A quantitative analysis of swimming pool recirculation system efficiency

Amir Alansari, James Amburgey and Nathan Madding

ABSTRACT

The primary objective of this study was to conduct a quantitative analysis of the hydraulic efficiency of a 1:25 bench-scale swimming pool and to determine whether the recirculation efficiency could be increased by modifying parameters such as turnover rate, inlet/out configuration, and extent of mixing within the pool. Salt tracer studies were conducted using KCl to determine the residence time distribution and describe the hydraulic characteristics of the pool. The results indicated that the removal of the tracer always followed an exponential decay curve, i.e. 63, 86, 95% for the first, second, and third turnover periods, respectively. In the majority of experiments, the exponential decay rate matched the inverse of the theoretical hydraulic detention time of the system. The results showed that none of the investigated parameters had any significant impact on the tracer removal efficiency. Increasing removal efficiencies of current treatment technologies such as sand and cartridge filters from approximately 25–90% would provide significant improvements in the rate of removal of *Cryptosporidium*-sized particles. Improving the treatment efficiency beyond 90% would have little additional impact, but further improvements could be achieved by decreasing the system turnover rate.

Key words | reactor model, recirculation efficiency, recreational water treatment, swimming pools, treatment efficiency

Amir Alansari (corresponding author)
James Amburgey
Department of Civil and Environmental Engineering,
UNC Charlotte,
Charlotte, NC 28223,
USA
E-mail: *amiralansari89@gmail.com*

Nathan Madding
Huber Technology Inc.,
Huntersville, NC 28078,
USA

INTRODUCTION

Recreational water illnesses (RWI) are a source for great concern in the recreational water industry. While chlorination inactivates many of the harmful bacteria and viruses that can cause RWI, some of the more troublesome pathogens are resistant to chlorination. The protozoan *Cryptosporidium* can remain infective in properly chlorinated pools for more than 10 days (Amburgey *et al.* 2012). Infections from *Cryptosporidium* can be caused by as few as 10 oocysts while an infected person can shed from 6×10^6 to 1.2×10^9 oocysts a day with infections lasting up to 21 days (Goodgame *et al.* 1993; Chappell *et al.* 2006; Yoder *et al.* 2012). To remove these chlorine-resistant pathogens, aquatic venues typically use methods of treatment such as diatomaceous earth, cartridge, or sand filtration as a primary treatment system. Even when properly operated and maintained, these treatment systems vary widely in performance providing 25–99.9% of *Cryptosporidium* oocyst removal per filter pass (Croll *et al.* 2007; Amburgey *et al.* 2009, 2012; Hayes *et al.* 2009).

Swimming pools can generally be modeled as continuous flow reactors. Inlets, skimmers, drains, and bather activity are all parameters that can potentially influence contaminant fate and transport in swimming pools. The shape and design of the reactor, as well as the position and number of the inlets and outlets, can also influence the hydraulics and mixing in the reactor (Kjellstrand *et al.* 2005). Reactor models can be applied to swimming pools to quantify hydraulic efficiency, reaction kinetics, and to visualize the extent of mixing, short-circuiting, and dead volumes. A residence time distribution curve, which quantifies the amount of time a substance spends inside a reactor, can be used to quantify the hydraulic efficiency of

doi: 10.2166/wh.2018.223

the reactor (Danckwerts 1953). By comparing ideal and non-ideal reactor curves, conclusions can be drawn regarding mixing, bypass and dead volumes, and system efficiency (Danckwerts 1953; Levenspiel 1999; Stamou 2008; Crittenden *et al.* 2012; Tsai & Chen 2013; Fogler 2016).

Current United States pool regulations advocate that pools have a maximum turnover rate of 6 hours (MAHC, CDC 2014). Ideally, during a single turnover, the entire volume of the pool would pass through the treatment system. It should be noted that the removal rates for current treatment systems are based only on the volume of water that actually passes through the treatment devices. Thus, these removal rates are based on the assumption that all of the pool system water reaches the treatment system. The prevalent theory (since 1926) has been that only a maximum of 63% of a pool's volume actually reaches the treatment system during a turnover period. Gage and Bidwell's 'Law of Dilution' states that only 63% of the pool's water reaches the treatment system during any given turnover period (Gage *et al.* 1926). In fact, Gage and Bidwell's model closely matches an exponential decay model where 63% of the contaminants would be removed at one turnover, 86% at the second, and so forth. This implies that the overall treatment efficiency would be limited by the percentage of contaminants delivered to the treatment system and not by the treatment system removal efficiency itself. The removal of a contaminant from an ideal continuous flow stirred-tank reactor (CSTR) can be described using Equation (1):

$$C_t = C_0 e^{-(1/\tau)t} \tag{1}$$

where C_t = concentration at time = t; C_0 = concentration at time = 0; τ = theoretical detention time; t = time.

The theoretical detention time or turnover rate of the system can be calculated by dividing the system flow rate by the volume of the pool. Equation (1) can be rearranged to calculate the fraction of contaminants removed from the system at a given time:

$$\frac{C_t}{C_0} = 1 - \ e^{-(1/\tau)t} \tag{2}$$

Suppose a swimming pool has a turnover rate of 6 hours. Using Equation (2), we see that for one turnover period ($t = 6$ h), the amount of contaminant removed from the system would be approximately 0.63 or 63%. After two turnover periods ($t = 12$ h), the amount of contaminant removed would be approximately 0.86 or 86%.

Understanding pool recirculation efficiency has great implications for treatment system operation and the handling of RWI incidences. The primary objective of this study was to conduct a quantitative analysis of the hydraulic efficiency of a 1:25 bench-scale swimming pool and to determine whether the recirculation efficiency can be enhanced by modifying the turnover rate or flow patterns. The study was carried out in two phases. The first phase consisted of salt tracer studies with fresh water replacement (instead of recirculation of the system) to quantify the hydraulic efficiency of moving water (and contaminants) to the treatment system and evaluate the hydraulics of the pool system. In the second phase, recirculation was employed to simulate normal pool operating conditions and describe the initial distribution of the salt tracer.

METHODS

Model swimming pool

The investigated pool was a 1:25 bench-scale Junior Olympic swimming pool modeled after the UNC Charlotte campus pool (Figure 1). The pool had five zones, a shallow zone, two transitional zones, a deep zone, and a ledge. The pool had seven outlet skimmers and six inlet jets per side. There were also three bottom drains located at regular intervals in the deepest section of the pool. The pool inlets and outlets were fabricated by inserting a 1/16th inch (1.59 mm) polypropylene nozzle into a ¼ inch (6.35 mm) threaded polypropylene fitting. The skimmers were positioned at the surface of the water while the inlet jets were placed 3 cm below the surface. The threaded fittings had single barb ends and were connected in series with flexible silicone tubing with a 4.8 mm inside diameter (Cole-Parmer, Masterflex L/S 15, Vernon Hills, IL, USA). The overall volume of the pool was approximately 87 L (0.087 m^3).

Pool system setup

The system was designed to allow for operation in non-recirculating and recirculating modes. A flow schematic of the

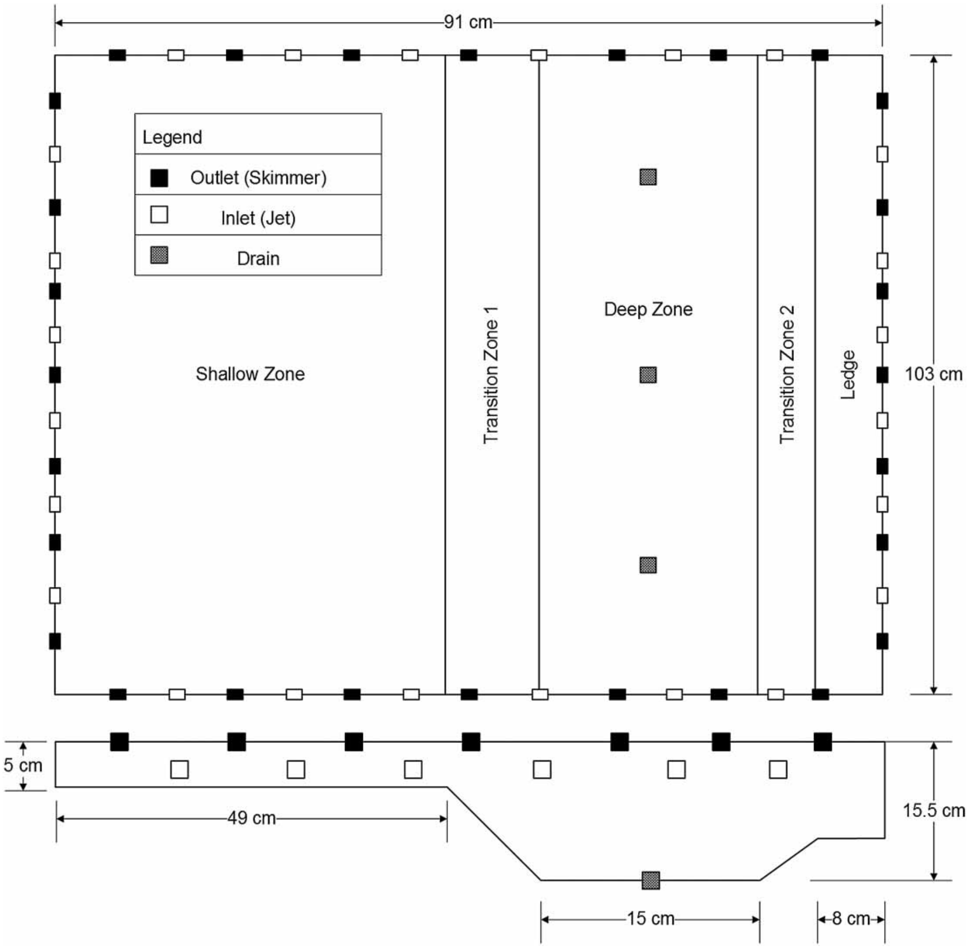

Figure 1 | Schematic of 1:25 bench-scale Junior Olympic swimming pool.

system is shown in Figure 2. Under the non-recirculating mode, deionized water (DI) with an average conductivity of less than 1 μS/cm was continuously supplied to the system while the water that exited the system was sent to drain. The influent flow rate was measured using a Coriolis flowmeter (Endress-Hauser, Promass 83A04, Reinach,

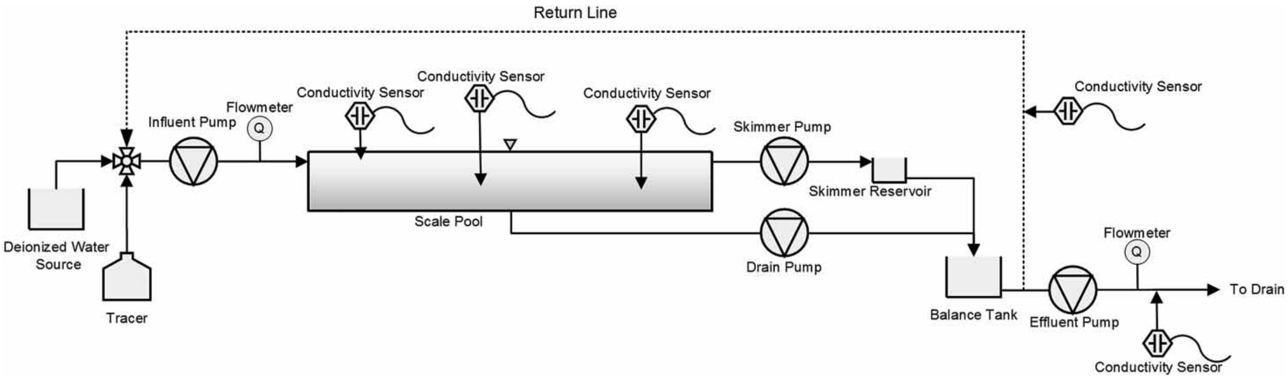

Figure 2 | Flow schematic.

Switzerland) downstream of a digital peristaltic pump (Cole-Parmer, Masterflex P/S, Vernon Hills, IL, USA) equipped with two pump heads (Cole-Parmer, 7518-10, Vernon Hills, IL, USA). Water from the skimmers was pumped into a skimmer reservoir by a digital peristaltic pump (Cole-Parmer, Masterflex P/S, Vernon Hills, IL, USA) with two pump heads (Cole-Parmer, 77200-62, Vernon Hills, IL, USA). The skimmer reservoir was necessary for removing air from the skimmer lines before the balance tank. Water from the floor drains was pumped directly into the balance tank using a digital peristaltic pump (Cole-Parmer, Masterflex P/S, Vernon Hills, IL, USA) equipped with a pump head (Cole-Parmer, 7518-02, Vernon Hills, IL, USA). Under normal operating conditions, the skimmers contributed 75% of the effluent flow while the bottom drains contributed the remainder of the flow. Water from the balance tank was pumped out using a digital peristaltic pump (Cole-Parmer, Masterflex P/S, Vernon Hills, IL, USA) equipped with a pump head (Thermo Scientific, 956-000, Waltham, MA, USA). The effluent flowrate was measured using a mass flowmeter (Krohne, Optimass 7050C, Houston, TX, USA). Under recirculating mode, water was recycled back into the pool from the balance tank. Output signals from the flowmeters were logged at 10 second intervals using an analog to digital data acquisition device (Measurement Computing, 1208LS, Norton, MA, USA) via a computer running LabVIEW 8.5 (National Instruments, Austin, TX, USA).

Tracer study

The tracer needed to be easily measurable, inert, soluble, and to have a similar density to the water. Potassium chloride (Fisher Scientific, P217-3, Hampton, NH, USA) was selected as the tracer in this study. Teefy (1996) recommended that the density of the tracer solution should be kept within 1% of the pool water density. Thus, the selected concentrations for the KCl solutions were 0.02, 0.2, and 1 M which resulted in a density difference of approximately 0.1, 0.94, and 4.41% at 25 °C, respectively (Novotny & Sohnel 1988). The latter concentration was selected in order to test the recommendations made by Teefy (1996). The volume of the tracer solution injected for each experiment was 870 mL, or 1% of the total pool volume. For experiments where the water was not recirculated, the slug-dose injection method was used, while a step-dose method was used for the experiments with recirculation (Teefy 1996; Fogler 2016).

To measure the concentration of the salt tracer in the system, a network of conductivity sensors (HACH, 3400sc, Loveland, CO, USA) were placed throughout the pool system connected to a central controller (HACH, SC1000, Loveland, CO, USA). In total, six conductivity sensors were used to characterize the flow pattern and concentration of the salt tracer throughout the system. Three sensors were placed just below the surface in a diagonal pattern in the main pool body. The fourth sensor measured the conductivity of the combined flow from the skimmers, while the fifth measured the conductivity of the water leaving the pool through the bottom drains. Water from the skimmers and the bottom drains flowed into a balance tank before being recirculated or sent to the drain. The final sensor measured the conductivity of water downstream of the balance tank. Conductivity and temperature measurements were logged in 10 second intervals.

Residence time distribution curves

The residence time distribution of a reactor is often expressed using two curves: the exit age distribution (E-curve) and the cumulative exit age (F-curve). The E-curve can be simply thought of as quantifying the time a tracer has spent in the reactor before exiting, while the F-curve describes the cumulative percentage of tracer that spent less than a given time t in the reactor (Danckwerts 1953; Levenspiel 1999; Fogler 2016). The mean residence time of the reactor can be estimated by calculating the area under the product of the time and exit age distribution curve. In order to compare reactors, it is often necessary to normalize the E- and F-curves with respect to a normalized time, θ. The normalized time can also be regarded as the number of turnovers. All the equations relevant for calculating the residence time distribution curves are presented in Table 1. Conductivity measurements from the sensor placed downstream of the balance tank was used to calculate the distribution functions. Data analysis was performed using *OriginPro 9.0* (OriginLab, Northampton, MA, USA).

Table 1 | Residence time distribution functions

Parameter	**Equation**
Exit age distribution, $E(t)$	$E(t) = \dfrac{C(t)}{\int_0^\infty C(t)dt}$
Cumulative exit age, $F(t)$	$F(t) = \int_0^t E(t)dt$
Mean residence time, τ_m	$\tau_m = \int_0^\infty tE(t)dt$
Normalized time, θ	$\theta = \dfrac{t}{\tau_m}$
Normalized exit age, $E(\theta)$	$E(\theta) = \tau E(t)$
Normalized cumulative exit age, $F(\theta)$	$F(\theta) = \int_0^\theta E(\theta)d\theta$

t = time, $C(t)$ = concentration leaving reactor at time t.

Investigated conditions

Several swimming pool hydraulic parameters were investigated in this study to determine their effect on hydraulic efficiencies in the model pool. This included (1) turnover rate, (2) inlet/outlet configuration, and (3) extent of mixing. The baseline standard condition matched the full-scale system, which had a 6-hour turnover rate with all inlets and outlets on all sides operational. Influent and effluent flow rates were set to 241 mL/min with 75% of the effluent exiting through the skimmers and the remainder through the bottom drains. The parameters investigated were turnover rate, inlet/out configuration, and extent of mixing within the pool. The examined turnover rates were 1-, 6-, 12-, and 24-hours. Except for the turnover rate, all other pool operating conditions were kept constant. To assess the impact of different flow patterns, the inlet and outlet configurations were changed. The first pattern was designed to create a diagonal flow pattern. Water entered the pool from the top and left jets and exited the pool from the bottom and right skimmers (Figure 1). A second reconfiguration pattern, designated as 'equal flow', was based on the ratio of skimmer to drain where both the skimmer and bottom drains contributed equal flow to the effluent while the inlet pattern was kept the same. A third reconfiguration pattern, designated as 'crossflow', had water entering the pool from the top and bottom side jets only and exiting the pool through the right and left side skimmers as well as the bottom drain. Two extremes were considered for the experiments that investigated the extent of mixing in the pool. In the first case, an overhead mixer (IKA Eurostar, Staufen, Germany) was placed in the center of the pool to simulate a CSTR. The mixer was fitted with a 4.3 inch (109 mm), three bladed, hydrofoil impeller and was operated at 300 rev/min for the duration of the experiment. In the second case, water entered only from the left side (shallow zone) of the pool and exited through the bottom drains to encourage plug flow conditions. The impact of salt tracer solution concentration on the accuracy of the exit-age distribution results was also investigated. The investigated KCl tracer solution concentrations were 1, 0.2, and 0.02 M. At 25 °C, this corresponded to a density difference of 4.42, 0.94, and 0.10%, respectively.

Most experiments were replicated. To simplify the presentation of replicate experiments in this report, the results were averaged using a 'multiple curve averaging' tool of a data analysis software *OriginPro 9*. The criteria for averaging points was for all common time values with a tolerance of $1^\circ 10^{-5}$ minutes. Exit-age distribution curves were fitted using *OriginPro 9*'s built-in nonlinear two-parameter exponential function which was similar in form to Equation (1).

RESULTS AND DISCUSSION

The primary goal of this study was to quantify the hydraulic efficiency of a model swimming pool in terms of salt tracer removal under different pool operating conditions. Figure 3 shows the normalized exit-age distribution of all the investigated conditions. The results showed that most of the variability between the results occurred in the initial 15% of the duration of the first turnover. For example, a relatively sharp peak was observed at the start of the experiment when the turnover rate was changed from 6 to 24 hours under the same conditions. However, after the initial peak, the trend of the exit-age distribution of all the experiments followed an exponential decay curve. It took between 4–6 turnovers to return the effluent conductivity of the pool back to baseline levels (<1 μS/cm) in all the investigated conditions. Sharp peaks in the early stages were observed under the following conditions, (1) 24-hour turnover period, (2) 1 M tracer solution, and (3) equal flow and diagonal inlet/outlet configurations. Early stage sharp peaks were most likely a case of short-circuiting (Levenspiel 1999; Davis & Davis 2012; Fogler 2016). Short-circuiting could potentially have a negative consequence

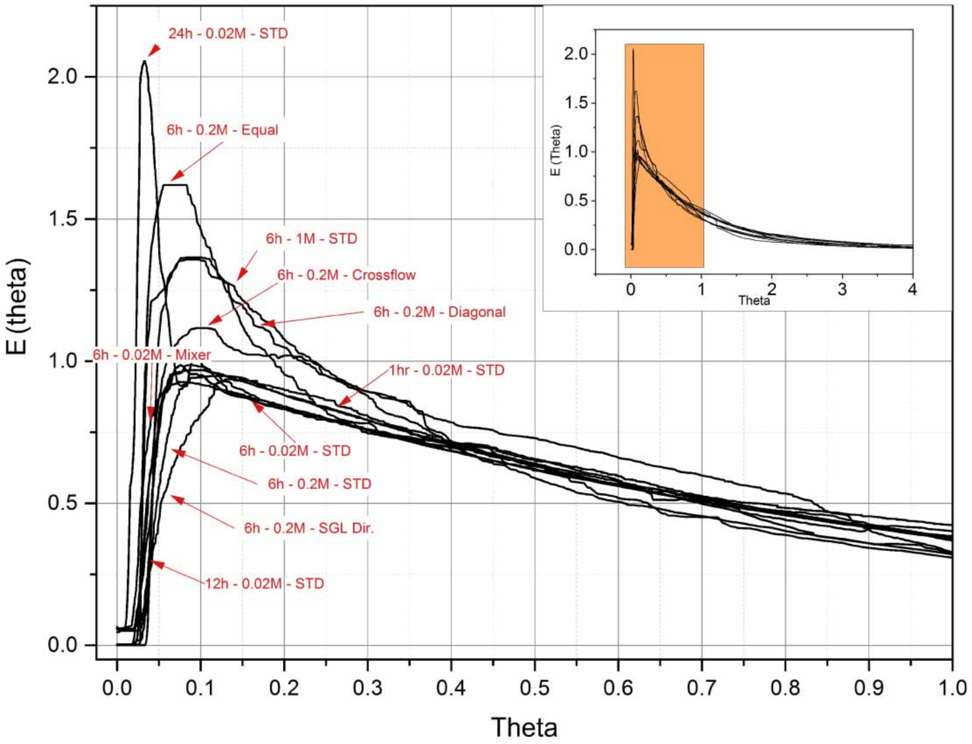

Figure 3 | Normalized exit-age distribution of all investigated conditions.

on chlorine distribution in the swimming pool. Instead of being uniformly mixed inside the pool, incoming chlorine could go directly to the effluent. Density currents were clearly visible with the highest tracer concentration (1 M) and the longest turnover rate (24 hour) where the salt solution was observed to flow directly to the bottom of the pool and out through the bottom drains. These results agreed with the recommendations made by Teefy (1996) with regards to the recommended salt tracer concentrations and density differences. According to Chen *et al.* (2012), tracer density effects would also become more pronounced as the flow rate in the system decreases. One possible explanation for the occurrence of short-circuiting when the inlet/outlet configuration was changed could be due to the increased flow rate in the bottom drains, as was the case with the equal flow configuration, or that flow patterns within the system created preferential flows to the bottom drains and from inlets and outlets located at adjacent corners, as was also the case with the diagonal pattern.

Figure 4 provides a summary of the tracer study results in terms of the fraction of tracer removed from the swimming pool after the first three turnover periods for all the investigated conditions. The values on the right axis of Figure 4 represent the fraction of tracer that would be removed in an ideal CSTR with an exponential decay rate calculated using Equation (2). All the experiments were performed using a 6-hour turnover rate, except where noted. The results showed that while the pool design, turnover rate, and hydraulic conditions varied significantly, the deviation of the fraction of tracer removed was less than 6% for the first turnover and less than 2% for the second and third turnovers of the theoretical values for all the investigated conditions. This implies that the model swimming pool behaved similarly to an ideal CSTR, and the fraction of salt tracer remaining in the system can be predicted by using the inverse value of the theoretical detention time as the exponential decay rate parameter in Equation (2). However, a closer examination of the exit-age distribution curve would still be required in order to diagnose any potential short-circuiting issues. In the cases where short-circuiting was evident, the fraction of tracer removed was always higher than would

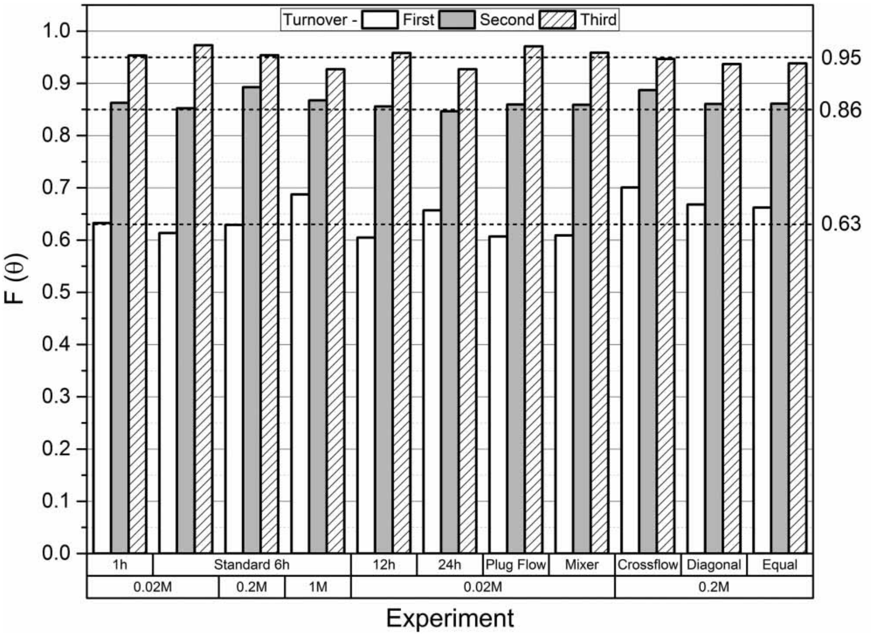

Figure 4 | Fraction of salt tracer removed from the pool during the first three turnover periods (error bars represent the standard deviation about the mean).

be observed in an ideal CSTR at the first turnover (63%), as shown in Figure 4.

Figure 5 presents some examples of the observed exit-age distribution curves along with their fitted curve functions. The range of data considered for curve fitting did not include the sharp peaks observed in the early stages of the experiments. The computed mean residence times were always found to be within 13% of the actual theoretical detention time, as shown in Table 2. According to Equation (1), the theoretical exponential decay rates would be 1, 0.17, 0.083, and 0.042 [1/h] for the 1-, 6-, 12-, and 24-hour turnover periods, respectively. There was no statistical difference ($p > 0.05$) between the theoretical exponential decay rates and the average fitted exponential decay rates for most of the conditions. A statistical analysis for the 24-hour turnover period and the inlet/outlet configuration experiments could not be performed due to the lack of replicate experiments.

In the second phase of experimentation, the bench-scale pool was operated in recirculating mode (Figure 2). Operating with recirculation allowed the tracer to start at zero and eventually reach a steady state concentration. The results of the recirculation phase helped define the initial mixing and lend understanding to the timescales on which pool mixing occurs. With no tracer exiting the system, plotting an exit-age distribution curve was not possible, however, plotting conductivity measurements versus time provided an adequate description of the initial mixing conditions. Figure 6 shows the average effluent conductivity measurements under recirculating and non-recirculating modes. The results showed that steady state was reached with recirculation at approximately 30 minutes. Without recirculation, the conductivity also peaked at approximately 30 minutes. Figure 3 shows that, on average, the peaks occurred at approximately 8–10% of the investigated turnover periods, with the exception of the 24-hour turnover period. This has practical implications when considering the distribution of chlorine into swimming pools. While it may take 4–6 turnovers (as much as 36 hours) to approach treating all of the water in a pool due to mixing, it only takes 8–10% of one turnover (up to 36 minutes) to replenish the chlorine concentration and adjust the pH due to the same mixing.

Under the non-recirculating mode, water that exited the pool was sent to the drain. This was analogous to having a treatment system that was 100% efficient at removing contaminants from the water. In reality, even when properly operated and maintained, treatment systems provide between 25–99.9% of *Cryptosporidium* oocyst removal per pass (Croll *et al.* 2007; Amburgey *et al.* 2009, 2012; Hayes *et al.* 2009). Equation (3) is a modification of Equation (1)

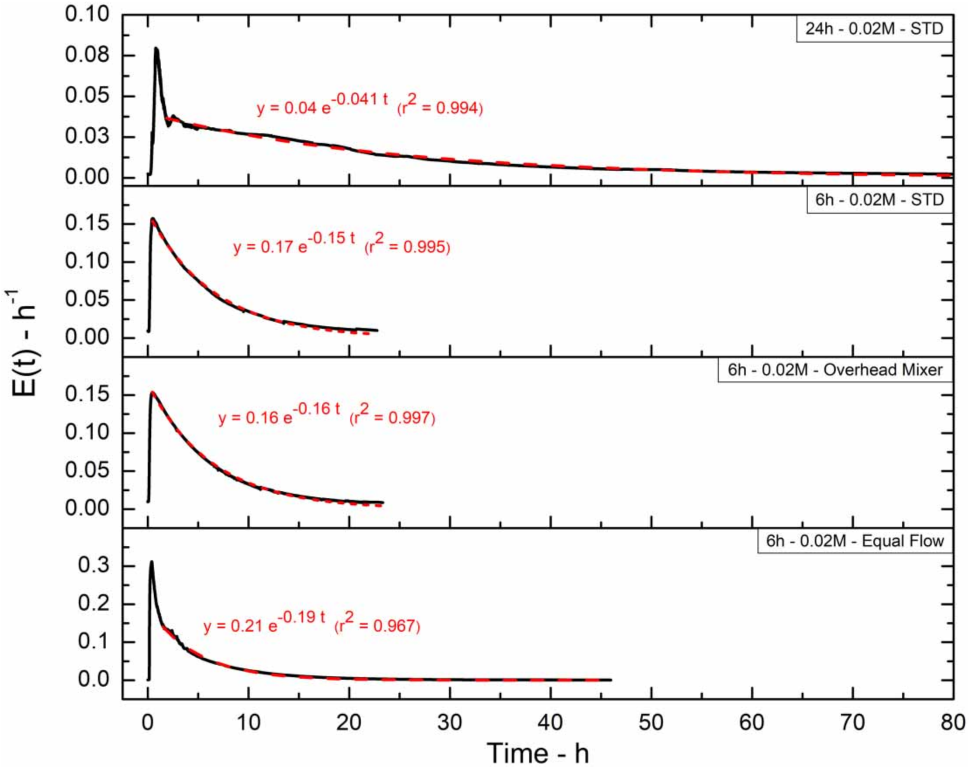

Figure 5 | Examples of exit-age distribution curve fitting.

which considers the efficiency of the treatment system and can be used to calculate the concentration of the contaminant remaining in the system at a given time.

$$C_t = C_0 e^{-(1/\tau)t\alpha} \tag{3}$$

where C_t = concentration at time = t; C_0 = concentration at time = 0; τ = theoretical detention time; t = time; α = treatment efficiency.

Suppose a 50,000-gal (189,250 L) swimming pool with a 25% efficient filter and a 6-hour detention time is

Table 2 | Investigated conditions fitting functions

Turnover rate (h)	**Tracer concentration (M)**	**Operating mode**	**Calculated mean residence time (h)**	**Fitting function (r^2)**
1	0.02	Standard[a]	1.1	E (t) = $e^{-0.95t}$ *(0.998)*
6	0.02	Standard	6.5	E (t) = 0.17 $e^{-0.15t}$ *(0.995)*
	0.02	Overhead mixer	6.0	E (t) = 0.16 $e^{-0.16t}$ *(0.997)*
	0.02	Single direction	6.3	E (t) = 0.16 $e^{-0.15t}$ *(0.997)*
	0.2	Standard	5.7	E (t) = 0.20 $e^{-0.19t}$ *(0.997)*
	0.2	Equal flow	5.4	E (t) = 0.21 $e^{-0.19t}$ *(0.967)*
	0.2	Diagonal	6.1	E (t) = 0.22 $e^{-0.24t}$ *(0.986)*
	0.2	Crossflow	6.7	E (t) = 0.2 $e^{-0.19t}$ *(0.995)*
	1	Standard	5.2	E (t) = 0.27 $e^{-0.24t}$ *(0.967)*
12	0.02	Standard	12.4	E (t) = 0.083 $e^{-0.079t}$ *(0.994)*
24	0.02	Standard	27.0	E (t) = 0.04 $e^{-0.041t}$ *(0.994)*

[a] All inlets and skimmers outlets were operational with 75% of the effluent flow coming from the skimmers.

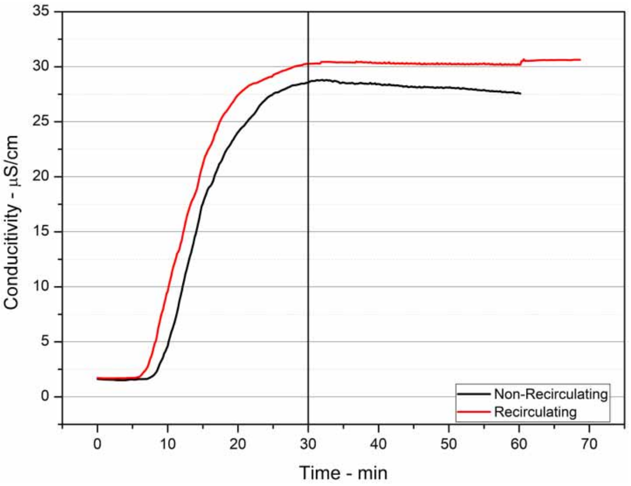

Figure 6 | Average effluent conductivity measurements under non-recirculating ($n = 3$) and recirculating modes ($n = 3$).

contaminated with 1×10^9 *Cryptosporidium* oocysts. After one turnover, the number of oocysts in the system will be approximately 7.79×10^8 oocysts. In other words, only about 22% of the oocysts will be removed from the pool system after the first turnover (by removing 25% of the *Cryptosporidium* from 63% of water recirculated). It would take approximately 28 turnovers (7 days) to reduce the total *Cryptosporidium* counts by 99.9%. For practical reasons, operators would be compelled to achieve their treatment goals in the shortest time possible. Figure 7 compares the time and volume required to achieve a 99.9% reduction of *Cryptosporidium* oocysts with different treatment system removal efficiencies and turnover rates. For a given treatment efficiency, reducing the turnover rate by a factor of 3 (from 6 to 2 hours) reduces the time required by the same factor. However, since reducing the turnover rate increases the flow rate in the system, the total volume of water required would remain the same for any given treatment efficiency. Similarly, the time required to achieve 99.9% reduction decreases by the same factor as the treatment efficiency increases for a given turnover rate. Since the reduction in time occurs without a change in the turnover rate, the total volume required would also decrease by the same factor. The time required to achieve a certain removal percentage of contaminant (based on the turnover time and treatment efficiency) can be calculated by rearranging Equation (3) and solving for time:

$$t_n = \frac{-\ln(1-n)}{\alpha}\,\tau \tag{4}$$

where t_n = time required to achieve desired contaminant removal fraction; n = desired contaminant removal fraction; τ = theoretical detention time; α = treatment efficiency.

Figure 7 also shows that it would be more practical for a swimming pool with a 25% efficient treatment system to improve the efficiency of their treatment system as opposed

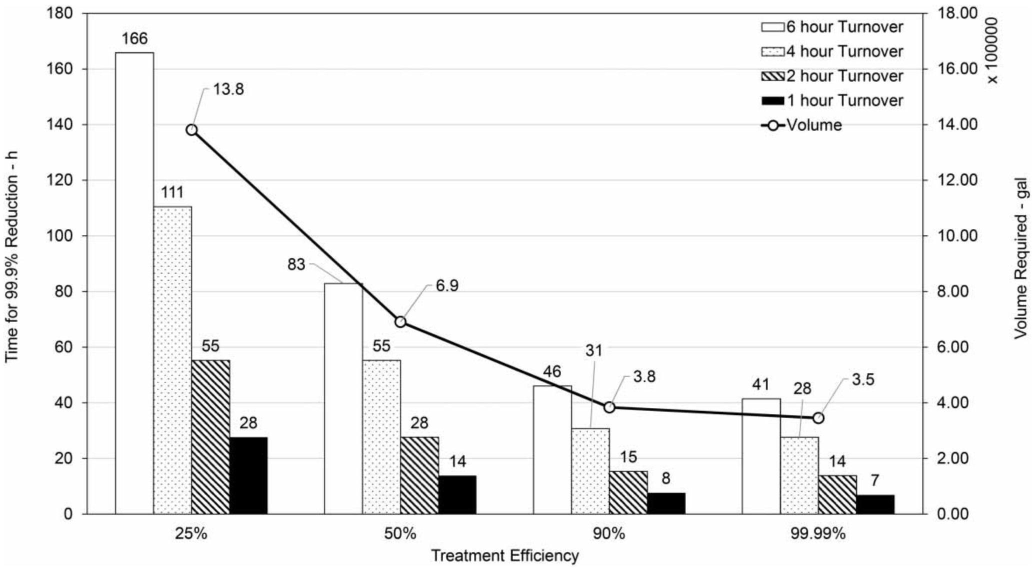

Figure 7 | Comparison of time and volume required to achieve a 99.9% reduction of *Cryptosporidium* in a 50,000-gal (189,250 L) swimming pool.

to reducing the turnover rate in order to reduce the total time and volume required to achieve their desired treatment levels. However, there is no practical benefit in improving the treatment efficiency beyond 90% since the total time/volume reduction would be insignificant. Instead, systems with greater than 90% treatment efficiency should reduce the turnover rate to reduce the required time. Equation (5) can be used to estimate the factor by which the total time would be reduced if the turnover and/or treatment efficiency is changed:

$$\beta = \frac{\tau_c}{\tau_p} \times \frac{\alpha_p}{\alpha_c} \tag{5}$$

where $\beta =$ time reduction factor; $\tau_c =$ existing theoretical detention time; $\alpha_c =$ existing treatment efficiency; $\tau_p =$ proposed theoretical detention time; $\alpha_p =$ proposed treatment efficiency.

For example, if a swimming pool changes its treatment efficiency from 25 to 90% and turnover rate from 6 to 2 hours, then the total time will be reduced by a factor of 10.8. Since the treatment efficiency was changed, the total volume would be reduced by the treatment efficiency improvement factor.

CONCLUSIONS

The primary objective of this study was to conduct a quantitative analysis of the hydraulic efficiency of a 1:25 bench-scale swimming pool and to determine whether the recirculation efficiency could be enhanced by modifying the turnover period or flow patterns. The results showed that the removal of salt tracer from the system per turnover period could not be significantly altered by changing the turnover period, inlet/outlet configurations, or extent of internal mixing. The results could be modeled using an exponential decay model (Gage *et al.* 1926). In all cases, the pool behaved similar to a CSTR, where the removal of the salt tracer from the pool system was 63, 86, and 95% for the first, second, and third turnover periods, respectively. The results also showed that in most cases, the fitted exponential decay rate could be approximated using the inverse of the theoretical detention time. Based on the results of this study, the authors conclude that the design of inlets and outlets has little actual effect on recirculation system efficiency or overall contaminant removal rates. The practical implications of the reported findings suggest that increasing removal efficiencies of current technologies such as sand or cartridge filters from 25 to 90% would provide measurable improvements both in terms of reducing the total time as well as the total volume required to achieve desired treatment goals. Reducing turnover rates would only reduce the time required while having no effect on the total volume. For more efficient treatment systems (above 90%), decreasing the pool turnover times (as opposed to more efficient disinfection or filtration systems) would be the most practical means of increasing the rate of contaminant removal, provided that increasing the turnover time/flow rate has no negative impacts on the treatment system performance. The factor by which the total time required would be reduced can be calculated by the product of the turnover rate reduction factor (current turnover divided by proposed turnover) and the treatment efficiency improvement factor (proposed treatment efficiency divided by current treatment efficiency).

REFERENCES

Amburgey, J. E., Fielding, R. R. & Arrowood, M. J. 2009 Filtration removals and swim diaper retention of Cryptosporidium in swimming pools. In: *Paper Read at Proc. 2009 Swimming Pool and Spa Int. Conf.*, London, UK (CD-ROM).

Amburgey, J. E., Goodman, J. M., Aborisade, O., Lu, P., Peeler, C. L., Shull, W. H., Fielding, R. R., Arrowood, M. J., Murphy, J. L. & Hill, V. R. 2012 Are swimming pool filters really removing Cryptosporidium? In: *Proceedings Fourth International Conference Swimming Pools and Spas*, Porto, Portugal.

Chappell, C. L., Okhuysen, P. C., Langer-Curry, R., Widmer, G., Akiyoshi, D. E., Tanriverdi, S. & Tzipori, S. 2006 *Cryptosporidium hominis*: experimental challenge of healthy adults. *Am. J. Trop. Med. Hyg.* **75** (5), 851–857.

Chen, C., Cheng, G., Sun, H., Hou, Z., Wang, X. & Zhang, J. 2012 Effects of salt tracer amount, concentration and kind on the fluid flow behavior in a hydrodynamic model of continuous casting tundish. *Steel Res. Int.* **83** (12), 1141–1151.

Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J. & Tchobanoglous, G. 2012 *MWH's Water Treatment: Principles and Design*. John Wiley & Sons, Hoboken, NJ.

Croll, B. T., Hayes, C. R. & Moss, S. 2007 Simulated Cryptosporidium removal under swimming pool filtration conditions. *Water Environ. J.* **21** (2), 149–156.

Danckwerts, P. V. 1953 Continuous flow systems: distribution of residence times. *Chem. Eng. Sci.* **2** (1), 1–13.

Davis, M. E. & Davis, R. J. 2012 *Fundamentals of Chemical Reaction Engineering*. Courier Corporation, North Chelmsford, MA.

Fogler, H. S. 2016 *Elements of Chemical Reaction Engineering*. Prentice-Hall, NJ, USA.

Gage, S. D., Ferguson, H. F., Gillespie, C. G., Messer, R., Tisdale, E. S., Hinman Jr, J. J. & Green, H. W. 1926 Swimming pools and other public bathing places. *Am. J. Public Health* **16** (12), 1186–1201.

Goodgame, R. W., Genta, R. M., White, A. C. & Chappell, C. L. 1993 Intensity of infection in AIDS-associated cryptosporidiosis. *J. Infect. Dis.* **167** (3), 704–709.

Hayes, C. R., Croll, B. T., Wright, C., Rowlands, D., Anex, C. & Henley, H. 2009 Removal of Cryptosporidium oocysts by filtration in the treatment of swimming pool waters. In: *Paper Read at Proceedings of the Third International Swimming Pool and Spa Conference*, March, London, UK.

Kjellstrand, R., Mattsson, A., Niklasson, C. & Taherzadeh, M. J. 2005 Short circuiting in a denitrifying activated sludge tank. *Water Sci. Technol.* **52** (10–11), 79–87.

Levenspiel, O. 1999 Chemical reaction engineering. *Ind. Eng. Chem. Res.* **38** (11), 4140–4143.

MAHC, CDC 2014 *Model Aquatic Health Code (MAHC): A National Model Swimming Pool and Spa Code*. Centers for Disease Control and Prevention, Altanta, GA, USA.

Novotny, P. & Sohnel, O. 1988 Densities of binary aqueous solutions of 306 inorganic substances. *J. Chem. Eng. Data* **33** (1), 49–55.

Stamou, A. I. 2008 Improving the hydraulic efficiency of water process tanks using CFD models. *Chem. Eng. Process. Process Intens.* **47** (8), 1179–1189.

Teefy, S. 1996 *Tracer Studies in Water Treatment Facilities: A Protocol and Case Studies*. American Water Works Association, Denver, CO, USA.

Tsai, D. D.-W. & Chen, P. H. 2013 Differentiation criteria study for continuous stirred tank reactor and plug flow reactor. *Theor. Found. Chem. Eng.* **47** (6), 750–757.

Yoder, J. S., Wallace, R. W., Collier, S. A., Beach, M. J. & Hlavsa, M. C. 2012 Cryptosporidiosis surveillance – United States, 2009–2010. *Morbid. Mortal. Wkly Rep.* **61** (5), 1–12.

First received 2 October 2017; accepted in revised form 31 January 2018. Available online 4 April 2018