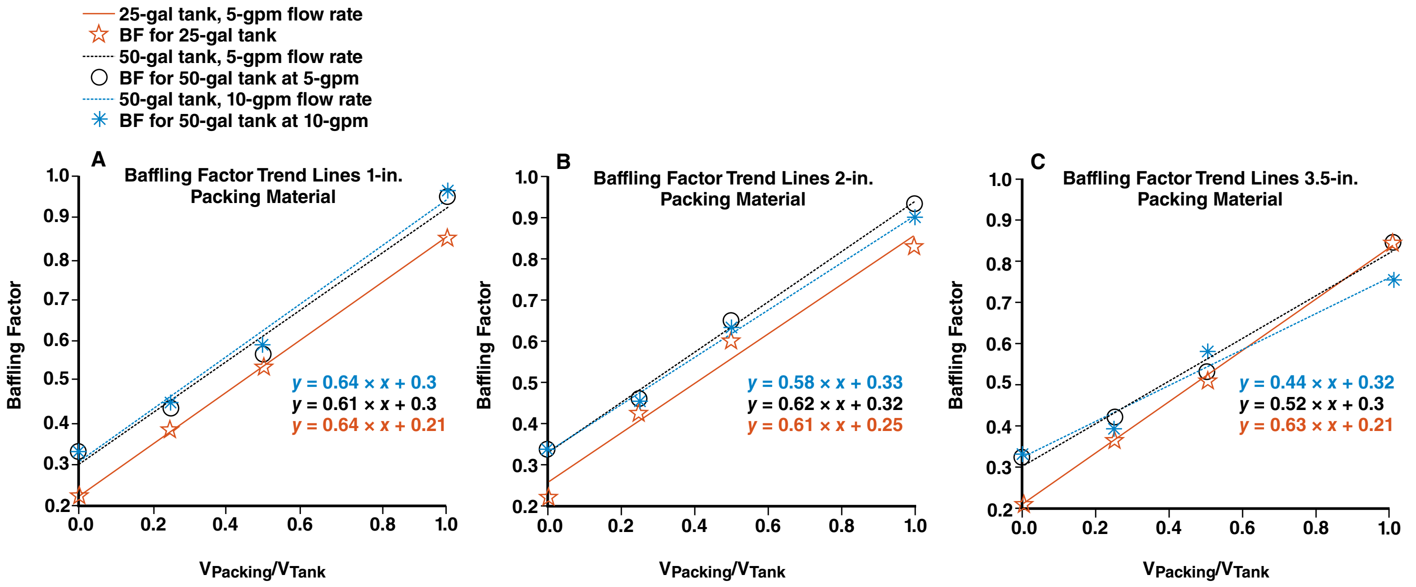


BF—baffling factor, *C/Cmax*—the measured background value of a tracer material at a given time (*t*) divided by the tracer's maximum concentration at the system outlet, *t*/TDT—contact time divided by a system's theoretical detention time, $V_{Packing}/V_{Tank}$—volume of material packed into tank divided by volume of tank

Head loss and compatibility with the disinfectant are also important aspects that must be taken into account with drinking water contact systems. When the head loss in a nonpressurized system becomes too large, it will cause the contact tank to overflow. The current study did not quantify the head loss caused by packing material within the contact tank; however, the addition of random packing material to any contact tank would cause an increase in system head loss. Though the polypropylene material tested would not be suitable for systems using ozonation or ultraviolet light radiation, it would work for systems that use aqueous chlorine as a disinfectant (Borealis, 2001).

Although other methods exist for improving the hydraulic efficiency of contact tanks (e.g., inlet–outlet modification, installation of intrabasin baffles), they fall short of random packing material when it comes to cost, ease of installation, and gain in system performance. Inlet and outlet modifications can be inexpensive, and they typically yield a net gain of 0.1 or 0.2 in the baffling factor. Installing intrabasin baffling can result in a net gain of up to 0.6 in the baffling factor, but this modification is expensive to install and is difficult to implement in nonpressurized water storage tanks similar to those used in this study. Random packing material offers the efficiency gains seen with intrabasin baffling and is as easy to install as an inlet–outlet

FIGURE 6 Baffling factor trend lines



BF—baffling factor, $V_{Packing}/V_{Tank}$—volume of material packed into tank divided by volume of tank

modification. It appears that the ability of random packing material to quickly and evenly disperse the flow within a contact tank is unparalleled, but the limitations of the material's application in practice are yet to be determined—especially for contact tanks larger than those tested in this study.

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FOOTNOTE

[1] EcoSense EC300A conductivity meter, YSI Inc., Yellow Springs, Ohio

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PEER REVIEW

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