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Particle separator with vortex claw: an efficient and new technology

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ABSTRACT

Despite facing many challenges, the exploration of using natural forces and mechanisms besides gravity to enhance particle settling has never ceased. A novel particle separator design, which utilizes multiple vortexes to enhance particle settling, was proposed in this study. The basic principle is using the fluid's energy to generate small swirling currents in a specially designed vortex claw generator. These currents bring suspended particles from the rapid and turbulent inflow to relatively quiet water regions, separating them from the main flows and reducing their travel distance to the wall. To verify the new separator design's performance, comparison studies were carried out in the laboratory using physical models. The results showed that the new design had much higher particle capture rates for the same inflow rates and tested particle sizes. Most importantly, it was able to effectively remove small particles, and particle capture rates were much less affected by fluctuations in inflow rates. Since most existing particle separators failed to perform well under large inflow rates, these characteristics make the new design stand out from other separators. Due to its special structure, its treatment capacity can also be easily increased without changing its horizontal separator size.

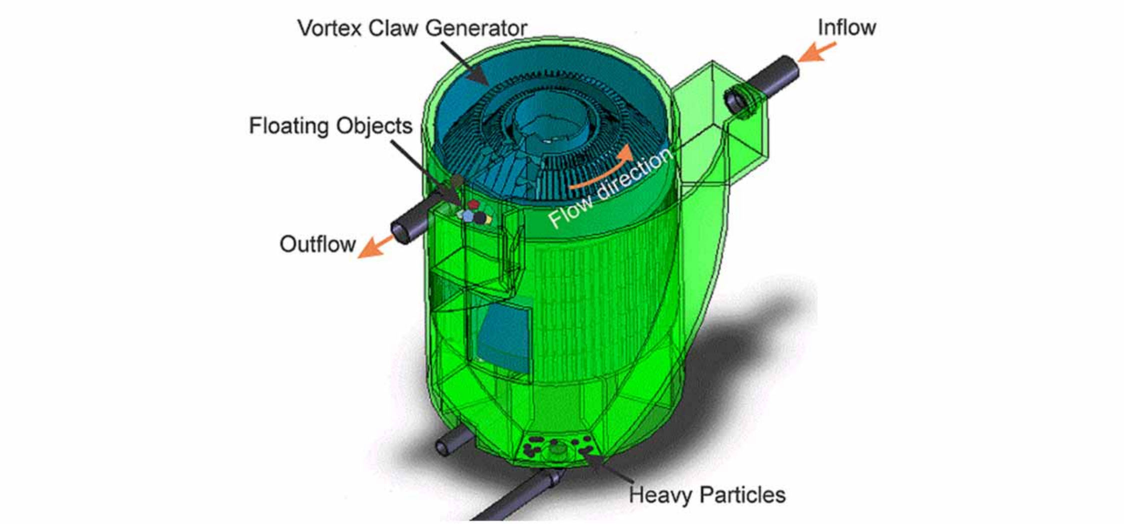
Key words: enhancing particle settling, physical modeling, vortex separator

HIGHLIGHTS

- Enhance solid–liquid separation with a novel method.
- Utilizing vortexes generated by inflows to collect suspended particles.
- In contrast to most solid–liquid separators, it can remove small particles more effectively at high flow rates.
- Particle capture rates are much less affected by fluctuations in inflow rates.
- With the same footprint, treatment capacity can be easily increased.

GRAPHICAL ABSTRACT

A novel particle separator, which utilizes flow energy generated multiple vortexes to enhance particle settling, was proposed and tested.



INTRODUCTION

During the rainy season, urban rainwater runoff and combined overflow sewage pose a significant threat to the environment due to their high volume, suspended solid content, and pollution load. Directly discharging these untreated waters into urban water bodies can cause severe pollution. To reduce this pollution load, it is crucial to rapidly remove suspended solids from these large instantaneous flows. However, effectively and economically removing pollutant particles from such large-flow rainwater has always been a challenge in the water treatment industry. Particle separators are widely used due to their low cost, large processing capacity, and small footprint, making them ideal for non-point source pollution treatment. However, one of their greatest weaknesses is that they are incapable of capturing particles in large quantities under large inflow rates.

Many designs for particle separators have been proposed and implemented to address this issue. One of the earliest designs, the Lamellas particle separator, was first suggested by Hazen in 1904 and was further explored by others such as Camp (1946); Culp *et al.* (1968), and Yao (1973). The basic concept involves inserting inclined plates into the clarifier, which are spaced closely together to increase the clarifier's surface area and enhance the settling of particles. This principle is based on the fact that the flow in the boundary layer is generally weaker than the outer region's flow. Yao's theoretical analysis of various clarifier geometries and laminar flows between plates in 1970 indicated that clarifier flow conditions need to be well-controlled, and settled particles cannot be resuspended under higher-than-expected inflows. Meeting these conditions is challenging, and most high-rate clarifiers use chemical additions to improve their performance. However, there have been few new developments in the Past few decades regarding the creation of new inclined plates.

The hydrodynamic vortex separator (HDVS) is a popular type of particle–liquid separator that mimics natural phenomena such as hurricanes, tornados, and whirlpools. It has been widely employed in stormwater management practices to reduce discharges of solids and pollutants into receiving water. HDVSs come in various formats and operate on the principle of strong vertical pulling forces induced by rotating flows. However, it is important to note that not all horizontal swirling motions can produce strong vertical velocities and forces, HDVSs may not produce high particle removal rates as expected (He *et al.* 2022).

Numerous evaluations have been conducted on various HDVSs in both field and laboratory settings, with varying results (Tyack et al. 1992; Michelbach & Wohrle 1993; Andoh & Smisson 1994; Averill *et al.* 1997; Arnett & Gurney 1998; Turner *et al.* 2000; Okamoto et al 2002; Davidson & Summerfelt 2005). However, determining the true performance of these devices is a subject of debate due to uncertainties in the test results. For instance, the assumption that inflow and outflow rates are consistent and reproducible when using simultaneous sample collection at the inlet and outlet to determine particle removal rates is often not met in practice. Moreover, there is no universal approach to representatively sampling particle concentration in the inflow and outflow, and the sampling method depends on the situation, whether vertical or horizontal, or both. In addition, reliable results require consistent inlet and outlet samples over a long enough period to ensure repeatable testing results. In laboratory tests, obtaining accurate absolute particle removal rates of a particle separator requires a full-size unit, as the gravity force on settling particles cannot be scaled, this results in particle settling speed and travel distances being unable to be scaled in the same way as dimensions and flow rates. Physical scaled models can, however, be used to reliably conduct laboratory comparison tests of different devices under the same testing conditions since the gravitational force effect on the tested devices is the same, and the comparison results obtained do not require gravity to be scaled.

When it comes to gravity settling, turbulence is often seen as a negative influence on particle settling, causing sediment re-suspension, especially in areas far from the boundaries or near sediment-bare beds. However, in the boundary layer, this may not always be the case, as evidenced by experiments. Cuthbertson *et al.* (1998) discovered that fine non-cohesive particles settling velocities near the bed in a turbulent open channel flow over a rough porous bed were 2.5 times greater than in still water. This was because vortexes generated by the rough bottom increased the transfer of particles from the high-speed outer flow to the near-bed low-speed flow. Research on particle behavior in the wall region of turbulent boundary layers with coherent structures (Marchioli & Soldati 2002) revealed that coherent sweeps and ejections provided efficient transfer mechanisms for particles generated by quasi-streamwise vortexes. Heavy particles tend to migrate towards the wall, and when in the wall layer, they segregate preferentially in regions characterized by streamwise velocity lower than the mean velocity. The relationship between turbulence structure and particle dynamics explains particle behavior in turbulent boundary layers. When a particle is entrained in a sweep, it is expected to continue within the sweep and approach the wall. The local flow structure prevents most particles that have entered the wall layer from being entrained toward the outer flow. In fact, only particles that enter the wall layer with a specific trajectory curvature may be able to be entrained back into the outer flow. Studies on particle deposition in pits in the bottom of an annular flume by Yager *et al.* (1993) showed that increasing bed roughness changed the flow structure, resulting in increased vertical velocity component of particles and creating sheltered spaces in the gravel bed for particle deposition. Under certain conditions, pits tend to fill in with finer-than-background sediments. All of these research results demonstrated that vertical vortexes near the boundary increase suspended particle flux towards the boundary.

Over the course of several decades, there has been a lack of significant advancements in the technology used to effectively remove smaller contaminated suspended particles under high flow rates without chemical additions (Ferreira & Stenstrom 2013). The primary devices utilized have been the Lamella inclined plates and various HDVSs utilizing vortex technology. Additionally, some designs have incorporated flow baffles to increase flow travel distance or resident time. Although these separators differ in design, they share a common issue: suspended particles travel along with the faster and often turbulent main flow when passing through a separator, resulting in low rates of particle removal, especially for smaller and lighter particles (Ferreira & Stenstrom 2013). Inflow rates also strongly impact the performance of these separators. In this study, an innovative design based on a cone-shaped vortex claw generator was proposed, it uses the inflow-generated small vortexes in the open slots built on the cone wall surface to convey suspended particles away from the main flow. It prompts sedimentation in three ways: (1) by separating suspended particles from the carrier by transferring the particles from fast and strong inflows to a quiet flow region, thereby making the inflow and particles travel through separate channels, (2) by reducing the distances of suspended particles traveling to the boundary, and (3) increasing the settling area by stacking the vortex claw generators vertically together. A physical model of the newly designed particle separator and a general hydrodynamic vortex-based separator of similar size were built to evaluate their performance.

VORTEX PHENOMENON

Vortexes can be present in many complex forms, however, there are two important special types (Milne-Thomson 1968): irrotational vortexes (induced) and rotational vortexes (forced). In order to maintain a rotational vortex indefinitely, one must apply some external forces, such as flow passing through the top of an open slot in directions not parallel to the long axis of the open slot. Figure 1 shows the numerically simulated flow pattern in an open slot. As can be seen, flow passing the top of the parallel-arranged open slots produced many small vortexes. The small vortexes can convey particles from the outside fast flow into the slot when they reach the opening of the slot, where the flow field is much quieter than the outside fast flow region. Consequently, particles in the slot have a much better chance of reaching and staying on the bottom of the slot without being flushed away by the fast flow outside, resulting in particle separation from their carriers. This is the basic

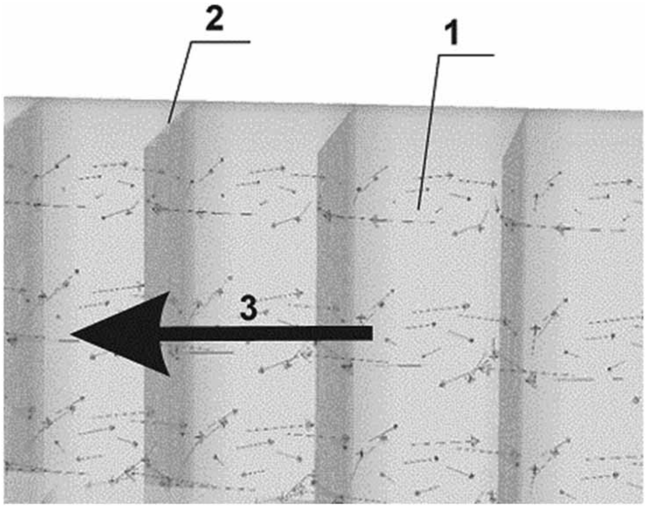


Figure 1 | Simulated flow patterns in narrow slots of the proposed vortex claw generator. Strong swirl flow is generated by the horizontal flow. In graphic: (1) vortex; (2) slot sidewall; (3) horizontal flow.

principle used by the newly proposed particle separator presented in this study; using small vortexes to grip the suspended particles from the rapid and turbulent inflow to relatively quiet water regions to enhance sedimentations. It needs to be pointed out that under a slow rotation angular speed as is the case for the generated vortexes in the slot, the vortex suction effect is very limited if there is any (He *et al.* 2022). Therefore, in this study, the vortex suction effect is not the main mechanism used to enhance particle settling.

NEW SEPARATOR DESIGN

Based on the above-mentioned idea of using vortexes to separate suspended particles from carriers in the separator by making them travel from different paths, a novel solid–liquid separator has been developed and tested. Figure 2 shows the overview unit, its main structure comprises of multiple cone-shaped vortex claw generators stacked vertically in a cylinder tank, the bottom of the tank is designed for particle capture storage. There is an inflow channel located on the outside wall of the particle separation tank that is used to remove the floats using a floating collection tank located at the end of the inflow channel.

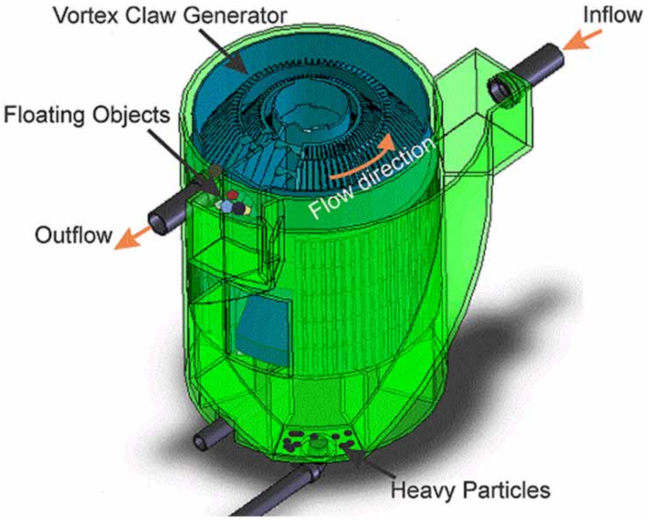


Figure 2 | The computer model of the newly designed VCPS. It comprises of multiple cone-shaped vortex claw generators and an inflow channel attaches on the outside wall of the tank for removing the floats.

The large and heavy particles will sink to the bottom of the inlet channel and slide down to a large particle collecting tank located at the bottom. Through the middle opening, suspended particles will enter the vortex claws particle separator (VCPS). It is designed so that inflow and outflow flow in the same direction for easy use in practice. As shown in Figure 3, the basic layout for a cone-shaped vortex claw generator consists of many parallel slots placed in uniform spacing, which are created by placing perpendicular ribs along the side face. In the tested unit, the top and bottom opening diameters of the cone are 16.7 and 52.4 cm, respectively. In each cone, there are 79 slots, whose depth is constant and approximately 2.5 cm, but their width gradually increases from top to bottom.

The sidewalls of the cone have a slope of about 60 degrees. Each of the slots is connected to a vertical closed particle transport channel as shown in Figure 3 that will transport particles down along the slot bed to a sediment collection chamber located at the bottom of the particle separator. The structures of the vortex claw generators at different stacking positions are very similar. These dimensions are rationalized primarily by the ease with which particles slide down, the generation of vortices in the slots, as well as the capacity of the used 3D printer. However, they have not been optimized in any way. The inlet and outlet pipes of 5.08 cm in diameter are aligned in the same direction and connected from the opposite sides of the tested unit (other configurations are also possible), making the connection of the vortex claw separator easier in an application. The inlet channel is attached to the outside of the cylindrical tank about half perimeter length. The inflows, after coming out from the inflow pipe, have to first flow through the inflow channel before entering the settling tank. The lighter floating objects will be pushed into the floater collection tank, located at the topmost downstream end of the inflow channel, by the inflow. For much heavier and large particles, they sink down to the bottom-most downstream collecting area of the inflow channel. The height of the flow entrance on the separator tank wall is about the same height as the bottom edges between the lowest to highest vortex claw generator. Thus, after flowing into the separator, the inflows will be evenly distributed among the flow paths between the vortex claw generators. The bottom sediment collection chamber is created with the bottom of the lowest vortex generator and the inverted cone of the cylinder tank bottom as shown by the cross-section cut in Figure 4. The bottom sediment collection chamber connects to all vortex claw generator slots through particle transport channels. However, it is isolated from inflow for the purpose of reducing the possibility of second-time pollution induced by new storm events. When inflows travel along flow paths in between the vortex claws generators bypassing the opening of the slot top, it generates vortexes in these parallel-arranged slots, and such vortexes will grab nearby suspended particles, entrain them, and make them move (slide) downward inside slots. When it reaches the low end of the slot, it will fall into vertical particle transport channels and are conveyed to the bottom sediment collection

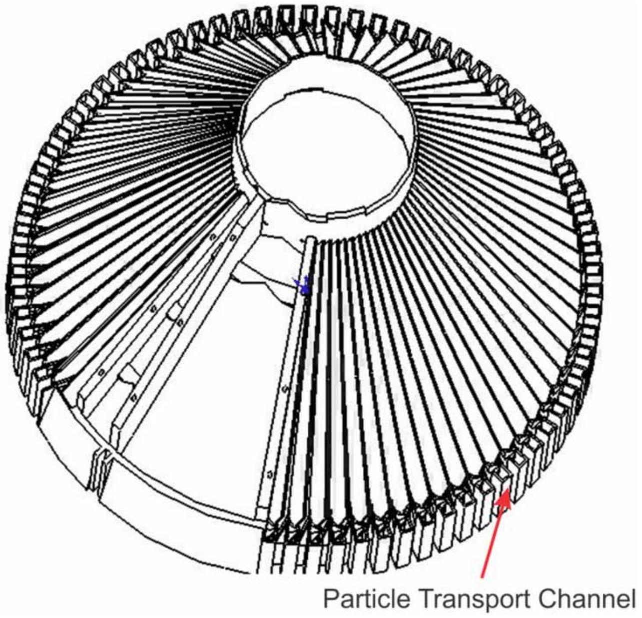


Figure 3 | A computer model of an individual vortex claw generator.

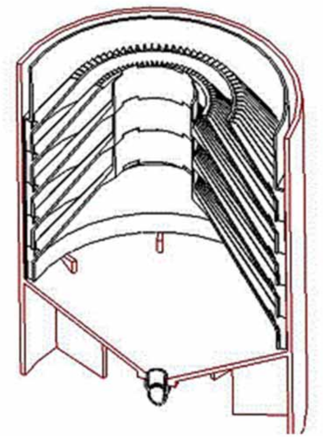


Figure 4 | In the newly designed VCPS, multiple vortex claw generators are stacked vertically. The arrows show the flow moving direction in the VCPS.

chamber. Because the vortex is generated by ambient cross flow, the faster the cross flow, the stronger the vortex. And also, because the slots shelter the particles contained inside the slot against strong inflow disturbances, the new particle separator should be potentially more effective in the removal of suspended solids under high flows as well as even lighter particles should have improved chances to settle compared to the conventional smooth lamellar plates and vortex-based particle separators. The newly designed separator prompts the particle settling in several ways: (1) utilizing inflow-generated small vortexes to grab the suspended particles from their carrier during the entire time of flow traveling through the separator. (2) Separated particles travel in the separator through their own quiet and protected paths down to an isolated sediment collection chamber. (3) Shortening particles settling distance from the boundary. (4) Greatly increased surface area. Furthermore, the advantages of this novel design configuration compared to many others are: (1) flows pass through the separator smoothly without being forced to make a sharp turn, therefore, the head loss is minimal. (2) By increasing the number of stacked vortex generators, treatment efficiency and capacity can be easily increased without increasing the device's horizontal footprint. (3) It does not require an underflow to generate a downward flow for increasing the efficiency of particle removal as well as an overpass baffler to prevent the risk of an overflowing unit. As a result, it can treat all permitted inflows for a wider range of purposes. (4) Since the particle settling process occurs inside the separator, and inflow conditions have less influence on particle removal rates, a long straight inlet channel for particle pre-settling and inflow pre-condition is unnecessary. (5) The structures of all vortex generators are similar, which reduces manufacturing costs. (6) Vortex generators are freely placed within the cylinder tank, making them easy to clean if necessary.

COMPARISON TESTS

To objectively assess the performance of a particle separator, especially for their absolute particle removal rates, is not an easy task due to its complexity and many uncertainties as mentioned in the introduction as well as it is difficult to realistically represent real treated input particles in practice regardless of the type of particle used, in addition, there is not a widely accepted standard testing method. As a result, the absolute particle removal rate of a particle separator is not very meaningful. To avoid all unnecessary and unmeasurable arguments, in this study, physical models were used to assess the performance of the newly designed vortex claw particle separator by comparing it to a general vortex-based separator, rather than determining the absolute removal rates of vortex claw separator.

EXPERIMENTS SETTINGS

Two physical models used in this study, a general vortex and newly developed particle separators, are shown in panels A and B of Figure 5. To facilitate comparisons, a physical model of a hydrodynamic vortex particle separator was constructed in accordance with the principles required by vortex-based separators (tangential inlet, center outlet, and sediment isolation chamber). In spite of being designed as a reference, the model was not a replica of an existing unit. The internal parts of

Figure 5 | Picture of physical models used to compare tests. The left side shows a commonly used hydrodynamic vortex particle separator, while the right side shows a newly developed VCPS.

both models were designed using SolidWorks$^{\circledR}$ modeling software and printed using polylactic acid (PLA) plastic on a 3D printer. Its external case was constructed from transparent polyvinyl chloride (PVC) stands for polyvinyl chloride, to be water-tight and structurally sound. The configuration of the compared general hydrodynamic vortex particle separator is shown in panel A of Figure 5. It reflects the typical operating qualities of a HDVS. The tangential direction inflow generates a large and stable vortex, even at low flow rates. The new separator design can be seen in panel B of Figure 5, which has the same outside dimensions as the general hydrodynamic vortex particle separator.

A schematic diagram of the experimental setup and the physical model's main dimensions are shown in Figure 6. In this closed-loop system, water is pumped from a large water supply tank (A) into the separator (B). A flow meter (C) and a control valve (D) are located between the pump and the water supply tank, with the flow exiting from a central discharge pipe (from the outlet pipe for the new design) after passing through the separator. Upon discharge from the particle separator, the outflow is required to pass through a 75 μm particle capture screen (E) (screen opening size is smaller than the smallest particle size in the sample) before flowing into the water supply tank.

In storm runoff, particle sizes, densities, and types vary considerably depending on location, time, and many other factors. Their size can range from 30 μm to a few millimeters. No matter what type of particles are, gravity and vortex will act on them

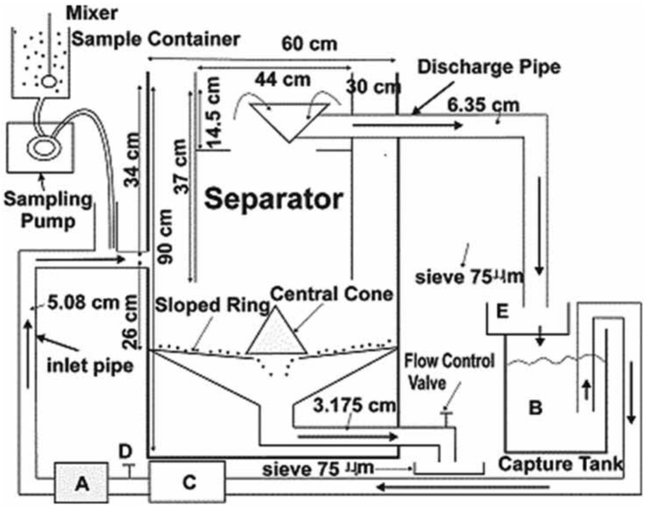


Figure 6 | Experimental arrangement for testing the removal of particles, using the commonly used hydrodynamic vortex particle separator as an example.

in the same manner. Considering that large and light particles are typically more sensitive to flow conditions than small and heavy ones, in this study, the crushed walnut shell particles with a density of 1.35 g/cm^3 and a size range of 90 to 355 mm were used to examine the characteristics of the newly designed VCPS and compare its performance with commonly used HDVSs. Multiple particle sizes (90–125 μm, 125–180 μm,180–250 μm, 250–355 μm) under various flow rates (0.5, 1, 1.5, 2, 2.6 l/s) were adopted in the comparison tests, which corresponded to sand particles of 45 to 175 μm and a density of 2.40 g/cm^3 for a comparable settling velocity (determined by Stokes' law). The particle sizes were sorted using a mechanic sieve machine. Although walnut particles can vary slightly in density and size after being wet and then dried, because this was a comparison study and the study procedure was consistent, the results should be comparable. The repeatability testing results as well as our other studies have confirmed this (He *et al.* 2015; He *et al.* 2022).

A sample of seed particles was prepared by mixing 200 g of crushed walnuts with 4 l of tap water, the generated suspended particle concentration is similar to that reported in a survey of stormwater best management practices (BMP) studies (Geosyntec Consultants 2008a). Particle samples were fed from the bottom of the container using a peristaltic sampling pump and flexible tubing with a diameter of 5 mm (inside diameter). In order to feed this material into the incoming flow path, the tubing was inserted into the bottom of the vertical feeding pipe approximately 300 mm upstream from the inlet mouth of the settling tank. The particle mixture should be well mixed by the incoming fast turbulent inflows in such an arrangement. A mixer (with a pitched blade impeller) was inserted in the sample container to disturb particles for the 4 min required to empty all particles into the inlet feed. The incoming flow continued for an additional 2 min, allowing all particles to have the opportunity passing through or settling in the separator. Captured particles were drained through a bottom drain (with a thorough separator rinse) of the separator and collected in a 75 mm screen located below the drainpipe exit. The captured particles were oven-dried overnight at 40°C (to prevent burning) and weighed to determine their total weight. The experiments were conducted under well-controlled conditions. For the experiment setting shown in Figure 6 and 1.25 l/s inflow rate, the standard deviation of the obtained particle removal rates ($n = 5$) was <0.9%. Therefore, no duplicate runs were performed in most particle removal rate tests.

RESULTS AND DISCUSSIONS

In Figure 7, particle removal rates were compared between the newly designed VCPS (represented by dashed curves) and a general hydrodynamic vortex particle separator (represented by solid curves). There were distinct differences between the curves. First and foremost, the slopes of the dashed curves were flatter than those of the solid curves, indicating that the particle removal rates of VCPS were less affected by variations in the inflow rate. As a result, even at large inflow rates, VCPS was able to perform adequately without experiencing significant degradation in particle removal rates. A second advantage of the newly designed VCPS was that it was significantly more effective at removing particles than a general

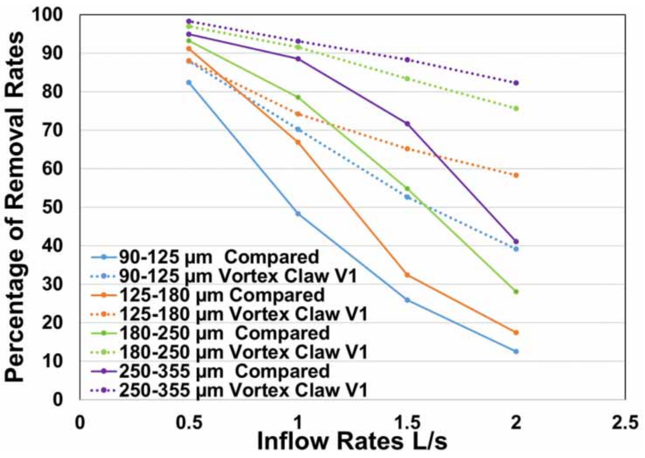


Figure 7 | A comparison of the particle removal rates for the newly designed VCPS (represented by dotted curves) and a general hydrodynamic vortex particle separator (represented by solid curves).

hydrodynamic vortex particle separator, particularly for smaller particles and at higher inflow rates, under the highest testing inflow rate, the average rate of particle removal for all sizes was greater than 30%. These observations demonstrated the effectiveness of the design principle of VCPS, which used inflow-generated small vortexes to capture suspended particles and directed them along different paths. It is important to highlight that the ability to effectively remove small particles under high flow rates is a crucial factor in measuring the performance of a particle separator. This is because smaller particles are known to carry most contamination (Herngren *et al.* 2005), as well as it is challenging to achieve effective removal due to their sizes. For instance, particles with a size of 0.01 mm have a surface area 10 times greater than particles with a size of 0.1 mm for the same mass, which means they can potentially carry 10 times more contamination. Therefore, the conventional method of assessing a particle separator's performance by measuring the removal of total suspended solids by weight does not accurately reflect its ability to remove carried contaminations. Even a slight increase in particle removal in the weight of finer particles can significantly reduce the amount of pollutants discharged into receiving waters.

In the comparison tests conducted above, the vortex claw generator with slots featuring straight vertical walls was used. This configuration was referred to as the standard vortex claw generator in this study. A vortex claw generator with slight modifications, as depicted in Figure 8, was also tested to investigate the impact of slot geometry on improving particle settling. It has tilted slots walls (see the bottom panel of Figure 8 for a cross-section view of the slots of the modified vortex claw generator). The intent of this structural design was to create shallower vortexes in the slot by allowing the downstream edge of the vortex edge to follow the slot wall pattern and move up earlier than it would in a straight wall situation. This was achieved without reducing the size of the slot opening, as shown in the bottom panel of Figure 8. So that the inward edge of the vortex does not reach all the way to the bottom of slot. Therefore, particles sliding down along the bottom of slots may be less likely to be disturbed by the above vortex. As a result of this tilted slot wall design, the slot side wall was slightly bowed in the direction of the main flow, which should result in a slight reduction of hydraulic resistance when the main flow passes through the vortex claw generator. Additionally, the longitudinal direction of the slot's walls of this particular vortex claw generator design forms a 10° tilt angle with the slot longitudinal axis as shown in the top panel of Figure 8. This arrangement generated small downward flows along the slot axis. It is intended that a vortex claw-generating slot should be positioned in such a way that one component of horizontal incoming flow has the same direction as the slot's longitudinal axis, causing particles to be pushed downward. Another potential advantage of this design is that the majority of settling particles would concentrate in the downstream corner of the slot, increasing the possibility that larger particles will be formed by collisions (coagulation). The testing results in Figure 9 were interesting and not fully expected. When observing the particle removal rates for various sizes in the four panels of Figure 9, it was evident that the tilted configuration of VCPS outperformed the normal structure VCPS for smaller particles (90–125 μm and 125–180 μm). However, for larger particles (180–250 μm and 250–355 μm), the normal structure VCPS yielded slightly better results. As the treated particle size increased, the benefits of using VCPS with tilted claw generator over the standard VCPS slowly disappeared. The explanations were not obvious. It was possible that smaller particles were more sensitive to flow conditions, and the slight structural differences between the two different claw generators only affected small and light particles.

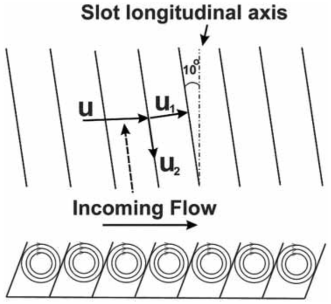


Figure 8 | In the top panel, it is illustrated that horizontal flow will create a downward velocity in parallel angled slots. The bottom panel shows that smaller vortexes are likely to form in slots with bent walls.

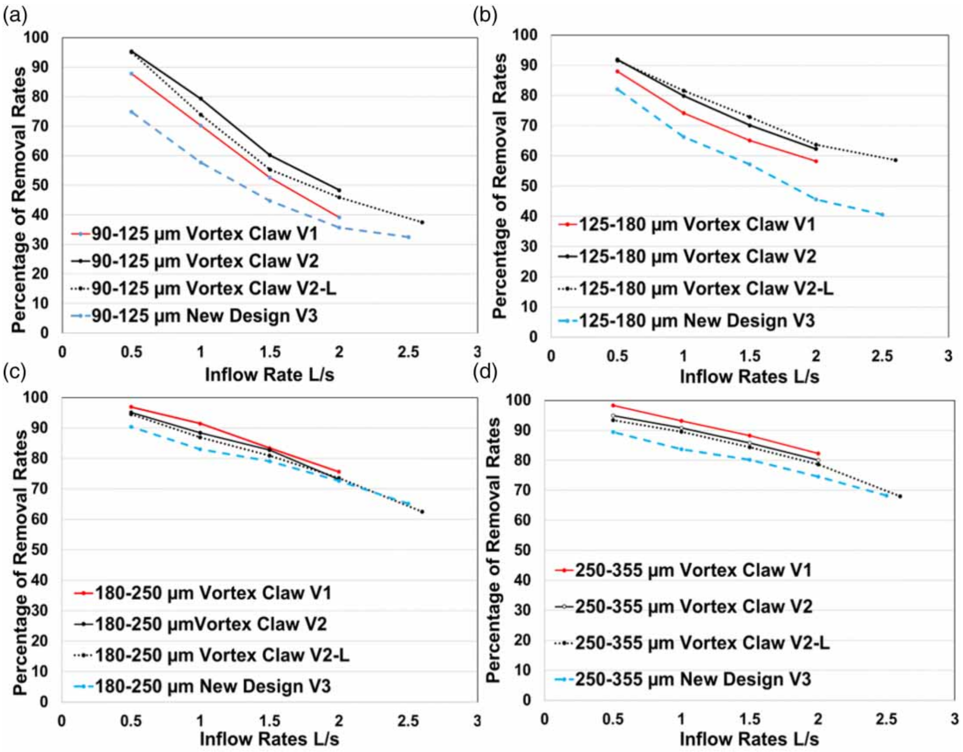


Figure 9 | The graph displays the particle removal rates of various types of separator structures. These include ones with straight slot walls of vortex claw generators (shown in black), tilted and bent slot walls of vortex claw generators (shown in red), and smooth cones (shown in blue). Each panel shows the test results for different particles.

Typically, the location and size of the outlet pipe on particle separators cannot be easily adjusted to meet design and functionality standards, which may raise concerns in some practical applications. To assess this issue for newly designed VCPS, sensitivity tests were conducted on the VCPS by altering the outlet pipe's location and size to evaluate their impact on overall performance. In all panels of Figure 9, the dotted black curves represented the rates of particle removal when the outlet pipe was shifted vertically from the top to the middle of the tank, and when the outlet pipe diameter was increased from 5.08 to 7.62 cm (commercially available 3″ pipe). By comparing the solid black curves (the outlet pipe was located at the top of the tank) to the dotted curves, it was evident that the two groups of curves followed each other closely. This indicated that lowering the outlet pipe location and increasing its size did not alter the flow dynamics within the separator, except for an increase in maximum treatable flow rates. This is a noteworthy advantage as it allows for an easy increase in treatment capacity without changing the size of the footprint, as compared to other particle separators.

In the experiments, the vortex claw generator had slot walls that protruded 25 mm above the surface of the vortex claw generator cone. To achieve optimal particle separation, multiple vortex claw generators were stacked in a vertical array within a limited tank size. Assuming the spacing between individual vortex claw generator base (without considering the slot wall height) was the same as that of smooth cones, the flow path's cross-section was reduced due to the height of the slot wall, resulting in increased flow speed and reduced residence time. One may wonder if the vortex claw generator can still outperform a stacked smooth cone array. To answer this question, a structure of stacked smooth cones (shown in Figure 10) was built and tested, and the results (presented by blue dashed curves in Figure 9) showed that, for all tested inflow rates and particle sizes, the vortex claw generator performed better than the stacked smooth cones. As a result of the vortex claws structure's ability to prompt particles to enter the protected slots, this improvement can reach as high as 20%, and it will be more apparent for small particles and large inflow rates. This directly proves the effectiveness of the principle of using the vortex claws to enhance particle settling, regardless of slight structure design differences.

Figure 10 | A stack of smooth-surfaced cones (lamella cones).

CONCLUSIONS

A novel technique for enhancing the separation of liquid and solid substances has been introduced. This innovative method involves using vortexes generated by inflow to extract solids from the primary inflow and transport them to calmer water areas. To investigate the efficiency of this approach, a scaled particle separator was built and evaluated by comparing its particle removal rates with those of a standard vortex particle removal method, as well as various vortex claw generator designs, at different inflow rates and particle sizes. The comparative tests were also performed using traditional smooth lamellas. Based on the results, it has been found that the newly proposed particle enhancing concept for the VCPS has significantly increased the particle removal rates, especially for smaller particles under high inflow rates, with the same footprint. This is a crucial development as it not only helps achieve higher particle removal, but also removes potential contaminations carried by the particles multiple times over. The new VCPS has shown impressive performance, displaying minimal vulnerability to inflow rate changes while exhibiting the ability to easily increase its treatment capacity and alter outlet vertical locations. These capabilities can be attributed to the flow properties around the vortex plate, which include: (a) steady vortexes generated within the slots, which entrain particles into the slots and allow for settling without hindrance from the main flow; (b) enhanced particle settling due to increased contact surface area and reduced travel distance (the vortex plate's surface area is twice that of a smooth lamella); (c) no baffles were present to force treaded flows to make sharp turns when passing through the VCPS, which expects to have less hydraulic resistance and head loss; and (d) increased particle collision frequency within the swirling flow of the slots, which promotes particle flocculation. In the context of this paper, deeper-level proving data is not necessary and cannot be obtained easily. Based on the findings of an exploratory study on the vortex claw concept, it is suggested that further research should be undertaken to investigate the impact of clarifier flow conditions on particle movement along the vortex claw generator. This will aid in the development of an optimal design. However, it is important to note that since the optimal dimensions of the vortex claw generator and the space between individual vortex claw generators are dependent on the rate of inflow, optimal construction designs were not conducted during this study. It would be more meaningful to conduct an optimal study after the main treated inflow rates were determined.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Andoh, R. Y. G. & Smisson, R. P. M. 1994 High Rate Sedimentation in Hydrodynamic Separators. In: *Proceedings of 2nd International Conference on Hydraulic Modelling Development and Application of Physical and Mathematical Models*, Stratford, UK, pp. 341–358.

Arnett, C. J. & Gurney, P. K. 1998 High rate solids removal and chemical and non-chemical UV disinfection alternatives for treatment of CSO's. In: *Innovation 2000, Conference on Treatment Innovation for the Next Century*, Cambridge, UK.

Averill, D., Mack-Mumford, D., Marsalek, J., Andoh, R. & Weatherbe, D. 1997 Field facility for research and demonstration of CSO treatment technologies. *Water Science & Technology* **36** (8–9), 391–396.

Camp, T. R. 1946 Sedimentation and the design of settling tanks. *Transactions of the ASCE* **111**, 895–936.

Culp, G., Hansen, S. & Richardson, G. 1968 High rate sedimentation in water treatment works. *Journal American Water Works Association* **60**, 681.

Cuthbertson, A. J. S., Ervine, D. A., Hoey, T. B. & Heinrich, O. 1998 settling characteristics of fine grained sediments in turbulent open channel flow. In: *Proceedings 3rd International Conference on Hydroscience and Engineering*, Cottbus/Berlin.

Davidson, J. & Summerfelt, S. T. 2005 Solids removal from a coldwater recirculating system comparison of a swirl separator and a radial-flow settle. *Aquacultural Engineering* **33** (1), 47–61.

Ferreira, M. & Stenstrom, M. K. 2013 The importance of particle characterization in stormwater runoff. *Water Environment Research* **85** (9), 833–842.

Geosyntec Consultants and Wright Water Engineers, Inc. 2008a Overview of Performance by BMP Category and Common Pollutant Type [1999–2008]; The International BMP Database. Available from: http://www.bmpdatabase.org/Docs/Performance%20Summary%20Cut%20 Sheet%20June%202008.pdf (accessed 4 February 2013).

Hazen, A. 1904 On sedimentation. *Transactions of the ASCE* **53**, 45–71.

He, C., Scott, E. & Rochfort, Q. 2015 Enhancing sedimentation by improving flow conditions using parallel retrofit baffles. *Journal of Environmental Management* **124** (30), 40–50.

He, C., Chittibabu, P., Nguyen, D. & Rochfort, Q. 2022 Investigating effectiveness of vortex enhancing particles settling in a hydraulic separator with physical modeling. *Journal of Environmental Engineering, ASCE* **148** (6), 04022027.

Herngren, L., Goonetilleke, A. & Ayoko, G. A. 2005 Understanding heavy metal and suspended solids relationships in urban stormwater using simulated rainfall. *Journal of Environmental Management* **76** (2), 149–158.

Marchioli, C. & Soldati, A. 2002 Mechanisms for particle transfer and segregation in a turbulent boundary layer. *Journal of Fluid Mechanics* **468**, 283–315.

Michelbach, S. & Wohrle, C. 1993 Settleable solids in a combined sewer system: measurement, quantity, characteristics. *Water Science & Technology* **27** (5), 153–164.

Milne-Thomson, L. M. 1968 *Theoretical Hydrodynamics*. MACMILLAN & CO LTD., London, pp. 351–354.

Okamoto, Y., Konugi, M. & Tsuchiya, H. 2002 Numerical simulation of the performance of a hydrodynamic separator. In: *9th ICUD Conference*, Portland, Oregon, USA.

Turner, B. G., Arnett, C. J. & & Boner, M. 2000 Performance Testing of Combined Sewer Overflow Control Technologies Demonstrates Chemical and Non-Chemical Disinfection Alternatives and Satisfies EPA CSO Policy. Disinfection 2000: Disinfection of Wastes in the New Millennium, WEF, March 2000, USA

Tyack, J. N., Hedges, P. D. & Smisson, R. P. M. 1992 The use of sewage settling velocity grading in combined sewer overflow design. In: *NOVATECH 92, International Conference on Innovative Technologies in the Domain of Urban Water Drainage*, Lyon (France), November 3–5.

Yager, P. L., Nowell, A. R. M. & Jumars, P. A. 1993 Enhanced deposition to pits: A local food source for benthos. *Journal of Marine Research* **51**, 209–236.

Yao, K. M. 1973 Design of high-rate settlers proc. *ASCE* **99** (EE5), 621–637.

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