Experimental and Numerical Modeling of VersaTrap Type W

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ABSTRACT

This paper investigates the performance of a vortex combination intended for solids and oil separation from wastewater. It also analyses the processes involved in this separation technique. VersaTrap type W (VTW) designed by Rocla for industrial wastewater treatment has been used in this project. The vortex is generated in a cylindrical chamber above the level of a cylindrical screen. Experimental and numerical analysis were performed on the scale model to establish the hydraulic characteristics and pollutant removal efficiencies (PRE). The VT type W with 0 and 50% blocked screen (for single and double baskets) was tested at Curtin University of Technology to replicate typical in situ conditions. The results were scaled up to provide data on the full range of full size units. Comparing Computational Fluid Dynamic (CFD) simulation and experimental results suggest that CFD software is an effective tool to assess the findings of the hydraulic treatment system. Data analysis has demonstrated that the headloss increases in proportion to flow rates. The removal efficiencies are inversely proportional to flow rates. The study outcomes have capabilities to optimize any other types of wastewater treatment systems.

Keywords: computational fluid dynamics, hydraulic characteristics, pollutant removal efficiencies.

1. INTRODUCTION

Domestic and industrial uses of water affect the water quality in the surrounding environment and hence wastewater should be treated before released to rivers, lakes and other receiving water bodies. Wastewater usually contains most of the constituents of the water supplied to an area with high impurities from local waste-producing processes. Contaminants may be present as large suspended solids, small suspended and colloidal solids, dissolved organic and inorganic solids, dissolved gases, immiscible liquids and heavy metals (Menezes et al 1996). The solids come from the fine particulate dust of the surrounding areas, dust and dirt transported and blown about by vehicular traffic, and the de-icing agents namely sand/salt mixtures (Thomson et al, 1997). Street surface particulate matter has been described by Sartor and Gaboury (1984) as having particle sizes ranging from about 74 to 3000 µm and less. Sansalone et al (1998) also performed particle studies in Cincinnati, Ohio and found solids ranging in size from smaller than 1 micron to greater than 10,000 micron. In many cases, wastewater treatment may be available for re-use within certain systems in industrial operations. There are three main groups of wastewater treatment processes:

- *Physical processes:* depend on the physical properties of the waste such as the particle size and the specific gravity. These include screening, sedimentation and filtration;
- *Chemical processes*: rely on the chemical properties of the waste or reagents. These include coagulation, flocculation/precipitation and ion exchange;
- *Biological processes*: involve biochemical reactions for the removal of impurities such as aerobic or anaerobic biochemical oxidation (Menezes et al, 1996).

In this project vortex technique was studied as physical separation process for removing pollutants from wastewater. The dynamic separator is known as a swirl concentrator, a hydrocyclone, or a vortex separator (Helliweila and Harper, 1993 & Pisano et al, 1990). Rocla VersaTrap type W is using vortex phenomenon to remove pollutants over a wide range of flow rates. Vortex separators remove pollutants by directing the flow tangentially into a cylindrical tank, creating a vortex. The vortex separator has no moving parts and is designed to operate under extremely high flow conditions. In some applications, no power is required for operation of the unit as the influent and underflows may be conveyed by gravity through the vortex separator depending on the available hydraulic head, pumping of the vortex influent flow or the underflow power may be required. Although the environmental problems associated with gross pollutants in urban waterways are recognized, there has been little research in Australia into gross pollutant characteristics and movement (Allison et al, 1997). There is also limited information available on the performance of structural devices to trap gross pollutants. Essentially gross pollutant traps, which can improve the water quality, combine the mechanisms of gross solid interception and retention**.** The pollutant removal efficiency of a gross pollutant trap (GPT) is one of the critical issues to be considered when selecting a GPT for a specific installation. GPTs when installed in a drainage system introduce additional head losses, which need to be taken into account in the design process. Therefore, pollutant removal efficiency and hydraulic characteristics were experimentally and numerically investigated.

2. TREATMENT MECHANISM

The VersaTrap scale model type W (VTW) has been designed to remove suspended solids and floatables, sediments and oil from the wastewater to prevent re-entrainment. The unit has two cylindrical chambers (e.g. internal and external). The internal chamber is called the active or treatment chamber, which has two screens at the bottom. Water enters into chamber through tangential inlet and initiates the swirling motion that causes an apparent centrifugal force on the fluid and pollutants within the separator. The majority of pollutants are captured at the basket/s and clean influent exits to the outlet/downstream through the external chamber. Ideally, the higher swirl rate, the higher the rate at which pollutants can be trapped. However, high flow rates result in increased turbulence, which disperses the pollutants and reduces the removal efficiency (Menezes et al 1996). Normally the size of a separator depends upon the size of the particles that need to be separated (Singh and Eckhoff, 1995). The most important part that should be considered of the vortex separator is the hydraulic conditions at the inlet because shearing of fluid in the inlet and in the pipe lead to in reduction in pollutant size (Menezes et al, 1996). Suspended solids and sediments are captured at the bottom of both baskets whilst floatables and oil contaminants are collected at the water surface in the active or both chamber/s. Emptying by vacuum eduction or removable basket/s removes accumulated sediments, suspended solids and floatable pollutants.

3. EXPERIMENTAL SETUP

The VTW model consists of two cylindrical chambers with diameters of 300 and 500 mm, two screen sizes of 3000 and 2500 μm and in/outlet pipes with same diameters of 50 mm (Figure 1). The VTW 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 (Figure 2). The flow rate of the wastewater 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 head pressure and the head velocity.

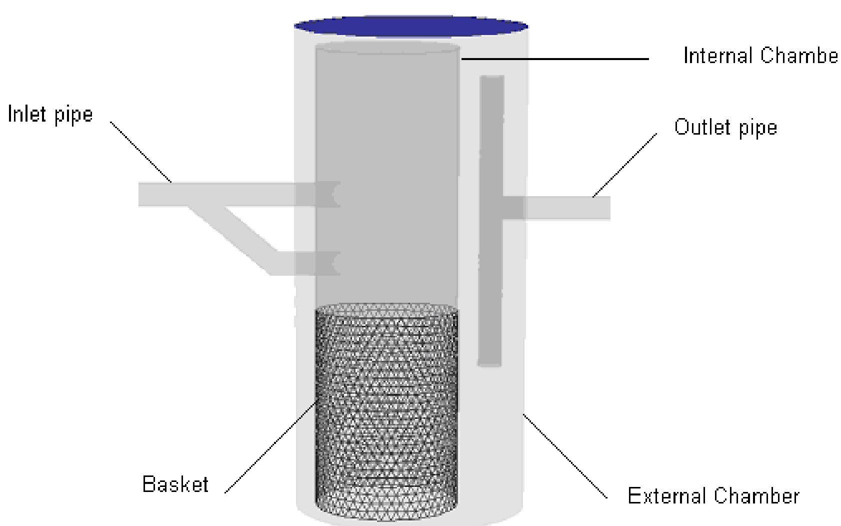

Figure 1. VersaTrap type W

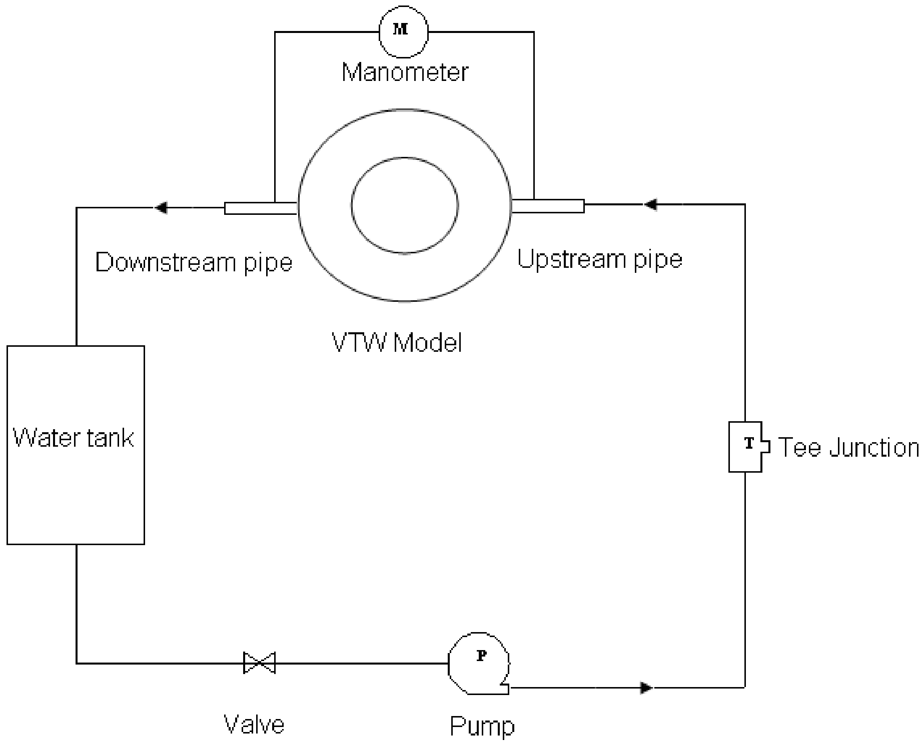

Figure 2. Schematic diagram of the experimental setup

4. TEST PROCEDURE

4.1. Hydraulic Testing

Hydraulic characteristics including velocity head and pressure head were determined for; Minimum Treatment Flow (MTF), Design Treatment Flow (DTF), Design Peak Flow (DPF) and Double Design Peak Flow (DDPF). The MTF (0.4 L s^{-1}) is defined as the flow at which the vortex establishes in treatment chamber. DTF (0.6 L s^{-1}) is 1.5 X MTF, considered to represent the mean flow rate. DPF (1.25 L s^{-1}) is 2 X DTF, and allows for peak flows of approximately double the average flow. DDPF (2.5 L s^{-1}) is considered to be the ultimate flow capacity of the device, being double the anticipated normal peak flow. This safety factor of 2 allows for potential exceptional events and/or blockages. The corresponding Headloss of the trap model was determined at the four different screen conditions namely; clean single screen, clean double screens, 50% blocked single screen and 50% blocked double screens. This interprets enough information of the trap in the actual field. The energy equation (1) is used to calculate the Headloss of the model in each screen condition (Ismail et al, 2006). Scale model of the VTW 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 at the inlet pipe, V_2 is the velocity at the outlet pipe, P_1 is the pressure at the inlet pipe, P_2 is the pressure at the outlet pipe, Z_1 is the elevation level at the inlet pipe, Z_2 is the elevation level at the outlet pipe, ρ is the water density (998 kg m^{-3}), g is the gravity (9.81 m s^{-2}) and HL is the total headloss (energy loss).

4.2. Pollutant Removal Efficiency Testing

Particle size distributions, suspended solids and oil were obtained for roadway drainage surfaces. These were used to simulate the predicted performance of the above model in the actual field conditions. Three different categories of pollutant samples were prepared and tested for VT type W. The pollutant categories such as suspended solids; sediments and oil were collected to represent the actual pollutant types that the wastewater carries. Each category was divided into three different samples with the same weight and quantities. Pollutant removal efficiency PRE for each test was determined with 50% double blocked baskets (Ismail et al, 2006).

The first three tests were carried out for the samples of suspended solids and floatables. The suspended solids and floatables that have been prepared were polystyrene balls, plastic straws, plastic paper, brushes, steel wool metal ball bearing and plastic beads. The amount of each represented sample was 105.7 grams.

The next three tests were sediment tests. Different sediment sizes were collected from all around Perth and dried up in the oven before tests. They were mixed together and separated into four samples (400 grams each) where three were used for testing purposes and one used to be tested in the laboratory for sieve analysis.

Finally, determining PRE in capturing oil was done as the last three tests of VTW model. Canola Oil, which has a density 917 kg m^{-3}, was used for the tests. This is because it has density close to the density of fuel, which is around 950 kg m^{-3} but it is bigger than typical density of gas/diesel oil of 835-850 kg m^{-3} (Christian Michelsen Research AS, 2005). The amount of oil for each sample was around 2 liters. Each sample was introduced through tee junction in the inlet pipe. The PRE tests were done at Design Treatment Flow (0.6 L s^{-1}), Design Peak Flow (1.25 L s^{-1}) and the Double Design Peak Flow (2.5 L s^{-1}). The PRE was determined by comparing the amount of pollutants being recovered from the treatment chamber to the pollutants introduced before the tests or by applying the following equation (2);

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

5. RESULTS AND DISCUSSION

5.1. Hydraulic Test Results

Hydraulic capacities and Headloss were measured at all selected flow rates with every screen condition. By using energy equation (1), the Headloss of the model was calculated. The Headloss increased as the flow rates increase. As found in hydraulic tests (Figure 3). At 0 and 50% blocked screen conditions, the Head losses were identical in each flow rates at single and double basket/s. It was found that the Head losses were 60 mm @ DTF and 93 mm @ DPF. This has been determined at the four hydraulic tests (e.g. for single/double basket). In double basket with 0 and 50% blocked screen conditions, the Headloss increased rapidly from 93 mm @ DPF (1.25 L s^{-1}) up to the highest 250 mm @ DDPF (2.5 L s^{-1}). In single basket with both screen conditions, the Headloss at DDPF was found to be 240 mm. This means, at DDPF the Headloss is only changing in double baskets. Therefore, the Headloss increased with the increasing of flow rates and number of baskets. However, it was identical in both blocked screen conditions for each configuration (single & double basket).

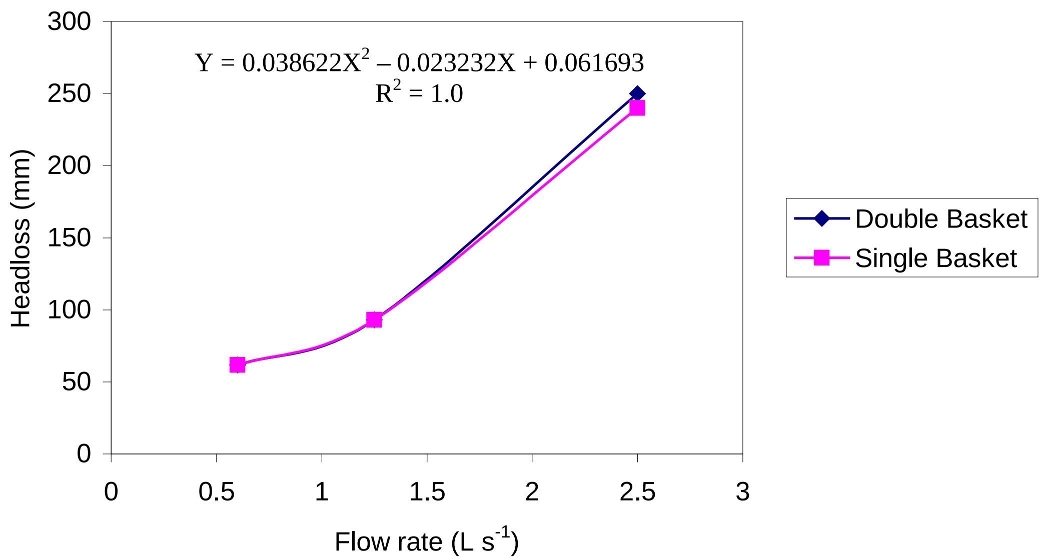

Figure 3. The relationship between Headloss and flow rates at 0 and 50% blocked screen conditions

After the Head losses of VT type W model were calculated, it has been necessary to scale them up to know the values of Headloss for all selected prototypes. From table 1, 6-scale factors were chosen as a real prototype sizes that might be used in the actual field. For example, at VT 22/13, which is 4.5-scale factor, the Headloss was 270 mm at DTF (25.77

L s^{-1}) and it was 1125 mm at DDPF (107.39 L s^{-1}). This may cause concern if this flow rate was experienced in the field, however for industrial areas it is very unlikely for flow rates above 55 L s^{-1} to occur as they have much smaller catchment areas and inflows. As a result, because the Headloss gradually increases as the scale up of the unit increased, it was advisable to choose an adequate size of a prototype before installing it. The smaller the particles, the smaller the separator that is required (Menezes et al, 1996).

Table 1 Hydraulic Test Results for VTW at Double Basket 50% Blocked Screen Condition

	Model	VT 10/06	VT 12/07	VT 15/09	VT 18/10	VT 21/12	VT 22/13
Scale Factor	1	2	2.5	3	3.5	4	4.5
Min TF (L s^{-1})	0.4	2.26	3.95	6.24	9.17	12.80	17.18
DTF (L s^{-1})	0.6	3.39	5.93	9.35	13.75	19.20	25.77
DPF (L s^{-1})	1.25	6.79	11.86	18.71	27.50	38.40	51.55
DDPF (L s^{-1})	2.5	14.14	24.70	38.97	57.29	80	107.39
HL @ DTF (mm)	60	120	150	180	210	240	270
HL @ DPF (mm)	93	186	232.5	279	325.5	372	418.5
HL @ DDPF (mm)	250	500	625	750	875	1000	1125
Pipe Diameter (mm)	50	100	125	150	175	200	225

5.2. Pollutant Removal Efficiency Results

5.2.1. Suspended Solids/Floatables Removal Efficiencies

The capture rate of VTW model in this test was found higher than other tests. It was also found that it decreased with the increasing of the flow rates of the discharge. Since the two screens used were 3000 and 2500 μm, most pollutants were not capable of passing through the perforations in the screens. The highest mass capture rate of the model 99.9% was determined at DTF. The lowest overall mass capture rate 98.39% was achieved at DDPF (2.5 L s^{-1}). The materials accumulated in the two baskets.

5.2.2. Sediment Removal Efficiencies

Sediment tests were done similarly as method of suspended solids and floatables tests. The capture rate decreased with decreasing particle size for all sands tested. Also, it was found that it decreased with the increasing flow rate of the discharge. The highest mass capture rate of the model was 93.768% for the first test particles flowing at DTF (0.6 L s^{-1}). The overall mass capture rates of the last two tests were 88.533% and 89.667% for DPF (1.25) and DDPF (2.5 L s^{-1}), respectively. The material accumulated between the screens and the treatment chamber wall and inside both screens.

5.2.3. Oil Removal Efficiencies

The oil removal efficiency of VTW model is a function of influent flow rates of the system. As the flow rates increase, the trapping removal efficiency decreases. The oil that was used for this experiment was Canola Oil with a density of 917 kg m^{-3}, similar to the density of fuel oil of around 820-950 kg m^{-3} (Walker, 1998). The capture rate of the model was 88.55% at DTF (0.6 L s^{-1}) and the other overall oil amount capture rate was 81.12% and 70.19% for DPF (1.25 L s^{-1}) and DDPF (2.5 L s^{-1}) respectively. In the first two tests, the oil was collected from the treatment chamber, however; it was collected from both chambers for the last test.

5.3. Computational Fluid Dynamics Simulation Studies

Since last decades, Computational Fluid Dynamics (CFD) fluid flow simulation software increasingly applied to study drainage systems and processes (Faram and Andoh, 1999 & 2000; Faram and 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 that designed to facilitate their removal, for instance, (Faram and Harwood, 2002 & 2003; Stovin et al 2001).

5.3.1. The Assessment Methodology of CFD

Throughout the study, the Fluent CFD software, (version 6.2.16) was used in conjunction with the associated Gambit software, (version 2.3.16). The model was simulated at inlet flow rates of 1.25 L s^{-1}, corresponding to the design peak flow of VTW. Three dimensional model was structured using tetrahedral meshes comprising of 212000 computational cells. Using an unstructured grid helps not only to eliminate the occurrence of singularities but provides full geometrical flexibility (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 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 calculated (equation 1). Also, by comparing the volume fraction of sand remained at time (t) to the volume that was introduced, the efficiency is obtained (equation 3).

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

Where time (t) can be measured from entry of particles into the model to the time after which is completed.

To replicate the experimental method, two models were used namely Volume of Fluid (VOF) and Mixture model. VOF model was used to determine the hydraulic characteristics of the model and Mixture 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 600 micrometer. The study has suggested that 2000 g of each particle size is sufficient to produce satisfactory valid efficiency predictions for a given set of particle characteristics. A validation study performed yielded good comparisons between experimental data and predictions for headloss and particle removal efficiency.

5.3.2. Flowfield Predictions

Figures 4 and 5 show vertical mid-sectional plane velocity vector and fluid pathline predictions for the system at an inlet design peak flow of 1.25 L s^{-1}. 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 with this denoting peak velocities. These velocities 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.

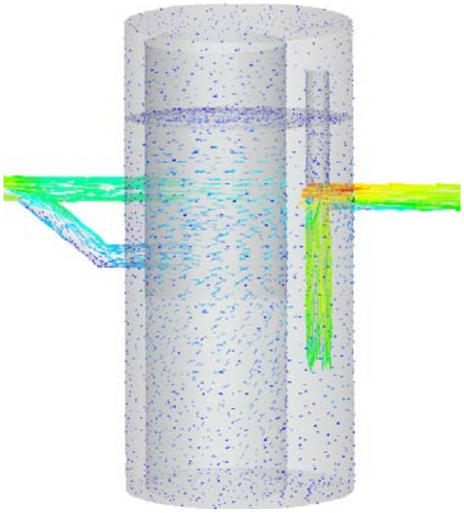

Figure 4 (a). Vertical plane velocity predictions at an inlet flow rates 1.25 L s^{-1}

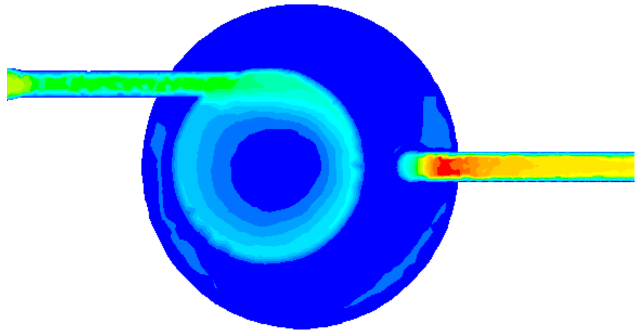

Figure 4 (b). Tangential-radial velocity predictions at an inlet flow rates 1.25 L s^{-1}

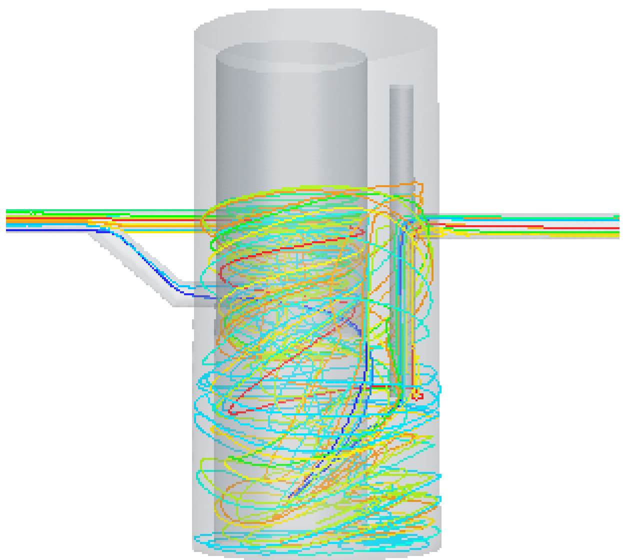

Figure 5. Fluid pathline predictions at an inlet flow rate of 1.25 L s^{-1}

The flowfields predicted for VTW (Figures 4 & 5) exhibit swirling behaviour as dictated by the tangential orientation of the inlet pipe. At design peak flow, fluid pathline predictions suggest that flow initially entering directly to the internal chamber and spiral down towards to the bottom then to the downstream pipe. Additionally, there is no evidence of flow short-circuiting for this system, due to the fact that there is no direct path from the unit inlet to the outlet. Indeed, such characteristics are likely to be conducive to positive performance attributes.

5.4. CFD Results

5.4.1. CFD Hydraulic Results

Three tests were performed to accomplish the headloss at the selected flow rates with 0% blocked screen condition. CFD resulted very similar outputs as of the experimental results; as the increase of the flow rate leads to the increase of the headloss. The headloss as found were 270.95 mm for DDPF, 131.766 mm for DPF and 64.8 mm for DTF L s^{-1}. CFD results suggests similarity to the experimental results with error percentages of 7.4% for DTF, 11.4% for DDPF, and 29.4% for DPF. These minor error percentages resulted from the fluctuations in the manometer. Figure 6 shows very good correspondence between the CFD predictions and the experimental data.

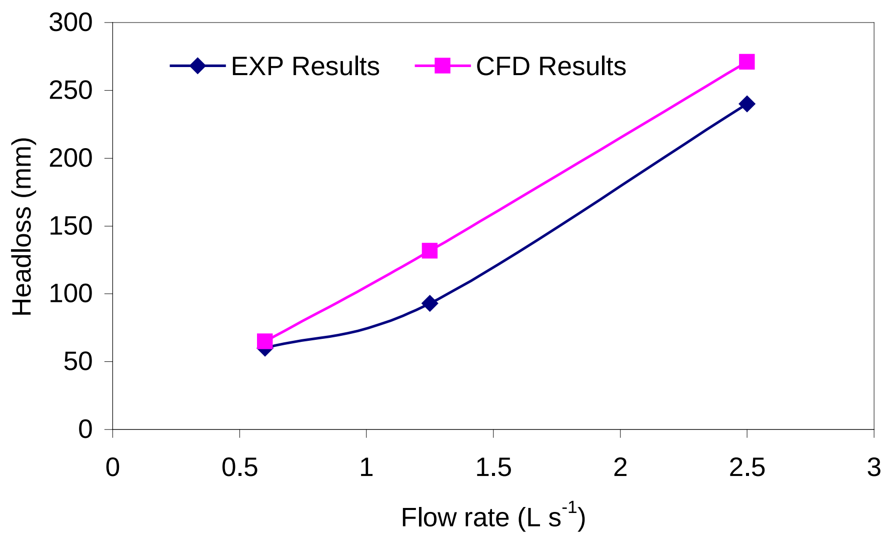

Figure 6. Experimental validation of headloss and flow rate at 0% conditions

5.4.2. CFD Efficiency Results

Mixture model was used to get the efficiency of VTW. Three tests were performed for the three different selected flow rates. The total trapped efficiency was found to decrease as the flow rate increase (see Figure 7). For example, comparing to sand tests, the highest trapped efficiency was found 99.99% at the DTF (0.6 L s^{-1}) corresponding to the experimental result of 93.768%. 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 425 and 600 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 8).

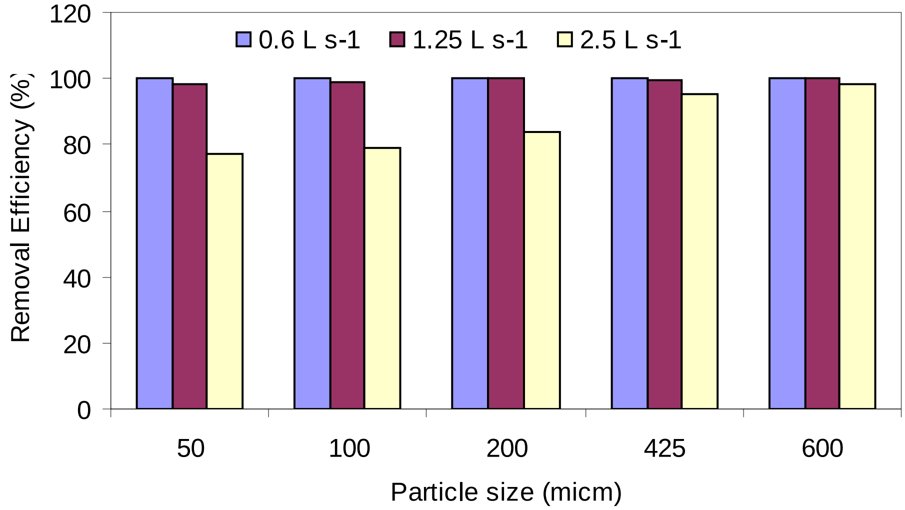

Figure 7. Particle removal efficiency predictions for different inlet flow rates

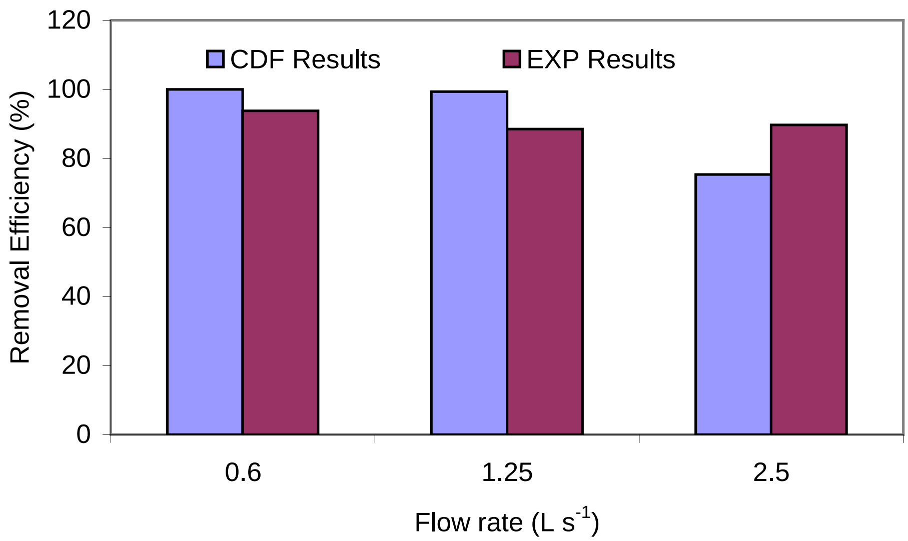

Figure 8. Experimental validation of particle removal efficiency

6. CONCLUSION

The paper was focused on the performance of Rocla's VersaTrap gross pollutant trap type W by means of their hydraulic performance and pollutant removal efficiency (PRE). Experimental and numerical study was conducted to determine the performance of VTW. Hydraulic tests found that the head losses increase as the flow rates increase in each configuration. PRE of pollutants were inversely proportional with the increase of flow rates.

The study 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. Comparisons between headloss and efficiency curves produced by experimental model and CFD simulation, suggest that CFD is an effective tool for predicting the outputs of the hydraulic treatment systems.

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