Prediction of storm tank performance using Computational Fluid Dynamics

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ABSTRACT: CFD has been employed to predict the retention time of neutrally buoyant particles in rectangular storm tanks under steady state conditions. Using 2-D width averaged models and the RNG k-ε turbulence model as the numerical solver, the flow field was predicted qualitatively in agreement with Clements (1966) and Kluck (1997). A discrete phase model was applied to mimic dye tracing. It was found that the computed retention times may be roughly estimated using a uniform flow assumption, with a deviation of less than 10%. The hydraulic performance of storm tanks was evaluated using a short-circuiting parameter, S, (Persson, 2000). A phenomenon was observed showing that tanks with a low length to depth ratio were subjected to more serious short-circuiting problems.

1 INTRODUCTION

Storm Tanks have been an integral part of the sewerage treatment process since the early 20th century. However, intermittent discharges from existing storm tanks are believed to be a major influencing factor in downstream river and coastal water quality. The underlying cause of the problem in storm tanks is yet to be fully understood. UK Water Industry Research Limited (UKWIR) conducted a review project of the current UK design criteria of storm tank (Ref. no.: WW17), in which the retention periods continue to be based on the Ministry of Housing Royal Commission (1970). One of the components of the project was to employ CFD as the tool to compute the retention time of neutrally buoyant particles in a range of rectangular storm tanks under steady state conditions, i.e. flow rate does not vary with time. This paper reports the results of the CFD analysis.

It was unfortunate that no suitable field data or literature was available to carry out precise quantitative analysis of the CFD results. Clements (1966) and Kluck (1997), who measured the flow velocity in rectangular storm tanks under turbulent conditions, may provide alternative validation sources.

The performance of the storm tanks was evaluated using a comparative parameter, nominal detention time, for brevity denoted as t_n, and a short-circuiting parameter, denoted as S, (Persson, 2000). The nominal detention time is the travel time under ideal uniform flow conditions and may be defined as the ratio of volume of water in the tank over discharge. This theoretical time was compared with the computed travel time, which was assumed to be equal to the arithmetic mean of the individual particle residence times.

2 MODEL CONFIGURATION

2.1 *Geometry of the storm tank model*

The tanks to be investigated are shown in Figure 1; a wide rectangular tank that is composed of a flat base, a full-width inlet and outlet weir. Strong three dimensional effects would not be expected with this configuration. Therefore, uniform flow conditions across the width were assumed.

To reduce computational efforts as well as to improve solution convergence, 2-D width averaged models were generated. The geometry of the tank models was further simplified and used a rectangular domain with two vertical planes representing the inlet and outlet at the top corners.

A range of storm tanks was chosen, based on typical storm tank dimensions in Yorkshire, UK. Six tank models were created and their dimensions are the combination of length (L) 10 m, 20 m and 30 m and depth (D) 3 m and 4 m. The six tanks were tested with three flow rates and the magnitude of the flow rate was calculated according to Equation 1 given the flow depth above the outlet weir (H) 50 mm, 100 mm, and 200 mm.

$$q = \frac{2}{3} C_d \sqrt{2g} H^{1.5} \tag{1}$$

where q = discharge per unit width ($m^3/s/m$); $C_d = 0.6$; $g = 9.81 m/s^2$ and H = flow depth above weir (m).

The simulations were undertaken using the Gambit (version 2) software for generation of the domains, and the Fluent (version 5) CFD software for numerical computation. To obtain solutions within a reasonable computation time, the maximum number of cells meshed was less than 500,000. For the same reasons, a structured quadrilateral mesh was used.

2.2 *Numerical models*

Detailed description of the numerical models used and the computational process can be found in the Fluent Manual (Fluent 1998) and Versteeg and Malalasekera (1995).

2.2.1 *RNG k-ε turbulence model*

The numerical model for solving the flow field was chosen according to the type of flow dominated in the storm tank. Using the Reynolds number equation for rectangular open channels and assuming a length to width ratio of 2.6 (based on typical storm tank dimensions in Yorkshire, UK), the lowest Reynolds number calculated, which is about 6800, is greater than the threshold value 500 for which turbulent flow generally occurs in open channel. Therefore, based on the research group’s experience and the *Fluent Manual* recommendation (Fluent 1998) the RNG k-ε turbulence model was chosen, by which a wider class of flow can be more accurately modeled compared with the standard k-ε turbulence model.

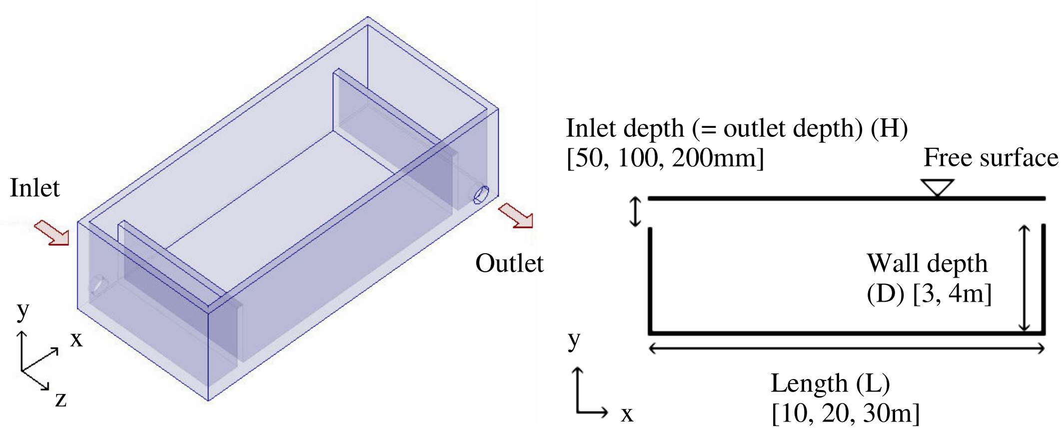

Figure 1. Layout of the tank to be modeled (Left – Isometric view of the original geometry; Right – Simplified 2D section.)

Boundary conditions were defined as follows: the *inlet* was defined as a velocity inlet, using a uniform velocity profile and 5% turbulence intensity; the *outlet* was defined as a pressure outlet; and a friction-free symmetry 'rigid lid' approximation was adopted to mimic the free water surface. A roughness height of 0.001 m was specified for the *wall* boundaries representing the base and walls of the tank.

One limitation of the k-ε turbulence model that is only valid in the turbulence governed regime; a 'standard wall function' approach was adopted to deal with the viscous dominated region near the wall. In all simulations 'Second Order Upwind' was adopted to discretize all convection terms; 'Standard' and 'SIMPLE' was selected for the pressure and the pressure-velocity coupling respectively. Detailed description of the discretization schemes can be found in the Fluent Manual (Fluent 1998).

2.2.2 *Discrete phase model*

Stovin and Saul (1998) and Adamsson *et al.* (2003) successfully predicted the results of sedimentation efficiency in hydraulic structures using a stochastic discrete phase model, also called particle tracking. With some manipulation of model output, it is possible to generate temporal concentration distributions using the same technique. In this instance the option to implement random eddy lifetimes was selected. 60,000 particles were injected in order to obtain a good representation of the statistical characteristics of the travel time distribution.

The simulated neutrally buoyant particles were assumed to have the same density as water, 998.2 kg/m^3, and a particle diameter of 1 μm (based on the recommendation of Grimm (2004)).

Additional boundary conditions are required to be specified in order to determine the fate of particle at the boundaries. Two boundary types were used, 'reflect' was set at all walls and 'escape' at the inlet and outlet. Particles were released uniformly and instantaneously over the inlet plane. The tracking process was terminated once it reached an 'escape' boundary.

3 RESULTS

3.1 *Flow field*

Figure 2 presents the flow field of a rectangular sedimentation tank with a length to depth ratio of 9, as measured by Clements (1966). It clearly shows a large recirculation just after the inlet wall and two relatively small eddies at the bottom corners.

In the computational flow field results two typical flow field patterns were observed, as shown in figure 3 and 4. Figure 3 shows the flow profile of the tank model (L20 m, D3 m, H100 mm). The main qualitative features of the flow field, i.e. the presence of a recirculation zone and a uniform flow region, are in good agreement with figure 2. However, a different hydraulic condition is evident in figure 4, which relates to the L10 m, D4 m, H200 mm configuration. The recirculation zone in figure 4 occupies nearly the entire storage tank, leaving only a small effective volume for the incoming water. The mixing of incoming water in this situation is not significant and uniform flow conditions do not prevail. The velocity of water near the surface remains high throughout the entire tank length compared with that in figure 3.

For the convenience of discussion in the later section, the six rectangular tanks are categorized into two types of tank based on the flow patterns found, here called 'typical' and 'short' tank, which 'short' tank corresponds to the tanks of 10 metres length and 'typical' tank corresponds to the others.

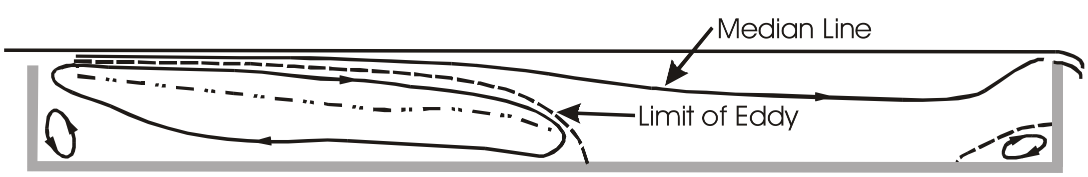

Figure 2. Flow profile of a rectangular storm tank measured by Clements (1966)

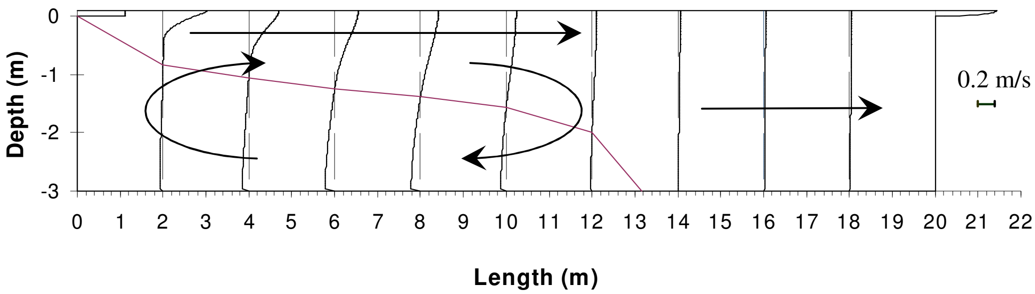

Figure 3. X-velocity profile of a ‘typical’ tank (L20, D3, H100) at 2 metre intervals (flow direction – left to right)

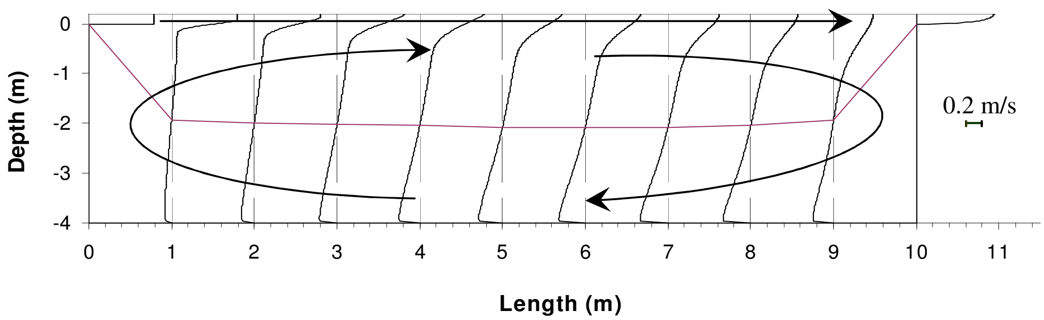

Figure 4. X-velocity profile of a ‘short’ tank (L10 D4 H200) at 1 metre intervals (flow direction – left to right)

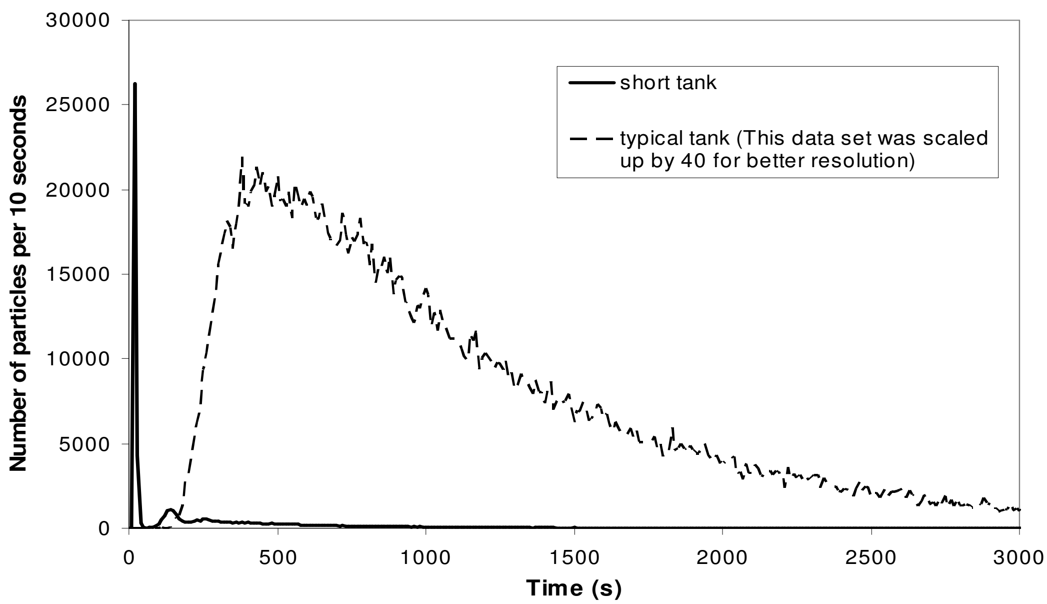

Figure 5. Comparison of the retention distribution curves of a ‘typical’ tank and a ‘short’ tank

3.2 *Retention time*

Since the discrete phase model totally relies on the flow field data, two distinct retention distribution curve types were anticipated. The model outputs are presented in figure 5. The curve that corresponds to the ‘short’ tank comprises two peaks and a long tail. The first spike illustrates serious ‘short-circuiting’ in which a substantial fraction of the particles propagate straight through the upper layer of the tank without undertaking significant vertical mixing. The successive peak and the long tail correspond to the particles which have dispersed in the recirculation zone. The distribution curve of the ‘typical’ tank showed a curve rising rapidly and decreasing exponentially. This is indicative of better mixing.

One of the advantages of using the discrete phase model is that full recovery of particles occurs. In field work erroneous estimation of travel time and other dispersion coefficients usually occurs when the information of the tail of the distribution curve is not captured or inaccurately measured (Wallis, 1994). Without losing any important information, the mean retention time was assumed equal to the mean value of all the residence times of individual particles.

4 DISCUSSION

4.1 *Storm tank performance*

Comparing the computed mean travel times to the theoretical times of the corresponding discharges, the actual time is within approximately $\pm$ 10% of the theoretical time (not shown). Although the assumption of uniform flow conditions may predict the actual time, other unseen problems, such as short-circuiting, recirculation, dead zones etc., which are believed to contribute to the poor performance of storm tanks, cannot be assessed by this simple approximation.

The performance of the tanks tested in three different flow rates was examined using a short-circuiting parameter, S, used by Persson (2000), in which the quotient was defined as the ratio of t_{16} and the nominal retention time, t_n, where t_{16} is the time for passage of the 16^{th} percentile through the outlet. A low value of S indicates short-circuiting. Figure 6 shows that the magnitude of short-circuiting parameter increases as the length to full depth ratio decreases. In addition, for the ‘typical’ tanks (L/(H+D) > 4) the short-circuiting problem was more severe at higher discharges, whereas the reverse was found for the ‘short’ tanks. One can imagine that the short-circuiting problem in the ‘short’ tanks would be especially serious if the design retention time was obtained on the basis of uniform flow assumption. For instance, according to figure 6 the first 16% of particles were retained for less than 10% of the nominal time in the tank under the range of discharge conditions. This might result in reducing the water treatment capability of a storm tank as a consequence. Although the six tanks have the same geometrical shape, i.e. rectangular, the length to full depth ratio was found to be a key determining factor for short-circuiting.

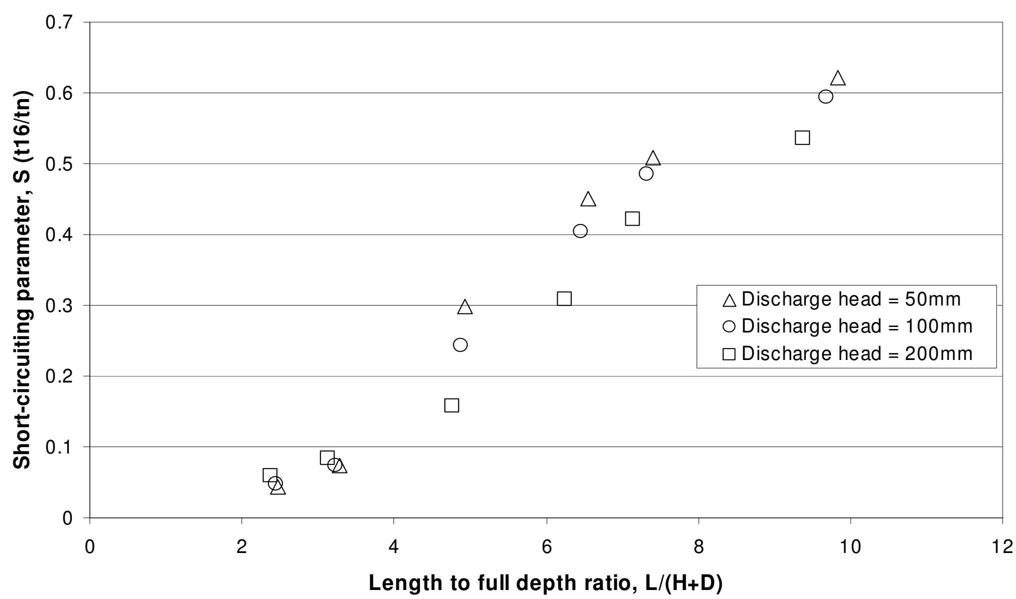

Figure 6. Variation of short circuiting parameter, S, with length to full depth ratio

4.2 *Possible numerical errors*

The solutions obtained are believed to be close to a grid-independent solution. With an increase of 25% in the grid spacing the computational results of retention time differ by less than 1 %.

It was unfortunate that without field data available a firm conclusion of the accuracy of the prediction in terms of flow field and travel time cannot be drawn. Another relevant validation data that may be used is the work of Kluck (1997), who compared the flow field in a scale model to that in 2-D width averaged CFD model. Similar flow features (not shown) to those illustrated in figure 3, such as the recirculation beyond the inlet weir and the uniform flow region after the recirculation zone, were qualitatively reproduced. However, he commented that the length of the recirculation in the streamwise direction should be around 7-9 times of the inlet wall (D). According to this rule all simulations produced appear to have under-predicted the recirculation length and hence the area of the recirculation zone. The effects of the under-prediction on the overall mean travel time require further investigation and field data to be verified.

5 CONCLUSION

- Six rectangular storm tanks were tested with three different discharges. In total 18 simulations were conducted.
- Among the six tanks two characteristic flow patterns were observed. Severe short-circuiting existed in the 'short' tanks, whereas the 'typical' tanks exhibited the more common mixing effects.
- The simulation results showed that the mean retention time may be predicted using uniform flow estimation, with a deviation of less than 10%. However, other features, like short-circuiting, flow through curve etc., are not possible to be seen using this simple approximation.
- It was found that short-circuiting parameter, S, is directly proportional to the length to full depth ratio. In addition, the short-circuiting problem was more severe in the 'typical' tanks under high discharge conditions, whereas the reverse was found for the 'short' tanks.
- The RNG k-ε turbulence model can predict flow field qualitatively in agreement with Clements (1966) and Kluck (1997), however the volume of the recirculation zone might be under-predicted.

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