Experimental and Numerical Modeling of VersaTrap Type G

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ABSTRACT

This paper presents the processes and results of experiments carried out on the solids separation performance of a vortex combination. The vortex is generated in a cylindrical chamber above the level of a cylindrical screen. Rocla VersaTrap type G (VTG) which is designed to treat stormwater pollutants from commercial and residential developments was used in this research. Experimental and numerical analysis were conducted on the scale model to establish the hydraulic characteristics and pollutant removal efficiencies (PRE). To replicate typical in situ conditions, the VTG with 0%, 25%, 50%, 75% and 100% blocked screen conditions, were experimentally tested at Curtin University of Technology. Comparing Computational Fluid Dynamic simulation and experimental results suggest that CFD software is an effective tool for assessing the outcomes of the hydraulic treatment system. Data analysis has proved that the head loss increases in proportion to screen blockage condition. The separation efficiencies are inversely proportional to flow rates. The study findings have capabilities to optimize any other types of stormwater treatment systems.

Keywords: Hydraulic characteristics, PRE, CFD, Australia.

1. INTRODUCTION

With the increase of urbanization, stormwater discharge makes a significant contribution to pollution problems in most urban areas. This is because pollutants such as grit, oil, pesticides, metals, and fertilizers tend to settle on impervious/impermeable surfaces such as streets and parking areas. A heavy rainstorm often carries a high sediment load with other associated pollutants (untreated pollutants) into drainage systems. As a result, these inlets have a very detrimental impact on receiving watercourses. Recent environmental studies have shown that stormwater runoff plays a significant role in the problems of 13% of polluted rivers, 21% of polluted lakes and 45% of polluted estuaries (Andoh, 2006).

Sediments which is considered as one of the main sources of pollution in the US stormwater runoff (US EPA, 1998), phases I and II of the stormwater program, promulgated by Environmental Protection Agency's (EPA) 1990 and 2000 under the Clean Water Act, are leading to improve the quality of the nation's streams, rivers, lakes, and estuaries by managing stormwater runoff from urban and suburban areas, construction projects, and industrial sites. In developing a product to address the challenges of facilities covered by Phase II requirements, the goal of the research was to build a separator that would remove 90% of sediment and avoid the washout of stored pollutants while also capturing oil and floatables. The idea was to let the fluid motion through the device do all of the work so it operates without any moving parts and without filtration systems that might potentially clog and require maintenance.

In most applications, no power is required for operation of the unit as the influent and underflows are conveyed by gravity through the separator depending on the available hydraulic head. The most popular separators are typically installed immediately at the stormwater downstream intake points (US EPA, 1999). Faram et al (2003) have categorised the sediment's separators into three generic groups namely; Gravity Sedimentation Devises (GSD), Simple Vortex Separators (SVS) and Advance Vortex Separators (AVS). VersaTraps are almost similar to (AVS) unit which utilize especially designed internal components to control and enhance performance and provide isolated storage zones for trapped pollutants.

Historically, simple catchbasins which have been used as entry point to the stormwater drainage systems were designed to remove debris from stormwater and prevent clogging in the receiving water pipe. The study of Lager et al (1977) and Butler & Karunaratne (1995) both identified the limitations of the catchbasins effectiveness. During the heavy runoff, such systems can be prone to the phenomenon of washout whereby collected pollutant is remobilized and discharged (Faram & Harwood, 2002). The paper presents both experimental testing and Computational Fluid Dynamics (CFD) simulation results for VersaTrap type G. The study was focused not only on the pollutant removal efficiency but the headloss of the model at many different configurations.

2. VERSATRAP TYPE G

The VersaTrap type G is a below ground removal method. The vortex phenomenon may be used in gross pollutant traps (GPTs), to remove pollutants over a wide range of flow rates. VTG has been designed to remove suspended solids, floatables and sediments from the stormwater and to prevent re-entrainment. The unit has no moving parts and is designed to have two cylindrical chambers (e.g. internal and external) and a bypass for over capacity stormwater (e.g. bypass flow). The internal chamber is called the separation or treatment chamber, which has screen at the bottom. VersaTrap type G removes pollutants by directing the flow tangentially into a cylindrical chamber (Internal chamber), creating a vortex. Suspended solids and sediments are captured at the bottom of the basket whilst floatables contaminants are collected at the water surface in the treatment chamber. Emptying by vacuum eduction or removable basket removes accumulated sediments, suspended solids and floatable pollutants.

3. EXPERIMENTAL TECHNIQUE

3.1 Experimental Setup

A graphical representation of the model is presented in Figure 1. It is basically consist of two cylindrical chambers with diameters of 300 and 500 mm, screen size of 2500 μm and in/outlet pipes with same diameters of 150 mm. Both pipes were also designed with same elevation (e.g. 500 mm above the base of the sediment storage region). The model has maximum height of 1020 mm for external chamber. The weirs of the bypass had height of 0.8D (inlet pipe diameter). The VTG model was fitted in the treatment system downstream of a reservoir tank. A centrifugal pump was used to pump water from the tank to the model through a pipe as shown in Figure 2. The flow rate of the stormwater to the separator was adjusted using a valve immediately upstream to the pump. Pollutants are introduced through a tee junction upstream of the inlet. There were also manometers connected to the up and downstream of the unit to measure the pressure head and the velocity head.

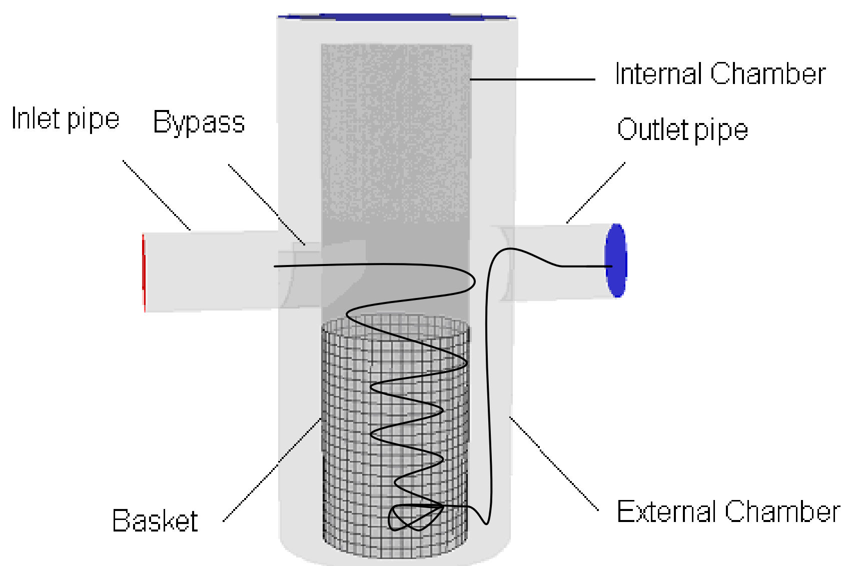

Figure 1. VersaTrap type G schematic

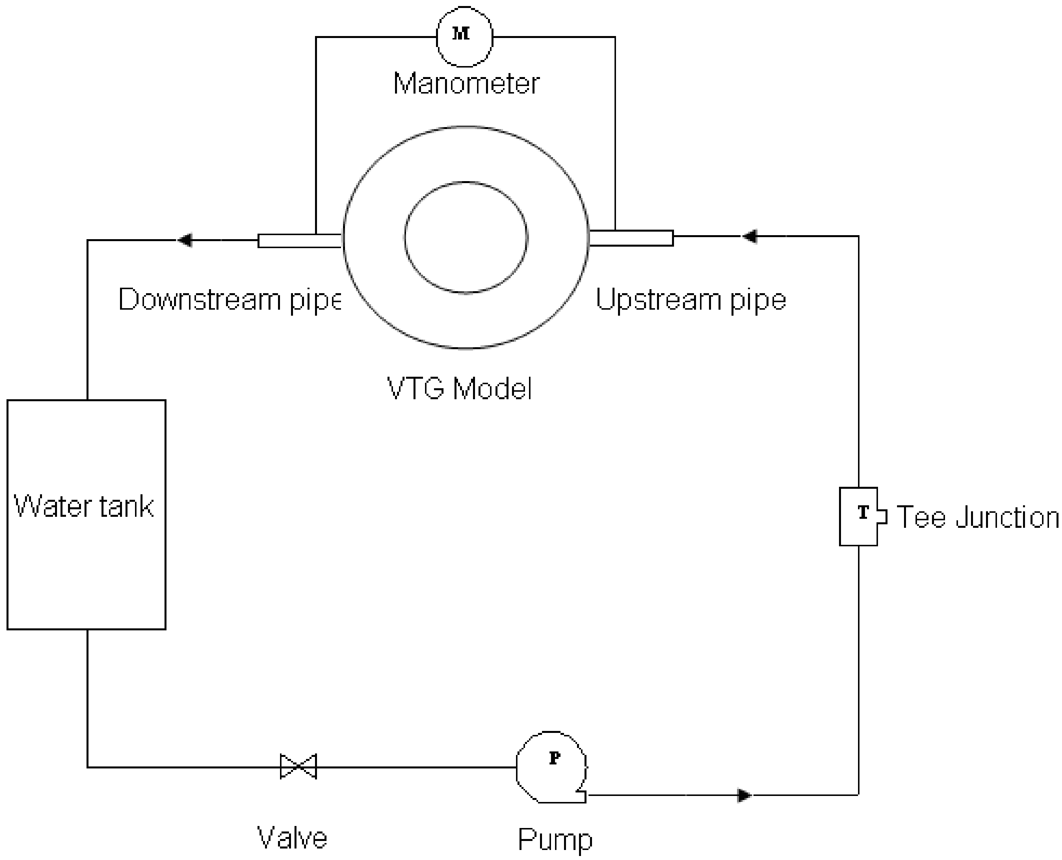

Figure 2. Schematic diagram of the experimental setup

3.2 Experimental Procedure

3.2.1 Hydraulics

VersaTrap type G has a built-in bypass facility; therefore the hydraulic testing procedures of the model were more extensive. The hydraulic tests involved the determination of treatment flows and the corresponding head losses with single basket at 0%, 25%, 50%, 75% and 100% blocked screen conditions. This was carried to represent the actual screen condition in the field. The energy equation (1) is used to calculate the headloss of the model in each screen condition. In the 100% blocked screen condition, water will not enter the basket in the treatment chamber but it goes straight to external chamber through the bypass then to downstream pipe. The method of hydraulic testing of VT type G for each screen conditions was to establish both a Design Treatment Flow (DTF) and Design Peak Flow (DPF). DTF is the maximum treatment flow with zero bypass flow. DPF is the maximum pipeline flow that is designed to carry (i.e. 20 L/s in the case of the VTG model). Scale model of the VTG was subjected to a range of hydraulic and capture performance testing, the results of which were scaled up to full size to give data on the range of full size units.

$$\frac{V_1^2}{2g} + \frac{p_1}{\rho g} + z_1 = \frac{V_2^2}{2g} + \frac{p_2}{\rho g} + z_2 + HL \qquad (1)$$

Where
V_1 is the velocity head at the inlet pipe, V_2 is the velocity head at the outlet pipe, P_1 is the pressure head at the inlet pipe, P_2 is the pressure head at the outlet pipe, Z_1 is the elevation level at the inlet pipe, Z_2 is the elevation level at the outlet pipe and HL is the headloss (energy loss)

3.2.2 Pollutant Removal Efficiency

To determine the PRE of VT type G, three different groups of pollutants have been prepared namely, organic and inorganic pollutants, sediments and oil. Every group of pollutants, which was scaled to represent the actual field pollutants, was divided into two samples with the same weight and quantities. As a result, six tests of PRE were done for the model with basket at 50% blocked screen condition. Firstly, both prepared organic and inorganic pollutants such as leaves, twigs, cigarettes, film caps, etc with different shapes and sizes were counted into two big piles of samples. To replicate actual situations that happen in the field, all of the pollutants used were chosen to be smaller than the actual ones that expected to be carried in the stormwater or cut down to smaller sizes. Secondly, two sediment samples were prepared with 2000 grams each, which were fractionated into four grain-size classes and analysed, starting from the coarser materials (>2.36 mm) into the finer fractions (<0.425 mm). Finally, capturing oil was the last tests to determine the PRE of VT type G model. Canola Oil that has density of 917 kg/m^3 was also used for both tests. An absorbent pillow, which was used to absorb the oil by capillary action, was located in the internal chamber of the VTG for both tests. The pollutants were introduced from an opening built along (tee junction) in the inlet pipe. To represent the actual fieldwork, there were two testing procedure for each group that were carried in two separate conditions. The first test involved the introduction of half of the pollutants at 50% DTF and the other half at DTF then the flow rate was decreased gradually to zero. The second test involved the introduction of half of the pollutants at 50% DTF; introduce the other half of pollutants at DTF, and increase the flow rate to DPF for around 3 minutes then the flow rate was decreased gradually to zero. The PRE was obtained by comparing the number of pollutants recovered after the test to the number that was introduced before the test or by applying the following equation (2).

$$\text{Pollutants Removal Efficiency (\%)} = \frac{\text{Load in - Load out}}{\text{Load in}} \qquad (2)$$

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Hydraulic Test Results

Because VTG unit was designed to trap stormwater pollutants in commercial and residential areas, it was designed to have a bypass facility. This bypass allows the overflow discharge to go directly to the downstream through the external chamber without entering the treatment chamber during major events. Thus more comprehensive tests were carried in trying to establish the true hydraulic characteristics of the model. At the five-selected screen conditions, which illustrate the actual conditions that are happening in the field as pollutants build up, all hydraulic characteristics, were done. Design Treatment Flow (DTF) depends on the screen condition; it decreases as the percentage of blocked screen condition increases. DTF slowly decreases down from 5.7 L/s for 0% blocked condition to 4 L/s for 75% blocked condition until reaches zero at 100% blocked screen condition. This obviously leads headloss to have different values in each configuration as revealed in Figure 3.

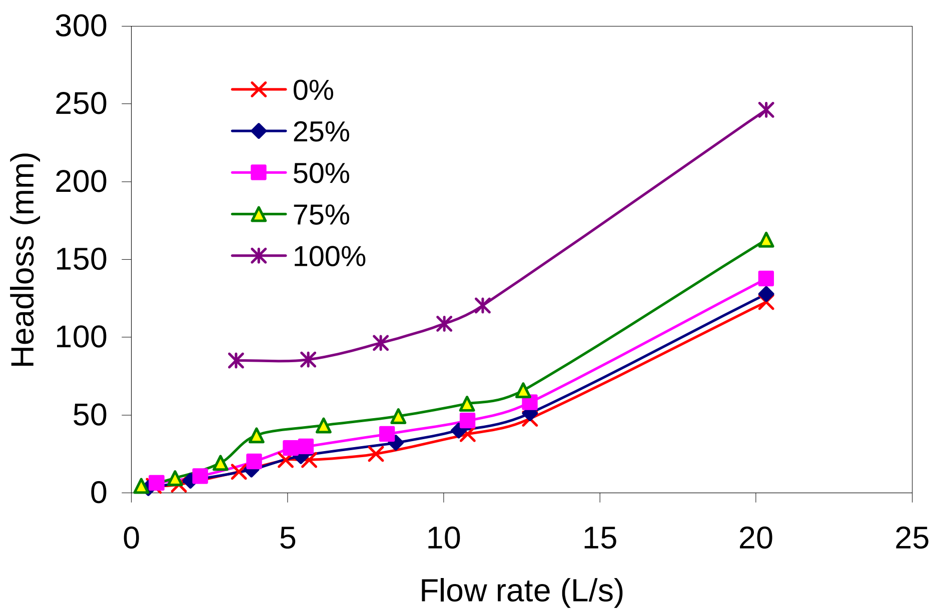

Figure 3. The system of headloss characteristic curves at all blocked screen conditions

It was found that the headloss curve had a similar pattern for the first four conditions. This is because the flow path geometries are same. The headloss increased as the flow rates and the percentage of blocked screen conditions increased. At 0% blocked screen condition, the HL was raised up from around 21mm at DTF (5.7 L/s) to 122.7 mm at DPF (20 L/s). Similarly, at 50% condition, it increased from 28.7 mm at DTF (5 L/s) up to around 138 mm at the DPF.

In the 100% blocked condition, the pattern of headloss curve was totally different. This was because there was no water entering treatment chamber; therefore the discharge went directly to downstream through the bypass. This created a very high headloss even in low flow rate as shown in Figure 3. The headloss rapidly increased from approximately 86 mm at flow rate 3.349 L/s up to 246 mm at DPF. As a result, the bypass weirs were causing a very high headloss even at the lowest flow rate.

Since the flow conditions in VersaTrap type G unit are often of open channel flow (non-pressurized flow), the fluid conditions will be under gravity action. Therefore, Froude number is very important to determine the velocity, discharge etc at all scale model factors. Table 1, 2 and 3 illustrate all hydraulic characteristics of 0%, 50% and 100% blocked screen conditions and its scaled up to different sizes of a real-life prototype.

Table 1. Hydraulic test results for 0% blocked screen condition at 20 L/s

	Model	VT 10/06	VT 12/07	VT 15/09	VT 18/10	VT 21/12	VT 22/13
Scale Factor (SF)	1	2	2.5	3	3.5	4	4.5
DTF (L/s)	5.68	32.17	56.20	88.66	130.35	182.01	244.33
DPF (L/s)	20.32	114.99	200.88	316.88	465.87	650.49	873.22
HL (mm) @ DPF	122.73	245.47	306.84	368.20	429.57	490.94	552.31
K_e	1.82	1.82	1.82	1.82	1.82	1.82	1.82
Pipe Diameter (mm)	150	300	375	450	525	600	675
Velocity in pipe (m/s)	1.15	1.62	1.81	1.99	2.15	2.30	2.44

Table 2. Hydraulic test results for 50% blocked screen condition at 20 L/s

	Model	VT 10/06	VT 12/07	VT 15/09	VT 18/10	VT 21/12	VT 22/13
Scale Factor (SF)	1	2	2.5	3	3.5	4	4.5
DTF (L/s)	5.11	28.90	50.49	79.65	117.10	163.52	219.50
DPF (L/s)	20.32	114.99	200.88	316.88	465.87	650.49	873.22
HL (mm) @ DPF	137.74	275.48	344.35	413.22	482.09	550.96	619.83
K_e	2.04	2.04	2.04	2.04	2.04	2.04	2.04
Pipe Diameter (mm)	150	300	375	450	525	600	675
Velocity in pipe (m/s)	1.15	1.62	1.81	1.99	2.15	2.30	2.44

Table 3. Hydraulic test results for 100% blocked screen condition at 20 L/s

	Model	VT 10/06	VT 12/07	VT 15/09	VT 18/10	VT 21/12	VT 22/13
Scale Factor (SF)	1	2	2.5	3	3.5	4	4.5
DTF (L/s)	0	0	0	0	0	0	0
DPF (L/s)	20.32	114.99	200.88	316.88	465.87	650.49	873.22
HL (mm) @ DPF	246.07	492.14	615.17	738.21	861.24	984.28	1107.31
K_e	3.64	3.64	3.64	3.64	3.64	3.64	3.64
Pipe Diameter (mm)	150	300	375	450	525	600	675
Velocity in pipe (m/s)	1.15	1.62	1.81	1.99	2.15	2.30	2.44

From the laboratory experiment, it can be found that VTG has DTF rates ranging approximately from 30 L/s for prototype VT 10/06 (SF=2) up to 174 L/s for VT 22/13 (SF=4.5). Also, the DPF of the smallest and biggest prototype have capacity rates to handle 115 L/s and 873 L/s respectively. Thus, the headloss of the same prototype sizes were 245 mm and 552 mm. These results indicate a satisfactory outcome for the hydraulic performance of the unit because the studies that were conducted by CDS Technologies the typical maximum headloss for the unit was around 400 mm at 550 L/s (Allison et al, 1998). It can also be found that the headloss for VT 22/13 at 50% was not much high compared to 0% blocked condition (e.g. 619.83 mm at the DPF). In the 100% blocked screen condition, the hydraulic performance of the VTG was done as the last test. It should be noted that there was no treatment flow; therefore the DTF equals zero (see Table 3). At the DPF, the headloss was found around 490 mm for the double scale factor prototype (VT 10/06) and approximately 1110 mm for VT 22/13.

Gross pollutant trap manufacturers usually use headloss coefficient (K_e) to show the hydraulic performance of their products. Therefore, it was decided to calculate the K_e in every blocked screen conditions. The small headloss makes the unit system suitable in a range of urban locations including low-lying areas. The K_e value at 0% blocked screen condition is 1.83, which is the same value in every prototype sizes (see Figure 4). This is a reasonable value when being compared with other GPTs used around Australia. For continued deflected separation (CDS) unit, the headloss coefficient value was around 1.3 (Wong, 1997). The headloss coefficient values of the first four screen conditions were ranging fairly reasonable from 1.89 for 0% up to 2.41 for 75% blocked condition. However, at the 100% condition, the headloss coefficient went significantly up to 3.64. This is nearly two times the 0% blocked screen condition. Therefore, until 75% blocked condition, the headloss coefficient value was very acceptable after that it dramatically increased to the top value.

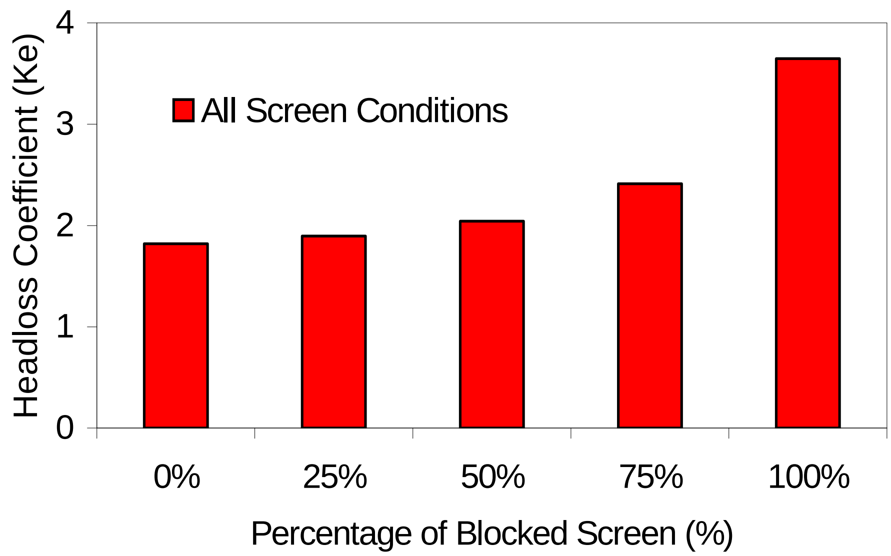

Figure 4. The relationship between headloss coefficient and blocked percentage of all screen conditions at DPF

4.2 Pollutant Removal Efficiencies

4.2.1 Suspended Solids/Floatables Removal Efficiencies

Using one screen 2500 μm and 50% blocked condition, the capture percentages of the two tests were found to be consistently high. The pollutant removal efficiency (PRE) of the model in both tests was determined approximately 94% and 92% respectively. The captured pollutants accumulated in the basket (Figure 5). Once again the main reason for determining the PRE of the VTG at the basket 50% condition was to simulate a more conservative approach to the solution because it was assumed that the GPT was tested after the first flush period where the majority of the pollutants were carried by this phenomenon.

Figure 5. Trapped pollutants in the internal chamber and the basket

4.2.2 Sediment Removal Efficiencies

By using the same method of VTG suspended solids/floatables test, the capture rate percentage was found to be very high as well. The total removal efficiency that VTG achieved in the first test was found to be 80.5%. The highest capture rate was found 96 % for 600 µm particle sizes flowing at maximum treatment flow, however; the poorest capture rate was around 56% for less than 425 µm particles. The overall mass capture rate for 2.36 mm and 425 µm is 91% and 66% respectively. The all particles were accumulated inside the basket however; some of the 2.36 mm were found in the upstream pipe.

The total removal efficiency of the second test was found 82.45%. The highest capture rate was 99.4% for the 600 µm particles; the poorest was 58.4% for less than 425 µm particles. Similarly in the first test, the majority material was accumulated in the basket and some in external chamber. From tests 1 and 2, it can be said clearly that the capture rate of the treatment chamber was found to decrease with decreasing particle size for all sands tested. As a result, it declined as the flow rates of the discharge inclined.

4.2.3 Oil Removal Efficiencies

An absorbent pillow was used to test oil trapping efficiency in the VTG model (Figure 6). By letting the absorbent pillow float in the internal chamber of the model, the assumption was that as the oil enters the chamber it would be absorbed straight away into the pillow. In both tests, the absorbent pillow was used to absorb the oil by capillary action. The efficiencies of the first and second methods were found 29.19% and 49.06% respectively. Therefore even though the VersaTrap type G was designed primarily as a gross pollutant trap (i.e., not an oil separator) the device still performed more than satisfactory under laboratory conditions as long as absorbent pillows were used.

Figure 6. The oil test by using an absorbent pillow

5. COMPUTATIONAL FLUID DYNAMICS SIMULATION STUDIES

Since last decades, Computational Fluid Dynamics (CFD) fluid flow simulation software was increasingly applied for the study of drainage systems and processes (Faram & Andoh, 1999, 2000; Faram & Harwood, 2000, 2002; Harwood, 1998, 1999, 2002; Okamoto et al., 2002). The program solves fluid flow equations including the continuity and momentum equations, which when applied within a control volume based finite difference framework, enable to predict the characteristics of the flow within complex fluid dynamic systems. Flow velocity and direction throughout the analytical domain can be predicted. It can also trace the path of particles of different sizes as they flow through the system. One major advantage of CFD is that a model can be created and evaluated within a week and at less than 20% of the cost of physical prototyping (Andoh, 2006). In addition, CFD provides far more information about the reasons behind the performance of a design concept. Many studies have been focused on the prediction of particle behaviour in the field of sewer and drainage systems which were designed to facilitate their removal, for instance, (Faram et al, 2000; Stovin et al, 2001; Faram et al 2002 and Faram et al 2003).

5.1 The Assessment Methodology of CFD

Throughout the study, the Fluent CFD software, (version 6.2.16) was used in conjunction with the associated Gambit, (version 2.3.16). The model was simulated at inlet flow rates of 20 L/s, corresponding to the design peak flow of VTG. Three dimensional model was structured using tetrahedral meshes comprising of 268000 computational cells. Using an unstructured grid helps not only to eliminate the occurrence of singularities but provides full geometrical facility (Doby et al, 2005).

Inlet flow rate was defined by uniform velocities across the inlet plane of the system. System outlets were defined with a pressure outlet corresponding to atmospheric pressure, representing a free discharge. The fluid free surfaces in each chamber were approximated by fixed friction wall boundaries, the locations of which were derived experimentally. Unsteady state flow field predictions were obtained and solutions were converged. By using data of the static pressure, velocity head of the inlet and outlet, the headloss was determined (Equation 1). Also, by comparing the volume fraction of sand at (t) to the volume that was introduced, the efficiency is obtained (Equation 3).

$$\text{Efficiency (\%) at time (t)} = 100 \times \frac{\text{Volume fraction remaining in the system at (t)}}{\text{Volume fraction injected}} \quad (3)$$

Where time (t) can be taken as the time from entry of particles into the model to the time at which it exits.

To replicate the experimental method, two models were used in the project namely Volume of Fluid (VOF) and Eularian-Eularian model. VOF model was used to determine the hydraulic characteristics of the model and Eularian_Eularian model was used to obtain the efficiency of the model at three different flow rates. The sand that has been injected into the flow domain was granular with a density of 2500 kg/m^3. The particle sizes that have been injected were ranged from 50 to 2360 micrometer. A validation study performed yielded good comparisons between experimental data and predictions for headloss and particle removal efficiency.

5.2 Flow Field Predictions

Figures 7 and 8 show vertical mid-sectional plane velocity vector and fluid pathline predictions for the system at an inlet design peak flow of 20 L/s. The velocity vectors are scaled by their colour, with light yellow denoting higher velocities, and with deep blue denoting lowest velocities, passing through green, and finally to orange/brown denoting peak velocities. It should be noted that these do not contain components to represent flows passing perpendicular to the plane. The fluid pathlines equivalent to neutrally buoyant experimental dye tracers, originate from the inlet and sediment storage region of the system.

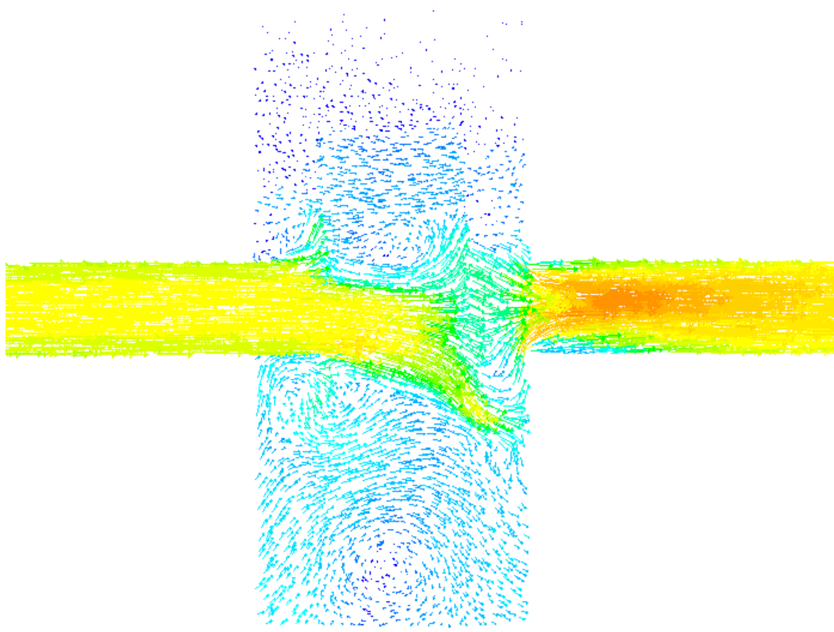

Figure 7 (a). Vertical plane velocity predictions at an inlet flow rates 20 L/s

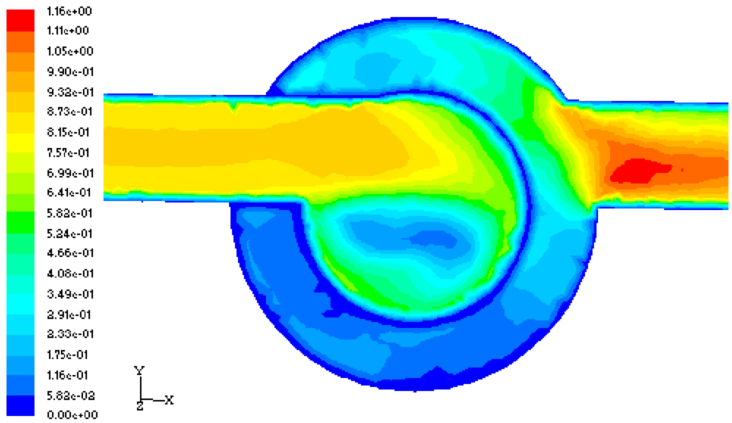

Figure 7 (b). Tangential-radial velocity predictions at an inlet flow rates 20 L/s

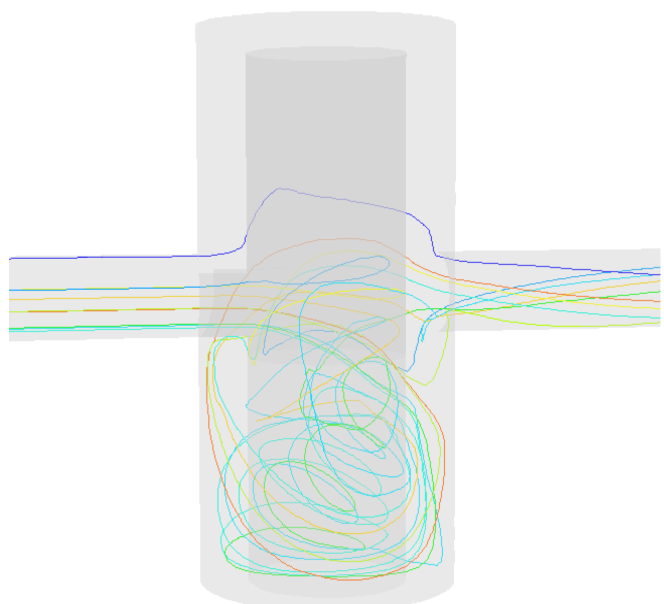

Figure 8. Fluid pathline predictions at an inlet flow rate of 20 L/s

The flow fields predicted for VTG (Figures 7 & 8) exhibit swirling behaviour as dictated by the tangential orientation of the inlet pipe. At design peak flow (20 L/s), fluid pathline predictions suggest that flows initially entering the internal chamber, external chamber either pass directly to the downstream pipe or spiral down the outer wall towards the bottom. Additionally, there will be short-circuiting for this system, due to the fact that at 20 L/s there is direct path from bypass to the outlet pipe. Such characteristics are likely to affect the performance of the unit at high flow.

6. CFD RESULTS AND DISCUSSION

6.1 CFD Hydraulic Results

Due to the large number of cells, three tests have been carried to accomplish the headloss at each of the two conditions of the screen blockage (e.g. 0% and 100%). CFD results demonstrated the same outcomes of the experimental results; as the increase of the flow rate leads to the increase in the headloss. At 0% condition, the highest headloss was found 155.42 mm at the DPF, 87.73 mm for 15 L/s and 41.248 mm for 10 L/s. When the screen was blocked 100%, it was also found that the headloss was 316.8 mm at 20 L/s, and 192.4 mm and 108.1 mm at 15 and 10 L/s respectively. CFD results suggests similar to the experimental results with error percentage of 22% for DPF. This error percentage resulted from the fluctuations in the manometer. Figure 9 shows very good comparison between the CFD predictions and the experimental data.

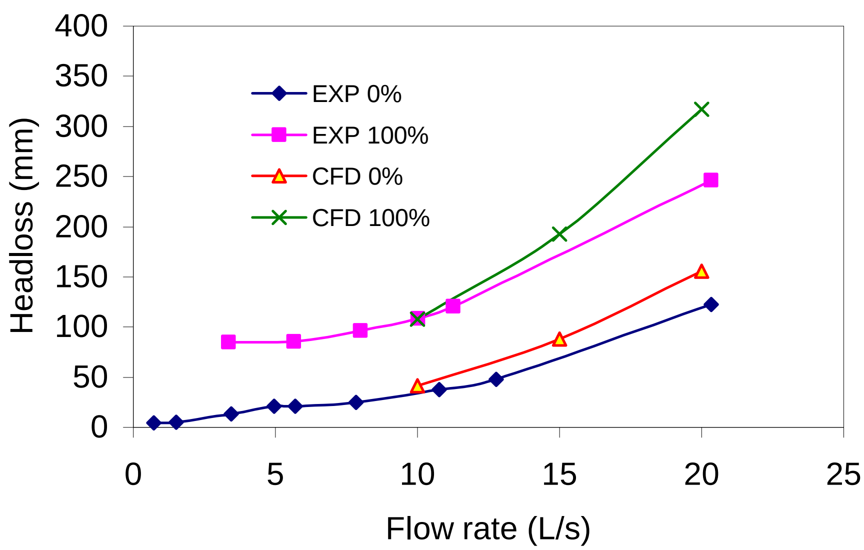

Figure 9. Experimental validation of headloss and flow rate at 0 and 100% conditions

6.2 CFD Efficiency Results

Eularian-Eularian model was used to get the efficiency of VTG. Three tests were carried for three selected flow rates; 5, 10 and 20 L/s. The total trapped efficiency was found to decrease as the flow rates increased (Figure 10). For example, comparing to sand tests, the highest trapped efficiency was found 86% at the DTF as compared to the experimental result of 80.5%. This was well above the 80% level required to achieve certification (Andoh, 2006). Similarly, the captured rate increased with the increase of particle sizes at each flow rate (e.g. it was almost 100% for 2360 micrometers at all flow rates). These close results of experimental and CFD methods, increased the confidence to use CFD as an alternate technique to that of experimental work (Figure 11).

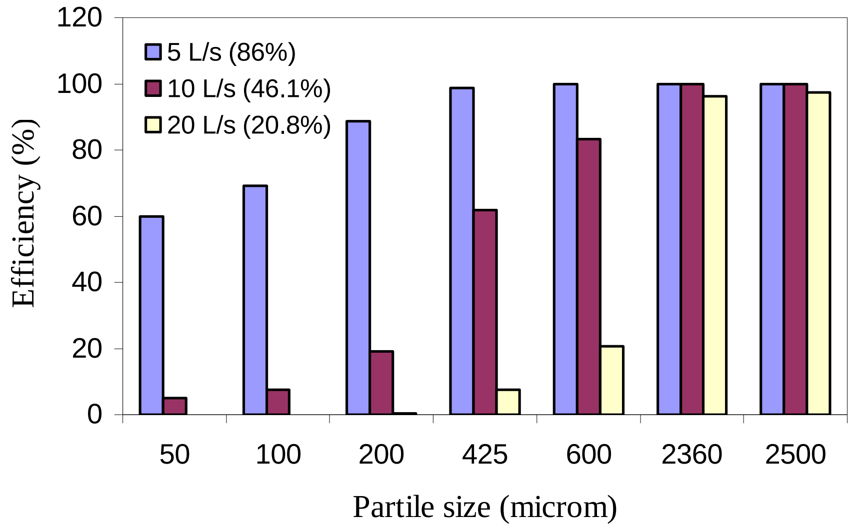

Figure 10. Particle removal efficiency predictions for different inlet flow rates

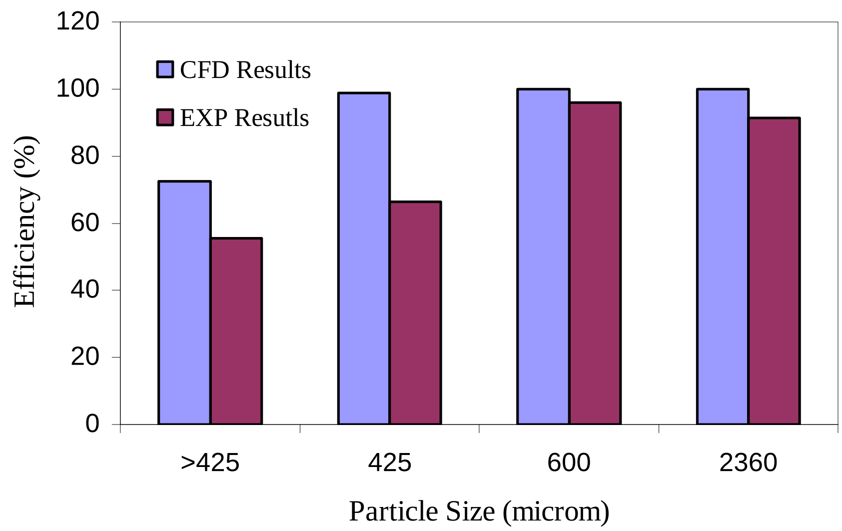

Figure 11. Experimental validation of particle removal efficiency

7. CONCLUSION

The paper was focused on the performance of Rocla VersaTrap type G by means of their hydraulic performance and pollutant removal efficiency (PRE). Experimental and numerical studies were conducted to determine the performance of the VersaTrap type G. Hydraulic tests found that the head losses increase as the flow rates increase in each configuration. PREs were inversely proportional with the increase of flow rates. Comparing pollutant removal efficiencies of VersaTrap type G and some stormwater GPTs (i.e. CDS, VORECHS and CleansAll) suggest that the captured rate percentage was found very high for VersaTrap unit.

The study has demonstrated that CFD simulation could be used to assess the relative impact of design change on a hydrodynamic separator, yielding direct savings in fabrication costs (e.g. improved operational characteristics and installation costs). Comparisons between headloss and efficiency curves produced by a well validated experimental model and those produced by the CFD simulation suggest that CFD is an effective tool for predicting the relative impact of change on the outputs of the hydraulic separation systems.

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