The application of computational fluid dynamics and small-scale physical models to assess the effects of operational practices on the risk to public health within large indoor swimming pools

Lowell Lewis, John Chew, Iain Woodley, Jeni Colbourne and Katherine Pond

ABSTRACT

Swimming pools provide an excellent facility for exercise and leisure but are also prone to contamination from microbial pathogens. The study modelled a 50-m × 20-m swimming pool using both a small-scale physical model and computational fluid dynamics to investigate how water and pathogens move around a pool in order to identify potential risk spots. Our study revealed a number of lessons for pool operators, designers and policy-makers: disinfection reaches the majority of a full-scale pool in approximately 16 minutes operating at the maximum permissible inlet velocity of 0.5 m/s. This suggests that where a pool is designed to have 15 paired inlets it is capable of distributing disinfectant throughout the water body within an acceptable time frame. However, the study also showed that the exchange rate of water is not uniform across the pool tank and that there is potential for areas of the pool tank to retain contaminated water for significant periods of time. 'Dead spots' exist at either end of the pool where pathogens could remain. This is particularly significant if there is a faecal release into the pool by bathers infected with *Cryptosporidium parvum*, increasing the potential for waterborne disease transmission.

Key words | computational fluid dynamics, public health, swimming pools

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INTRODUCTION

Microbial pathogens can be introduced to swimming pool water directly thorough accidental releases from infected users, through shedding from contaminated equipment and clothing or from contaminated source water. The pathogens that are associated with swimming pool water, together with their potential impacts on human health and methods for control, have been well researched and documented (Pond 2005; HSE 2006; WHO 2006; PWTAG 2009; HPA 2011). These include faecally derived hazards, such as *Cryptosporidium* and *Escherichia coli* O157, and non-faecally derived hazards, such as *Pseudomonas aeruginosa* and *Staphylococcus aureus* (Pond 2005). Eye and skin infections are also common. Studies show that acute gastrointestinal illnesses are more likely where swimmers have submerged their heads (Causer *et al.* 2006; Boehmer *et al.* 2009).

The regulation of swimming pools is notoriously piecemeal. In the UK for example, although there is not any regulation specifically aimed at the swimming industry some key aspects are covered by the general requirements

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of current UK legislation such as the Health and Safety at Work Act 1974 (HMSO 1974). The World Health Organization published guidelines for swimming pools in 2006 (WHO 2006) which include guidelines for the maximum permissible microbiological concentrations derived from the findings of numerous studies into the infective doses of each pathogen (WHO 2006). This guidance was included in the revised guidance published by the Pool Water Treatment Advisory Group (PWTAG) in 2009. However, neither of these documents is legally enforced and therefore adherence to the guidance is varied across the industry. Many pools have been shown to exceed national legal limits for microbiological quality (see, for example, Mavridou *et al.* 2014) and indeed, in some facilities, e.g. splash parks no consistent requirements for water treatment exist (de Man *et al.* 2014). The lack of regulations is partly due to the comparatively little conclusive evidence that has existed from which policy-makers could derive health-based standards.

The successful control of many common pathogens can be achieved through well-designed pool structures that enable the entire water body to be effectively treated by a disinfectant, such as chlorine. However, understanding how the water flows within the swimming pool basin is of importance as it can indicate potential 'dead spots' in the pool where pathogens may reside.

The potential presence of disinfectant resistant pathogens, such as *Cryptosporidium parvum*, introduces an extra requirement to ensure the entire water body passes through additional treatment processes in a relatively short timescale (Rose *et al.* 1997; PWTAG 2014). *Cryptosporidium* oocysts present a significant challenge for the swimming pool industry due to the combination of their high resistance to disinfection, small size and low infectious dose (RSC 2001; HPA 2011).

As a result of the continued occurrence of swimming pool-related outbreaks of Cryptosporidiosis, the presence, transport and fate of *C. parvum* oocysts within recreational water remains of significant interest in the industry (Lu *et al.* 2013). Owing to its highly resistant nature towards disinfection, the control methods for *C. parvum* in the pool environment are significantly different from other common waterborne pathogens, such as *E. coli* and *Pseudomonas aeruginosa* (Schets *et al.* 2004). *C. parvum* oocysts are largely unaffected by the common conditions within a swimming pool particularly where the pool is disinfected by chlorine and are therefore considered a relatively persistent risk to health, although *Cryptosporidium* oocysts have been identified to be susceptible to UV irradiation and ozone in various studies (Korich *et al.* 1990; Rennecker *et al.* 1999; Craik *et al.* 2001; Zimmer *et al.* 2003). Both of these methods cannot be implemented directly at source in the pool tank. It is therefore necessary for the oocysts to be removed from the pool tank for external treatment or filtration. For that reason, it is very important that the hydraulic design of the pool tank efficiently removes the oocysts and avoids the formation of dead zones within the water body. In addition, knowledge about the expected spread of oocysts throughout the water body would enable more effective facility management by operators following a faecal incident, reducing the risk of further contamination and transmission to other bathers.

Understanding the turnover of water and dispersion of disinfectants within a swimming pool is therefore an essential part of water quality management required for the protection of public health. Attempts to model the hydraulics of pools have been recently undertaken by Cloteaux *et al.* (2011, 2013), however they present insufficient detail and validation of the modelling methods used to enable the accuracy of the results to be determined. The hydraulic requirements of the two treatment mechanisms are fundamentally opposed as maximising the removal of water from the pool tank for ex-situ treatment requires a minimising of mixing within the pool tank, however this will reduce the efficacy of disinfectant treatment. Therefore, a balance between the two mechanisms will be required to operate the swimming pool efficiently.

Current guidance in the UK by PWTAG recommends maximum times for overall pool turnover for a range of pools in order to address these issues. The recommendations for pool turnover time, however, vary and are dependent on the type of pool facility (Table 1). The objective of these recommendations is to prevent the accumulation of chlorine-resistant pathogens and other dissolved pollutants. PWTAG (2009) also recommends that for all pools uniform dye dispersion should be achieved within a 15 minute period. This aims to ensure that adequate mixing takes place to maximise the efficiency of the treatment of non-chlorine-resistant pathogens. The combination of these guidelines aims to create a balance between plug flow and

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Table 1 | Recommended turnover times for various swimming pool facilities (adapted from PWTAG (2009))

Pool type	Pool turnover
Competition 50 m pool	3–4 hours
Diving pools	4–8 hours
Hydrotherapy pools	0.5–1.5 hours
Leisure pools (1–1.5 m deep)	1–2 hours
Leisure pools (>1.5 m deep)	2–2.5 hours

fully mixed hydraulic designs, however no evaluation with respect to the appropriateness of these specified guidelines has been published to date.

The pool turnover time is defined by PWTAG (2009) as the time required for the total volume of water in the pool to be exchanged using the recommended circulation rate. The recommended circulation rate is in turn related to the maximum bather load that is permissible on safety grounds. This combination of definitions, however, omits any consideration of the hydraulic design of the pool tank and the uniformity of the water exchange. This raises concerns that the current guidance does not place adequate requirements on pool designers to ensure that potential hazards are effectively removed.

The current energy efficiency agenda has encouraged the use of variable speed drives within the circulation system at many swimming pools (Carbon Trust 2006). These devices enable facilities to reduce the energy consumed by the water treatment plant by slowing down the circulation pumps during unoccupied periods. Although the potential environmental and financial benefits have been widely reported, there have been no studies to assess the potential impacts this change in operational practice can have on the effectiveness of pathogen control and therefore the risk to public health.

PATHOGEN PROPERTIES

Chlorine sensitive pathogens

A number of pathogens of interest are susceptible to chlorine, including *E. coli* and *Pseudomonas aeruginosa*. Various studies have shown that they can be successfully deactivated following contact with chlorine for a short period of time. CT (disinfection concentration multiplied by the contact time) values for chlorine disinfection of pathogens of concern are shown in Table 2 together with resulting disinfection times expected at common swimming pool chlorine concentrations of 1–2 mg/L.

The CT time and disinfectant distribution throughout the pool are key aspects to include in the modelling. The time that it takes for chlorine to reach all parts of the pool tank will indicate how long operators should allow before bathers can use the pool following interruptions in the treatment system. Similarly, it will assist in forecasting the requirement for a recovery period following a period of high bather occupation. Combined with data on chlorine consumption rates, this will enable a risk-based approach to be used to optimise the concentration of chlorine to use in the pool water and recovery time requirements.

Chlorine-resistant pathogens

Not all pathogens can be effectively controlled through chlorine disinfection as highlighted in Table 2. *Cryptosporidium* is a good example and due to current interest in the pathogen within the swimming industry was selected for assessment in this study. *Cryptosporidium* oocysts have a specific set of properties that govern their movement within a body of water. The oocysts are 4–6 μm in diameter with a density of 1,045 kg/m^3 (Medema *et al.* 1998). Medema *et al.* (1998) found that freely suspended oocysts have a settling velocity of approximately 0.4 μm/s. It was also observed by Medema *et al.* (1998) that the oocysts readily

Table 2 | Chlorine CT values for common pathogens in swimming pool environments

Pathogen	Chlorine CT value (mg min/L)	Disinfection time in pool conditions	Source
E. coli O157	0.04	1–2 seconds	WHO (2004)
Viruses	3	1.5–3 minutes	AwwaRF (2004)
Giardia	25	12.5–25 minutes	WHO (2004)
Cryptosporidium parvum	15,300	5–10 days	Shields *et al.* (2008)

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adhere to other particles within the water and therefore the actual settling velocity is dependent upon the clarity of the water and the nature of the solids associated with a faecal release. Brush *et al.* (1998) also observed that the conditions of the water and age can have an effect on the surface properties of *Cryptosporidium* oocysts, with older oocysts exhibiting greater adhesive properties. The low concentration of suspended solids in swimming pool water means that the flow of water is likely to be the dominant influence on the transport of oocysts within the pool tank rather than gravitational settling.

The second important set of properties relate to the infection potential of *Cryptosporidium* oocysts. The oocysts are infectious immediately with no maturation time required before they can potentially infect a new host and are relatively persistent in the environment with a natural die-off rate in water of 0.005–0.037 $\log_{10}$-units per day. The oocysts are highly resistant to common disinfection chemicals with CT values for chlorine and chlorine dioxide of 15,300 mg min/L and 1,000 mg min/L respectively (Shields *et al.* 2008; WHO 2009). This resistance combined with the infectious nature of *Cryptosporidium* creates a significant health risk to bathers if they are not removed immediately. Ozone is more effective at inactivating oocysts with a CT value of 3.5 mg min/L. UV is highly effective at inactivating oocysts with 99.98% inactivation achievable with doses as low as 19 mJ/cm^2. Both of these methods however cannot be directly applied to the water in the pool tank, therefore it requires the oocysts to be removed from the tank and deactivated in the treatment system.

The rate and uniformity of water removal is therefore another key aspect of swimming pool hydraulics. Understanding how long water from different areas of the pool will remain within the tank will provide information required to analyse the risk to bathers from various contamination scenarios.

The study presented in this paper has been undertaken using a combination of small-scale physical modelling and computational fluid dynamics (CFD) modelling to assess the effectiveness of chemical distribution and water removal for a commonly used tank design for competition pools. It also assesses the impact that changes in operational practices could have on the risk to public health in large public swimming pools.

METHODS

The study consisted of two approaches for assessing the distribution of chemicals and the retention time of water in a pool tank. The first approach used small-scale physical modelling and the second approach used CFD techniques available in a commercial software package.

Physical modelling experiments

A rectangular open surfaced tank measuring 100 cm long, 40 cm wide and 4 cm deep was built specifically for this study to simulate a swimming pool. These dimensions were selected in order to create a model tank that was geometrically similar to the tank dimensions commonly used for 50 m swimming pools, which was the focus of the current study. The geometric scaling ratio of 1:50 enabled the tank to be large enough for visualisation to be possible while reducing the size of the tank to a practical size for filling and emptying. Fifteen pairs of inlets were installed along the sides of the tank at a depth of 2 cm and measured 2 mm in diameter. The inlets were connected to a pipe network that was fed with mains water via an adjustable header tank and a volumetric flow meter. To minimise variation in the flow distribution equal lengths of tubing were used to connect each inlet. The water was allowed to overflow along both sides of the tank into two collection channels that were connected to the drain. This enabled the experiment to be run continuously in a controlled manner at a range of velocities and therefore start-up effects could be eliminated. A volumetric flow meter was installed to enable the flow rate of water from each header tank position to be measured. The experimental apparatus is shown in Figure 1.

To assess the dynamic similarity with large-scale tanks (or swimming pools) non-dimensional analysis was undertaken. Assuming jet width (w) is dependent on inlet jet velocity (u), gravity (g), density (ρ) and viscosity (μ) application of the Buckingham Pi Theorem shows that jet width to inlet diameter (d) ratio, w/d, and other non-dimensional flow parameters, will depend on Reynolds number (Re) and Froude number (Fr) only. The application of the Buckingham Pi Theorem is not presented in this paper as

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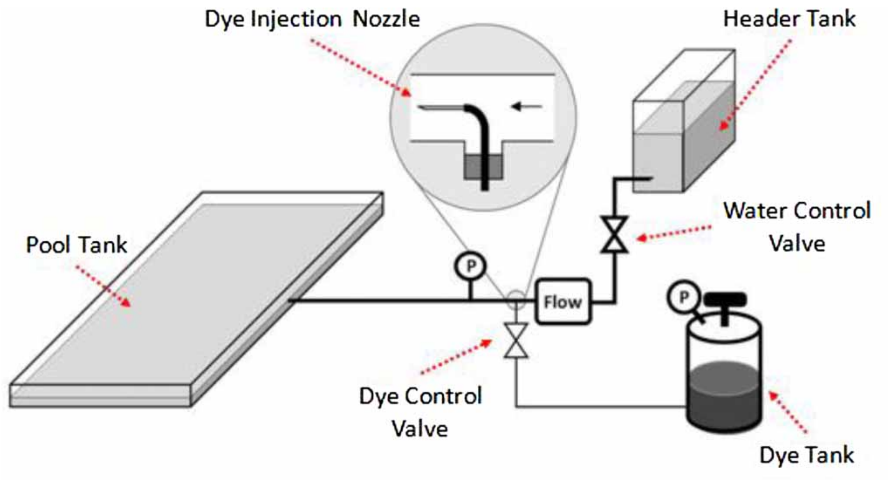

Figure 1 | Schematic of small-scale physical experimental apparatus (only one inlet connection shown).

it is a well-known procedure, however, the resulting non-dimensional parameters are defined in Equations (1) and (2) below:

$$\mathrm{Re} = \frac{\rho u \mathrm{d}}{\mu} \tag{1}$$

$$\mathrm{Fr} = \frac{u}{\sqrt{\mathrm{gh}}} \tag{2}$$

where h is the depth of the tank. In these experiments $h = 20\,d$. This non-dimensional analysis neglects any surface tension and buoyancy effects.

Considering the definitions of Froude number and Reynolds number, it is not possible to satisfy both Froude number similarity and Reynolds number similarity requirements for different scales without changing the kinematic viscosity of the fluid. Dynamic similarity requires the following relationship between the scaling factor for kinematic viscosity (F_υ) and the scaling factor for the geometry (F_l) (Hughes 1993).

$$F_\upsilon = F_l^{3/2} \tag{3}$$

It follows that in order to have hydrodynamic similarity with a water tank 50 times larger than the experimental model (which would represent a full-scale 50 m swimming pool) a fluid with a kinematic viscosity of approximately $3 \times 10^{-9}\ \mathrm{m^2/s}$ (1/350th of water) would be required. No such fluid exists and therefore it is necessary to make compromises in relation to the dynamic similarity. The experiments were undertaken using a Reynolds number of 4,600 and Froude Number of 3.69 to ensure that the inlet jet flows were turbulent while avoiding significant surface deformation effects.

This apparatus was used in two experiments. First, small-scale dye tests were undertaken to simulate disinfectant distribution throughout the tank. Secondly, surface water flows were investigated using small polystyrene beads. The addition of the beads enabled the surface water flows to be visualised and captured by a video camera.

Dye test experiment to investigate disinfectant distribution

To investigate the movement of disinfection around the 'pool' a dye test was undertaken. To enable the injection of dye into the inlet water stream a hand-pressurised dye tank was connected to a hypodermic needle located within the inlet pipework (Figure 1). A concentrated dye solution of 1.5 mg/L Brilliant Blue FCF food dye (CAS number 3844_45_9) was prepared and placed in the injection tank before being pressurised to 1.5 bar. The hypodermic needle enabled the impact on the inlet flow rate to be minimised while maintaining the injection of a reliable stream of dye. The injection of the dye took place after the flow meter

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to resolve issues with dye retention within the body of the flow meter. As a result an adjustment to the recorded flow rate was required. The flow rate of dye from the injector at 1.5 bar was calculated to be 0.08 L/min by recording the time taken to discharge 1 L of water. This volume was added to the fresh water flow rate, measured by the flow meter, in order to calculate the jet velocity at the inlets for each header tank location. Three inlet velocities were used in the experiments. Water meter readings used for flow calculations had an accuracy of ±2%.

The dispersion of dye was recorded using a video camera fixed above the tank to enable subsequent analysis of the dispersion patterns and the generation of images that could be compared with CFD outputs. A non-dimensional timestep (τ) was used in the analysis of the experimental footage to enable observations to be applied to the full-scale scenario. This was defined as shown in Equation (4) below, where u, t and l are the dimensional velocity (m/s), time (s) and tank width (m), respectively.

$$\tau = t\frac{u}{l} \tag{4}$$

Bead test experiment to investigate surface water movement

White polystyrene beads (3 mm in diameter) were used to visualise the surface water movement within the tank. In order for the polystyrene beads to be visible in the video footage, the water in the tank was coloured dark blue using a dye injected into the inlet water stream via a hand-pressurised tank as described previously. The properties of *Cryptosporidium* oocysts defined previously indicated that they would likely follow the water flows in the tank with minimal settling taking place. The type of pool considered in this investigation has significant overflow, causing a general upward flow in the tank and therefore it was determined that the direction of surface flows could influence the movement of oocysts released at shallow depths. The beads were dropped into the tank and their dispersion was recorded with the high frame rate video camera used for the dye test experiments. The non-dimensional time (τ) was again used r in the analysis of the footage.

CFD modelling

CFD is commonly used to investigate the flow properties of fluids in a wide range of industrial applications. In the case of a swimming pool, the flow type of interest is the turbulent jet. Jets provide dispersion, agitation and propulsion of fluids in both unconfined and confined environments. The interaction of jet flows with free surfaces, solid surfaces and other recirculating flows can affect the development and therefore the hydrodynamic characteristics of the jet flow. Knowledge about the behaviour of turbulent jets in these different scenarios is therefore needed to better inform the swimming pool industry.

Initial validation of CFD methodology

Initial validation of a CFD methodology using ANSYS Fluent 12.0, a commercial CFD software package, was undertaken using previously published experimental data on free and confined jet flows by Wygnanski & Fiedler (1969), Quinn (2006), Fellouah *et al.* (2009) and Shinneeb *et al.* (2011). This validation consisted of the investigation of free jet modelling (where the jet is not confined by any surfaces), shallow jet modelling (where the jet is only confined vertically by surfaces) and confined jet modelling (where the jet is confined in all directions by surfaces). Physical experiments were also undertaken using the apparatus described in Figure 1 to supplement the available published experimental data. Comparison of the experimental data with CFD solutions showed that the CFD methodology was capable of reasonably accurately representing the flow characteristics within the swimming pool tank.

In all cases, the jet inlet was defined by specifying a uniform inlet velocity, turbulence intensity and turbulence length scale. Similarly, in all cases, solid surfaces were defined with no slip boundary conditions. For the free jet case, the remaining far-field boundaries were defined by specifying pressure and turbulence intensity and eddy viscosity to molecular viscosity ratio for any inflow. This boundary condition was also applied to the tank outlets in the shallow jet and confined jet cases.

The free surface in the shallow jet and confined jet cases was approximated using a zero shear stress boundary

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Table 3 | Boundary conditions for free, shallow and confined jet cases

Boundary type	Free jet	Shallow jet	Confined jet
Jet inlet	Specified velocity (u), turbulence intensity (I), turbulence length scale (0.07 *d*)	Specified velocity (u), turbulence intensity (I), turbulence length scale (0.07 *d*)	Specified velocity (u), turbulence intensity (I), turbulence length scale (0.07 *d*)
Tank outlet	n/a	Specified pressure (0 Pa), turbulence intensity (0.05%), viscosity ratio (1%)	Specified pressure (0 Pa), turbulence intensity (0.05%), viscosity ratio (1%)
Far-field	Specified pressure (0 Pa), turbulence intensity (0.05%), viscosity ratio (1%)	Specified pressure (0 Pa), turbulence intensity (0.05%), viscosity ratio (1%)	n/a
Solid surface	No slip	No slip	No slip
Free surface	n/a	Zero shear stress	Zero shear stress

condition. This was considered appropriate as flow-induced surface deformations are observed to be negligible in large-scale applications of submerged jets at Reynolds numbers less than 50,000 and, as gravity was also not included, Froude number effects were not being modelled.

Turbulence intensity settings for the inlet were calculated using the relationship shown in Equation (5), where Re is the Reynolds number of the inlet flow (ANSYS 2009). Free jet verification studies showed the k-ϵ realisable turbulence model to be relatively insensitive to this parameter (ANSYS 2009).

$$I = 0.16 \times \mathrm{Re}^{-1/8} \qquad (5)$$

A summary of boundary conditions used in the CFD modelling cases is shown in Table 3.

In addition to the selection of appropriate boundary conditions, the initial validation studies were undertaken to assess the type of mesh and turbulence model required to accurately model the swimming pool scenario.

Five different two-equation turbulence models (standard k-ϵ, re-normalised group k-ϵ, realisable k-ϵ, standard k-ω and shear stress transport k-ω) that were available within the software package were used to model the free jet case and the sensitivity of the outputs produced from each was investigated by manipulating mesh density and domain size. The details of each turbulence model can be found in the Fluent User Manual (ANSYS 2009) and are therefore not presented here. Sensitivity towards far-field boundary conditions was investigated by running the simulation using the five cases in Table 4. For each case, the near-wall areas were resolved through the use of enhanced wall functions. This removed the requirement to fully resolve the flow in the near-wall region therefore reducing the mesh size significantly.

The realisable k-ϵ turbulence model and a 3D swept prism-based numerical mesh were ultimately selected for the shallow jet and confined jet cases as these techniques were found to generate free jet outputs in good agreement with published free jet data from Wygnanski & Fiedler (1969), Quinn (2006) and Fellouah *et al.* (2009) without being highly sensitive to inaccuracies in the boundary conditions, as shown in Figures 2 and 3. A double precision, steady-state, pressure-based solver was used to run the CFD simulations together with the SIMPLE pressure-velocity coupling scheme and first order pressure discretisation. Spatial discretisation used a cell-based least squares method while momentum, turbulent kinetic energy and

Table 4 | Settings used for far-field boundary condition sensitivity testing

Case	Inlet turbulence intensity (%)	Far-field turbulent intensity (%)	Far-field viscosity ratio
1	4.14	4	1
2	4.14	4	2
3	4.14	4	0.5
4	4.14	10	1
5	4.14	0.05	1

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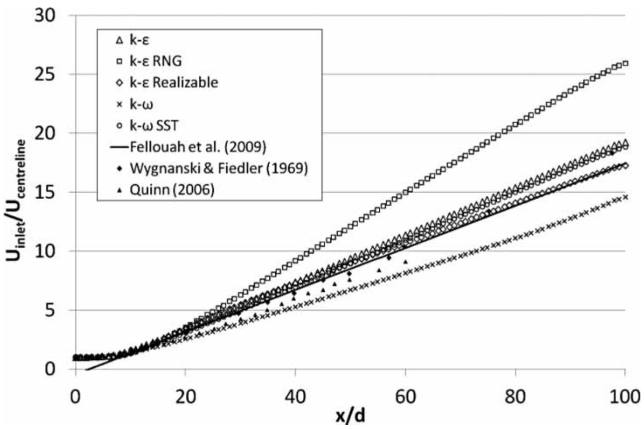

Figure 2 | Free jet centreline velocity variation with distance from jet exit for various turbulence models.

turbulent dissipation rate equations were all solved using second order upwind techniques.

CFD visualisation modelling to investigate disinfection dispersion

To produce images from the CFD for comparison with the dye test run in the physical model it was necessary to simulate the spread of dye in the tank. Unsteady CFD solutions were required to model the dye injection using the transient solver and the steady flow solutions as the starting point. The species modelling function was used to create a two-component mixture of water and dye. The dye was given the same density and viscosity as water and a mass diffusion rate of $1 \times 10^{-9}\ m^2/s$ was selected based on available literature (Coulson & Richardson 2000). The amount of dye in the inlet was set to have a constant mass fraction of 0.0015 to correlate with the experimental usage of 1.5 g of dye per litre of water. The results of the solution were saved at regular intervals to enable specific snapshots to be generated in the post-processing software. Post-processing software was used to generate 3D representations of the dye plume in order to compare the simulation results with the images from the physical model.

The process of generating 3D-rendered images of the CFD simulations required the specification of rendering criteria, therefore, a visual calibration test with the dye used in the physical model experiments was undertaken. The calibration test started with a solution of 1.5 g of dye per litre of water. This solution was placed into a clear glass container 45 mm in width so that the depth of water being viewed in the test was similar to that of the physical model experiment. After the colour intensity of the water was recorded by taking a photograph, the water sample was diluted with fresh water in a 1:1 ratio and re-photographed. This process continued until the camera was unable to capture a visible difference between the water sample and a blank sample containing no dye.

The water was observed to be opaque for dye concentrations greater than 9.38×10^{-2} g/L and was not clearly distinguishable from the blank sample below a dye concentration of 3.66×10^{-4} g/L. This information was used to

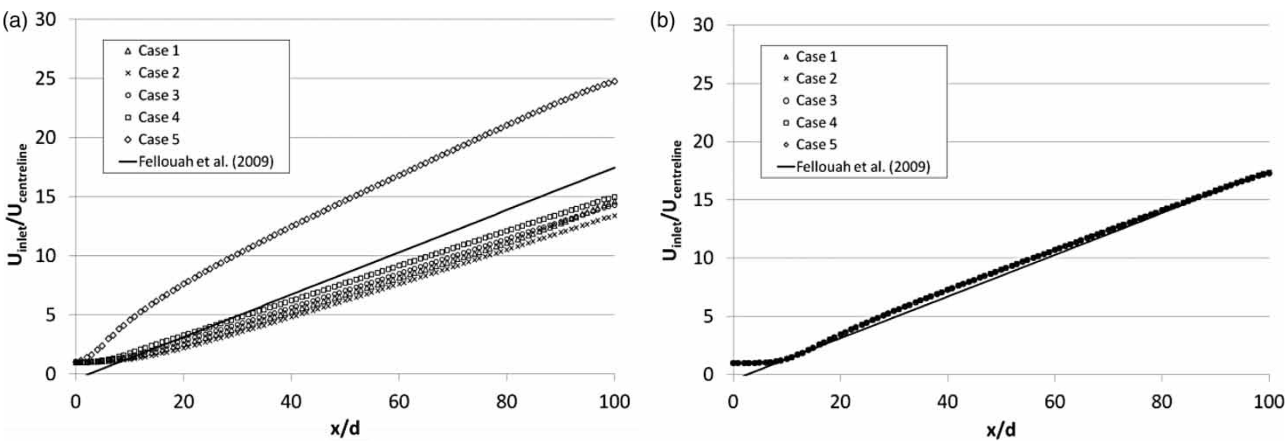

Figure 3 | Effect of changing far-field boundary conditions on centreline velocity profile for (a) *k-ω* model and (b) *k-ϵ* realisable model.

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specify the following rendering settings in post-processing CFD results:

- Render type: volume rendering
- Variable: dye mass fraction
- Transparent mass fraction: 1×10^{-7}
- Opaque mass fraction: 1×10^{-4}

Multi-phase CFD modelling to investigate water turnover rates

To analyse the rate of water removal from the pool tank, it was necessary to modify the CFD methodology to include a multi-phase water model. For the purposes of tracing the water, the water introduced through the inlets was specified to be a different phase than the water initially existing within the tank. Both phases were specified to have the same properties and were able to fully mix with each other. Following initialisation of the CFD model, the mass fraction of each phase was calculated both at the outlets and within the pool tank after each timestep. The model was then run until at least 90% of the original water contained within the pool tank had been removed.

RESULTS AND DISCUSSION

The studies undertaken in this investigation generated a large number of flow images and numerical data streams and therefore all the results cannot be effectively presented directly. The collected data, however, was used to create a series of graphical outputs that could be analysed with reference to aspects of the full-scale swimming pool application. More specifically the results were used to comment on three aspects of swimming pool operation: disinfectant distribution, surface water movement and pool turnover rate, as discussed below.

Disinfectant distribution

Both the CFD and physical modelling approaches provided results that could be used to evaluate the distribution of disinfectant throughout the pool tank. Close agreement was observed between the CFD and the physical modelling results following non-dimensional analysis as indicated by the example in Figure 4. Variations in the experimental images, such as some of the jets not being quite perpendicular, highlight the difficulty of accurately creating the scale model with the equipment available. It was also not possible using the available equipment to generate images that captured the similarity in the spread of dye in the vertical plane.

The dye was observed to reach the majority of the tank by a non-dimensional time of $\tau = 25$. This equates to an actual time of approximately 4 minutes for a full-scale pool operating at the maximum recommended inlet velocity of 2 m/s for deep areas and 16 minutes for the maximum recommended inlet velocity for shallow areas (PWTAG 2011). This suggests that where a pool is designed to have 15 paired inlets it can be concluded that it is capable of distributing disinfectant throughout the water body within an acceptable time frame; however, many swimming pool facilities operate at significantly lower flow rates than the maximum. The operational facility reviewed as part of the research work used an inlet velocity of 0.16 m/s meaning that a distribution time of over 50 minutes is expected. This is a significant period and therefore indicates the potential for health risks if a start-up period is not allowed for following interruptions to the treatment system, such as

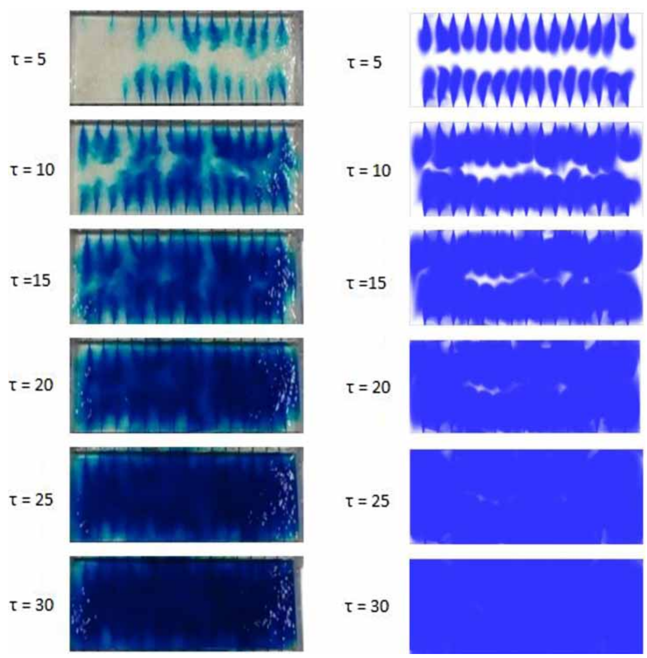

Figure 4 | Physical modelling (left image) and CFD images (right image) from small-scale dye distribution experiments at a range of non-dimensional time (τ) values.

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backwashing the sand filters. Undertaking a dye test in the full-scale pool is needed to provide final validation, however this was not possible during the investigation due to financial constraints and availability of the pool.

Surface water movement

Figure 5 shows the spread of beads when dropped in a central location in the tank. The beads were found to spread across the width of the tank to the overflowing edge by $\tau = 5$, with very little length-wise dispersion of the beads. This indicates that the flow on the free surface is predominantly in the x axis (jet) direction with very little in the z axis (perpendicular to jet) direction. The majority of beads had reached the edge of the tank by $\tau = 15$, however, a few beads took over twice as long. On average, the complete removal of beads, when placed centrally in the tank, was achieved by $\tau = 25$.

In the case of drop locations close to one end of the tank, the beads were found to spread further in the z direction. The length of time taken for the beads to reach the edge of the tank was also longer with the majority of the beads still within the tank at $\tau = 25$. On average, the complete removal of the beads when placed at one end of the tank was achieved by $\tau = 60$.

These observations indicate that surface water removal towards the ends of the pool tank is likely to take longer than in a more central location. This indicates that any contaminants released in these areas would likely take longer to be removed from the pool and therefore increase the potential for human exposure to harmful contaminants. Activities for the user groups most likely to cause a faecal release, namely young children or bathers with disabilities, are usually focussed at the ends of the pool tank. As reported by Suppes *et al.* (2014), more splashes to the face occur to younger swimmers who tend to ingest higher volumes of water than other groups, making them more vulnerable to ingestion of pathogens. These observations would suggest that enhancing the water removal rates at the ends of the tank could reduce the contamination risk following an incident in these areas.

Pool turnover rate

The mass fraction of original water present within the pool tank was recorded during the CFD simulations. The modelled water exchange profile for the pool is shown in Figure 6 together with the theoretical water exchange profile, calculated using current guidance published in *Swimming Pool Water* (PWTAG 2009), for comparison.

The proportion of original water actually exchanged during the design specified turnover period of 3.7 hours was found to be 62%. The simulation also showed that a 90% removal of original water was not achieved until more than double the recommended turnover period. This has important repercussions for determining whether the

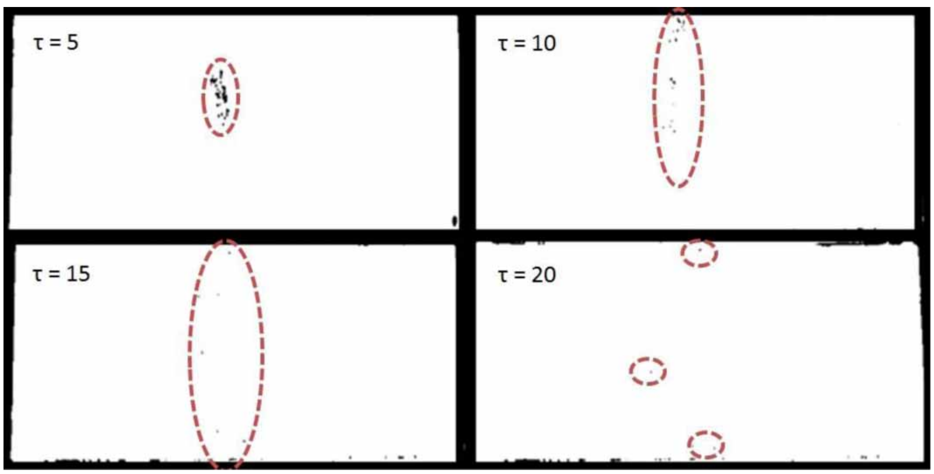

Figure 5 | Images at four non-dimensional timesteps of plastic bead dispersion from a central drop location in the small-scale physical experiments used for indicating surface flow patterns.

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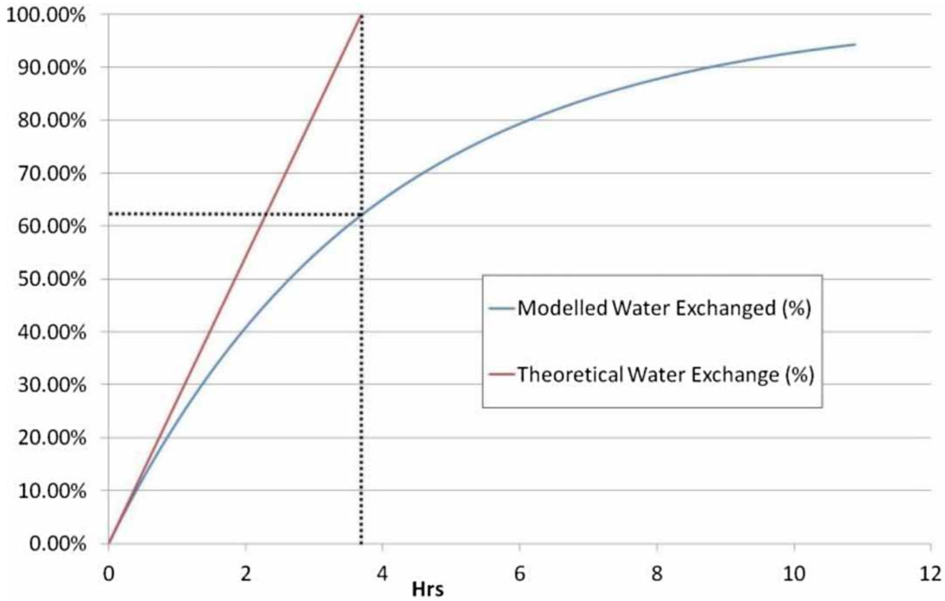

Figure 6 | Modelled and theoretical water exchange profiles for test pool scenario.

existing hydraulic design of pools is appropriate. In addition to the overall water exchange profile, the uniformity of the water in the pool tank was also examined. Figure 7 shows the areas of the pool tank that contained more than 70% of the original water after 6 hours of simulation. It indicates that, in the current configuration, the exchange rate of water is not uniform across the pool tank and that there is the potential for areas of the pool tank to retain contaminated water for a significant period of time.

Figure 7 | Simulation of a pool tank showing areas of the pool with >70% original water after 6 hours.

The simulation also indicated that the dead spots in this common pool configuration are likely to occur at either end of the pool tank. The presence of chlorine-resistant pathogens in these areas is therefore likely to persist longer than in other areas of the pool. This is of significant concern as bathers (particularly children and weak swimmers) were observed during the study to often spend most time at the end of the pool rather than in the middle of the pool. This not only increases the probability of contaminants being introduced in these locations initially, but also the risk of potential exposure to persistent pathogens. Water analysis undertaken by Lewis *et al.* (2011a, b) indicated that large variations in some water quality parameters did exist within the pool tank. Further developing these simulations to look at the retention time of pollutants introduced into different areas of the pool tank is recommended to enhance understanding of pollutant mobility and also support the selection of appropriate sampling locations for operational pools.

Limitations of the study

There were difficulties in the setting up of the physical experiment as the small-scale model also exhibited significant

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surface tension effects at the outflows of the tank which may have affected the surface flow patterns. Repeating the surface flow tests with a larger-scale model would enable the effects of surface tension to be assessed. Both experimental methodologies do not take into account the additional agitation of the water caused by the presence of bathers. This additional disruption of the water flows could significantly affect the nature of the water flows within a pool tank and the associated timescales for chemical dispersion and water exchange.

Similarly, limitations were encountered with both methods in relation to maintaining similarity of the inlets between the model and the real pool application. It was not possible to resolve the numerical mesh to capture the flow through the inlet diffuser. An investigation into the sensitivity of the simulation output on the inlet modelling methodology is required to compare the relative appropriateness of maintaining either jet width or jet velocity.

Undertaking a dye test on the actual pool would be valuable to verify the results. However, we were not granted permission to do this on the pool we used to model our experiments on as it would have required closure for a period of time.

Despite the limitations, the study has shown great potential for both CFD modelling and physical modelling of pools to assist pool designers, operators, regulators and even health surveillance experts reduce the public health risks associated with swimming pool use. Within the current study, we have identified four lessons related to water quality for those involved in pools. (1) We have shown that design of the pool is enormously important in reducing the potential health risks associated with them. (2) Through modelling, we have shown that 15 paired inlets is sufficient to ensure that disinfection is distributed throughout the pool configuration tested in this study within a reasonable time frame as long as sufficient inlet velocities are used but low inlet velocities could lead to health risks especially if a start-up period (the time between commencement of pumping and opening the pool for use) is not allowed for following interruptions to the treatment system, such as backwashing the sand filters or after a mechanical failure. (3) The identification of dead spots within the pool which can harbour pathogens can be used to improve operating practices and to influence future designs of pools in order to reduce this risk. This is especially important in dealing with *Cryptosporidium* which is highly resistant to chlorine. (4) Investigation into pool turnover rates has shown that they are significant in ensuring that pools do not retain contaminated water for long periods of time, potentially leading to ingestion by vulnerable bathers such as children or the elderly.

CONCLUSIONS

The CFD modelling indicated that, although dye could be effectively distributed within the short time frame desired, current pool design approaches are not as effective at exchanging the water within the tank. A common misconception in the swimming pool industry is that the turnover time is only dependent upon the volume of the tank and the water flow rate. The CFD modelling showed that approximately only 60% of the water volume is exchanged during the turnover time calculated using current methods. This is due to the mixing taking place in the tank. The methods in the current PWTAG guidance assumes pools operate on a plug flow basis which is unlikely to occur especially in large competition pools like the one investigated in this study.

The outputs of the simulations also indicated that it is important for accurate inlet flow velocities to be used when undertaking analysis of disinfectant dispersion. Operating at significantly lower flow rates than specified during the design purposes can result in an increased risk to public health due to a reduced removal of contaminants as well as reduced distribution rate of disinfectants. Further CFD studies could include investigation of the sensitivity of the flow to the representation and design of the jet inlets.

Several issues were identified with the experimental method trialled in this study. The 1:50 scale added significant difficulties in setting up the experiment as it required tight tolerances to be achieved. Similarly, the small-scale introduced significant surface tension effects which impacted the overflow of water from the tank. A larger-scale model would reduce these surface tension effects and assist with easing some of the experimental tolerances. Similarly, carrying out dye tests and residence time tracer tests on a fully operational facility would enable further

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validation of the simulation methodology to be undertaken. Unfortunately this was not permitted by the operator of the facility at the time the research project was being undertaken.

The potential of CFD modelling in pool operation, regulation, design and management is considerable. By varying the models to take into account different pool configurations as well as various structures in the pool, such as a moveable floor or slides it would be possible to identify both potential health risks and consequently the best management practices to deal with specific pools.

The current study indicates that there is a need for additional research to further investigate the influence of pool design and management practices on the water quality of pools. These investigations should focus on the transportation of substances around the water body and generation of full-scale data that can be used to validate a CFD methodology suitable for swimming pools. This would in turn assist policy-makers in the much needed task of drafting regulations based on scientific evidence for swimming pools and other artificial recreational water facilities.

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