

Investigating the Effectiveness of Vortex-Enhanced Particle Settling in a Hydraulic Separator Using Physical Modeling

Cheng He¹, Padala Chittibabu², David Nguyen³ and Quintin Rochfort⁴

Abstract: Hydraulic particle separators which incorporate “Vortex” technology often imply that they provide enhanced particle settling. In this study, a generic vortex particle separator was closely examined using physical modeling to help understand typical flow hydraulic conditions. The study was conducted using particle capture analyses under different internal structure configurations, inflow rates and inlet pipe configurations to examine how resulting changes to flow conditions influenced the settling of particles. The purpose of this paper was not to evaluate performance or obtain absolute particle removal rates of a particular particle separator design; instead, the focus was on understanding how modifications to the flow conditions in the examined separator could affect the particle settling efficiency. The comparison results showed that the inflow-generated large internal vortex does not effectively improve the particle settling; possible explanations were given based on hydraulics and physics principles. The study method and results can be extended to examine and improve other hydraulic particle separators.

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CE Database subject heading: vortex separator, physical modeling, enhancing particle settling, hydrodynamics.

28 **Introduction**

29 Hydraulic particle-liquid separators have been widely applied in stormwater best management
30 practices (Andoh and Saul, 2003; Faram et al., 2005; Lee et al., 2011; Yu et al., 2013) for reducing
31 discharges of solids and adsorbed pollutants into receiving waters, where they would affect water
32 quality and aquatic ecosystems. One type of widely used particle-liquid separator is called the
33 Hydrodynamic Vortex Separator (HDVS) (Andoh et al., 2002). The principle of these devices is
34 to mimic natural phenomena, such as hurricanes, tornados or whirlpools, because the rotating
35 flows (vortices) are often associated with strong vertical pulling forces, usually generated by a
36 sharp gradient of a physical parameter, such as temperature or fluid flow velocity. However, the
37 principle may give the wrong impression that any horizontal swirling motion can induce strong
38 vertical velocities and forces. Instead, what often happens in nature is that the strong flow vertical
39 movement induces the horizontal swirling motion, because horizontal swirl motion can supply the
40 needed flow mass with minimum hydraulic resistance. Strong horizontal flow movement is not
41 necessary to produce strong vertical flow, even though it can induce some weak secondary vertical
42 circulation, which may not necessarily augment particle sedimentation. For instance, a typical
43 solid-liquid separator or clarifier built with a closed bottom cylindrical container with a vortex
44 flow pattern inside is unlikely to generate a major vertical flow movement nor a strong central
45 suction effect to achieve the expected results for enhancing sedimentation. The flow behaviors in
46 such cylindrical containers can be compared to those generated in a stirred teacup. Any settleable
47 sediment would be conveyed by secondary circulation to the center of the cup bottom where the
48 bed shear stress is the smallest, creating the appearance of enhanced particle settling because all
49 particles agglomerate in the center.

50 Over the past 50 years, various HDVSs have been developed and commercialized worldwide.
51 HDVSs have been the subject of numerous performance evaluations in both field and laboratory
52 settings (Tyack et. al., 1992; Michelbach and Wohrle, 1993; and Andoh and Smisson, 1994;
53 Averill et. al., 1997; Arnett and Gurney, 1998; Turner, et. al., 2000; Okamoto et. al., 2002;
54 Davidson and Summerfelt, 2005). However, testing results of HDVS performance can vary greatly.
55 One of the reasons for such large variations among different studies is that there are many
56 uncertainties in the test results. For example, when using simultaneous sample collection at the
57 inlet and outlet to determine particle removal rates, it assumes that the inflow and outflow rates
58 are unvarying and reproducible, which is often not the case in practice. If negative removal rates

59 are obtained (which is that suspended particle concentrations measured in the outflow are higher
60 than those measured in the inflow), the error in the calculated results will be magnified (He et al.,
61 2014). In laboratory tests, to obtain the true performance (absolute particle removal rates) of a
62 particle separator, a full-size unit is often required because the gravity force on settling particles
63 cannot be scaled. For an accurate assessment, a large quantity of consistent inlet and outlet samples
64 are needed and the experiments have to be run for a long enough period to ensure repeatable testing
65 results. Even though many precautions are taken, uncontrolled errors can still easily occur in a
66 large-scale test, especially in handling of smaller-sized (e.g., silt and clay) particle samples. With
67 these large variations and uncertainties, it makes comparisons challenging and it is difficult to
68 accurately connect the effects of any changes to hydraulic conditions. To assess performances of
69 different particle separators of identical size and surface-loading rate, Davidson and Summerfelt
70 (2005) did a comparison study. A radial-flow settler (inflow from center of the unit) was found to
71 provide approximately twice the Total Suspended Solids removal efficiency of a swirl separator
72 (inflow from tangential pipe on the side wall of the unit), but detailed explanations of the observed
73 results were missing. This study used a physical scale model to investigate the abilities of vortex-
74 generated flows to affect enhanced particle settling. Particle capture efficiencies were determined
75 under various inflow rates and two different inlet pipe configurations. The focus was on examining
76 the vortex functionalities on enhancing light and smaller particle sedimentation, rather than assess
77 the overall performance of a particular particle separator, therefore, only relative, and not absolute
78 removal rates were important. To help understand the observed results, theoretical explanations were
79 given based on hydraulics and physics principles. Some suggestions for improving the
80 performance of the tested particle separator were also discussed.

81 **Description of the physical model**

82 The physical model (PM) used in this study was constructed using the basic requirements of a
83 theoretical vortex-based separator (baffling, inlet below outlet, center outlet, tangential flow inlet
84 etc.). The model was designed in reference to, but was not a replica of any existing units. The PM
85 internal parts were created in SolidWorks® modeling software and printed by a 3D printer with
86 PLA plastic, while the external case was built with transparent PVC to ensure water-tightness and
87 structural integrity. One of the tested configurations of the PM is shown in panel A of Fig. 1. This
88 particular hydraulic separator configuration was selected for use in this study because it reflected

89 the typical operating qualities of an HDVS. A large and stable vortex was generated by the
90 tangential direction inflow, even under low flows. In order to generate different flow patterns in
91 the separator for the comparison study, two inlet pipes of 5.1 cm in diameter were added to the
92 external wall. One pipe was oriented perpendicularly to the tank and the other was tangential
93 (tangential shown in Fig. 1). These were located opposite to the discharge pipe and at the same
94 height as the tangential inlet pipe. Since this second perpendicular inlet pipe was higher than the
95 bottom edge of the inner cylinder (baffle), the inflow impacted the wall of the inner cylinder to
96 force the inflow to flow out through both sides of the inner cylinder, therefore, no rotational flow
97 occurs in this configuration. Flow from the tangential inlet pipe was directed along the one side of
98 the inner cylinder with a large vortex in the settling chamber of the separator. During the tests,
99 only one inlet pipe was connected to the water supply at a time with the other one being blocked.

100 **Experimental Design and Procedures**

101 A schematic diagram of the experimental setup and the PM main dimensions are shown by Fig. 2.
102 It is a closed loop system; the flow is pumped (A) into the separator via a 5.1 cm inlet pipe from a
103 large water supply tank (B). Between the pump and the water supply tank, a flow meter (C) and a
104 control valve (D) were installed, with the latter as a means to regulate flow rates. After passing
105 through the separator, the flow exited from a central discharge pipe of 6.3 cm diameter. The free
106 discharge from this pipe was intercepted by a 75 μm particle capture screen (E) before flowing
107 back into the water supply tank. All of the sample particles were collected by this screen, so they
108 would not be recirculated through the system. The maximum inflow rate of the tested PM was
109 around 2.3 L/s.

110 Large and light particles are typically more sensitive to flow conditions than smaller and heavier
111 particles, so crushed walnut shell particles with density = 1.35 g/cm^3 and size range = 125 - 180
112 μm were chosen for all the experiments, which corresponded to sand particles from 62.5 μm to 90
113 μm and with a density of 2.40 g/cm^3 for an equivalent settling velocity (determined by Stokes'
114 law). Other advantages of using such particles included easy handling and recovery (preventing
115 their recirculation), and good visibility (given by their characteristic brownish color) which helped
116 with visual observations of flow conditions in the settling tank. Realizing that the density and size
117 of walnut particles can vary slightly after being wet and then dried, this was a comparison study
118 only. Providing that the study procedure was consistent for all tests, the results should be directly

119 comparable, although not absolute. This has been shown by our repeatability testing results as
120 well as our other studies (He and Marsalek 2009; He, et al., 2014; He, et al., 2014; He, et al.,
121 2015).

122 Seed particles were prepared before each experiment by mixing (using a pitched blade impeller
123 mixer) 500 g crushed walnuts with 4 L tap water in a container. A peristaltic sampling pump was
124 used to draw the particle samples from the bottom of the container through a 5 mm (inside diameter)
125 flexible tubing with a flow rate of 0.235 L/min. This was fed into the path of the incoming flow
126 by inserting the tubing into the bottom of the vertical feeding pipe about 300 mm upstream of the
127 settling tank inlet mouth. In such an arrangement, particles should be well mixed by the incoming
128 fast turbulent flows. A mixer (with a pitched blade impeller), was used to disturb particles in the
129 sample container for the 17 minutes required to empty all of the particles into the inlet feed. The
130 incoming flow continued for an additional three minutes, which ensured that all particles had a
131 chance to pass through or settle in the separator. Captured particles were drained through a bottom
132 drain (with thorough rinsing of the separator), and collected in a 75 μm screen located below the
133 exit of the drain pipe. The captured particles were oven dried overnight at a temperature of 40 $^{\circ}\text{C}$
134 (to prevent burning) and weighed to determine their total weight. Experiments were run under
135 well-controlled conditions; for the configuration shown in Fig. 1 and 1.25 L/s inflow rate, the
136 standard deviation of the obtained particle removal rates ($n = 5$) was $< 0.9 \%$. Therefore, no
137 duplicated runs were performed in most particle removal rates tests.

138 **Results and Discussion**

139 Fig. 3 shows the results for particle retention comparisons of the tested separator (PM) with various
140 internal baffles, two different inlet configurations and inflow rates of 0.75, 1.25 and 2.0 L/s. The
141 purpose of these comparison tests was to examine how internal modifications and different inlet
142 configurations could potentially affect hydraulic conditions and thus performance. It could also
143 demonstrate effects of the large vortex in the middle of the settling chamber on suspended particles.
144 The blue solid and dashed curves represent testing results of the empty tank (see Fig. 4) with
145 tangentially and perpendicularly connected inlets. It can be seen that the performance with the
146 tangential inlet pipe seems to be the greatest at midrange flow rates with a slight drop off at higher
147 flow rates. In this case, the inflows from the tangential pipe traveled a longer distance in the settling
148 tank by flowing along inside of the tank wall compared to the case of the perpendicularly-
149 connected inlet, where the inflow directly flowed toward to the outlet. Additional tests under the

150 same conditions but with an inner cylindrical baffle added in the settling chamber (see Fig. 5),
151 were also carried out; the results are shown by green solid and dashed curves in Fig. 3. Both of
152 these two different inlet connection configurations performed better than the empty tanks
153 (comparing particle removal rates of green curves with blue curves in Fig. 3). Interestingly, their
154 particle removal rates (see two green curves) were about the same, despite generated flow
155 conditions in the settling tank being very different. It can be seen then, that the vortex generated
156 from a tangential inflow did not appear to have any notably positive influences on particle settling.
157 The main functions of an inner cylinder are for removing the floating materials and increasing the
158 flow travel distance (which affects both tangential and perpendicular flows in a similar way), so
159 this result is understandable.

160 To further examine the vortex effects on enhancing particle sedimentation and examine tank-wide
161 vortex influences on the settled particle behaviors, experiments were conducted with and without
162 a bottom structure. This structure directs any particles which land upon its surface to slide down
163 into the protected tank bottom and takes advantage of the downward vortex currents, (see Fig. 1).
164 The results are shown by the red solid and dashed curves in Fig. 3. The results were unexpected,
165 because adding the bottom structure not only reduced performance under higher flow rates, but it
166 was noted that with the tangential inlet pipe, the results were no better than the empty tank.
167 Observations of the particle settling pattern on the bottom structure, as shown in Fig. 7, may help
168 to clarify the reasons. With the perpendicularly-connected inlet pipe, the wall of the inner
169 cylindrical baffle functioned to dampen inflow velocities, reducing momentum. The reduced
170 inflow velocities resulted in less penetration into the deeper areas of the settling chamber. This
171 encouraged the suspended particles to continue settling after they moved out of the turbulent region
172 until they reached the tank bottom, where they would likely stay undisturbed, or slide down into
173 the protected sediment collection chamber. A layer of sediment collected on the surface of the tank
174 bottom as shown in panels A and C of Fig. 7. The pictures in Fig. 7 were taken from experiments
175 with inflow rate of 1.25 and 2.0 L/s (two different inlet connection arrangements) after experiments
176 were stopped and water was slowly drained out. With the tangential inlet pipe configuration, the
177 results were very different. The particle distribution patterns on the tank bottom are shown in
178 panel B and D of Fig. 7. Only a very small amount of particles accumulated in the center of the
179 bottom. The possible explanation was that the rotational motion generated by the tangential inflow
180 reached deeper into the tank, with little energy loss and higher flow velocities. This means that

181 most of the settling particles (1) were pushed by strong rotational flow into the isolated sediment
182 storage space; (2) remained suspended (due to high-energy turbulent flows); and (3) settled on the
183 sloped bottom but could be resuspended (due to high bed shear stress caused by the strong vortex
184 flow).

185 However, the effects of the above-discussed hydraulic differences may be potentially reduced by
186 increasing the tank depth. This is why the performance of settling tests with the inner baffle only
187 (and no bottom structures), or even an empty tank, were better than those with the bottom structure
188 in place. In order to confirm the results, a duplicated test of the experiment with the solid red curve
189 was conducted and the results (solid black curve in Fig. 3) did not show any real differences with
190 previous test. A bottom structure with a much steeper slope (as shown by Fig. 6), designed to
191 increase particle sliding speed, was also tested with the tangentially connected inlet pipe. The
192 results were similar to the conventional sloped bottom and were not shown here. This implied that
193 large bed shear stress was still strong enough to keep particles in suspension and thus reduce
194 performance. The results of the simple comparisons above indicate that the generated tank-wide
195 vortex would be unlikely to enhance the particle settling and may in fact reduce performance. It
196 should be pointed out that there was no underflow (a small amount of discharge at the separator
197 bottom used to continuously convey settled particles away) in all tested cases because the small
198 underflow was not expected to have significant influences on the flow conditions in the tank main
199 chamber and made comparisons between settling conditions easier to assess.

200 The behaviors of the inflow-induced tank-wide vortex can also be examined from the point of fluid
201 dynamics theory, which may help further to understand its effects on the suspension of particles.
202 Vortices can be present in many complex forms, however, there are two important special types
203 (Milne-Thomson, 1968):

204 1) Irrotational Vortices

205 In the absence of external forces, a vortex usually develops fairly quickly toward the irrotational
206 flow pattern, where the flow tangential velocity V_t is inversely proportional to the distance R ,
207 except in the center core where the velocity is zero.

208 ,

209 where a is a constant and ω is the flow rotation angular speed. Irrotational vortices are also called
210 *free vortices*. The water draining in a bathtub and hurricanes or tornadoes induced by rising hot air
211 are good examples of irrotational vortices. They are generated to provide flow mass (mass
212 conservation) for fast flow vertical movement with the least flow resistance.

213 2) Rotational Vortex (Forced Vortex)

214 A rotational vortex can be maintained indefinitely in that state only through the application of
215 some external forces; it cannot be generated by the fluid motion itself. The flow tangential velocity
216 V_t can be estimated by,

$$217 \quad V_t = \quad R \quad (2)$$

218 For example, if a water bucket is spun at constant angular speed about its vertical axis, the water
219 will eventually rotate in rigid-body fashion. A tank wide vortex created by tangential inflow force
220 (as was the case in this study) is also a rotational vortex. Its tangential velocity distribution should
221 satisfy equation (2). This was confirmed from evidence of the settled particle pattern on the tank
222 bottom, because the tangential velocity is proportional to the distance from center. Higher bed
223 shear stress, which can scour settled particles, will be generated at the outer region of vortex.
224 Therefore, as shown by panels B and D in Fig. 7, only a small amount of sediments can stay at the
225 center of the tank bottom. A rotational vortex generated and maintained by a continuous external
226 force acting at the outer edge of the vortex is not necessarily associated with strong downward
227 force in the center; the accumulated sediment at the center of the vortex is simply due to the fact
228 that the bed shear stress is at a minimum in this location.

229 The flow velocity distributions in the two vortex types are quite different, even though the swirling
230 movement looks similar; the gradient of pressures created by the fluid motion in different vortices
231 can be in the opposite direction. In accordance with Bernoulli's principle,

$$232 \quad p + \frac{1}{2}\rho V^2 + \rho gh = constant \quad (3)$$

233 pressure decreases with increasing flow velocity. Where p is the pressure, ρ is the density of the
234 flow, V is the velocity of the flow, h is elevation, and g is the gravitational acceleration, Therefore,
235 based on the relationship between flow velocity with distance from the vortex center (equations

236 [1,2]) and the relationship between flow velocity and pressure (equation [3]), it is possible to
237 calculate that the force generated by pressure gradients in an irrotational and rotational vortex of a
238 fluid with constant density, is toward and away from the vortex center, respectively. The flow-
239 generated horizontal dynamic force in a rotational vortex will actually cause particles to move
240 away from the vortex center, instead of towards the vortex center as one might assume. As
241 mentioned before, the reason that the particles stay in the center of the bottom (as shown in Fig. 3)
242 is because this area has the least bed shear stress. Therefore, the concept of enhancing particle
243 settling using a vortex separator may not reflect what actually happens in practice. However, for
244 the examined HDVS, the direction of the pressure force (away from the vortex center) should
245 benefit the capture of the suspended particles. As the discharge is located in the center of the
246 vortex, it will reduce the possibility of particles being washed away in the exiting flow. These
247 effects tend to be minimal because the flow rotation speed is typically quite slow.

248 Another argument used to promote some HDVS (in some HDVS brochures) suggest that the tank-
249 wide vortex could potentially enhance sedimentation by creating additional forces that increase
250 the intensity of the acceleration field, thereby augmenting gravity to overcome drag forces and
251 increase the particle settling velocity for enhanced settling performance. The acceleration or force
252 is a vector, and identifying the direction of a vector is critical in any vector analysis. A forced
253 liquid vortex in an open top container gives the free surface in the form of a parabolic distribution
254 as described by following equation (Milne-Thomson, 1968):

$$255 \quad z - z_0 = \frac{\omega^2 R^2}{2g} \quad (4)$$

256 Where g is the constant of gravity acceleration and z is the vertical distance from the datum to the
257 free surface minimum (taken as z_0). The vortex free surface will increase with R , and in order to
258 conserve the mass, the free surface of a rotational vortex will be higher than the free surface of the
259 fluid at rest in the outer region and lower toward to center. The additional force produced by the
260 vortex has upward and downward components in outer and inner regions, respectively, which
261 maintains the shape of the vortex free surface. This will reduce and increase the gravity force
262 effects in outer and inner regions, rather than augmenting gravity everywhere; this extra force can
263 become very weak under low inflow rates. Regarding the function of the drag forces, due to the
264 location of the outlet relative to the inlet (i.e., in the center), the drag force in the outer region of

265 the vortex will be downward, but it will be upwards near the center. Vortex-generated additional
266 forces will reduce the drag force in the inner region of the vortex which will help particles to stay
267 in the settling chamber. However, in the outer region, the smaller drag force due to vortex-
268 generated additional force will slow down particles traveling to the tank bottom area and thus
269 increase the likelihood that particles will remain suspended and go directly to the outlet. The
270 additional vortex-generated forces can thus play both helping and hindering roles in such a settling
271 device, depending on the region, so it is difficult to assess whether this additional force provides
272 an overall positive or negative impact. This brings into question of the true assistance offered by
273 vortex-induced additional forces (accelerations) to enhance the particle settling.

274 The mechanisms of particle suspension and transport in turbulent flows and circular clarifiers can
275 be rather complex, and when analyzing such phenomena, substantial simplifications are often
276 needed, so scale models can be important tools to optimize designs. This study focused on the
277 potential effects of two different types of vortices. These differences tend to be magnified as flow
278 speed increases in the vortex. Other forces, such as gravity and centrifugal force, may have stronger
279 influences on vortex-carried suspended particles, but their effects on the particle movements in
280 different types of vortices will be similar.

281 **Conclusions**

282 From simple and direct physical modeling comparisons and theory analyses, the following
283 conclusions may be drawn:

- 284 1) Though the swirled-flow motion generated by a tangential inflow can potentially increase
285 the flow travel distance and bring the suspended solids to the tank bottom area, due to its
286 low momentum and energy loss, the flow can penetrate into deeper regions with a large-
287 enough bed shear stress to wash away particles which have already settled on the tank
288 bottom. These negative effects became worse with a shallower settling tank and increased
289 inflow rates. The comparison results with two different inlet pipe connections did not show
290 that the vortex in the settling chamber of the studied HDVS could notably enhance the
291 particle settling.
- 292 2) Behaviors of two important types of vortices were compared and briefly discussed. A
293 rotational vortex, as generated in most particle separators, usually does not have strong

294 upward or downward force at its center, due to the way it was induced and maintained. The
295 pressure (induced by flow movement in the vortex) will push the suspended particles away
296 from the vortex center because of the negative pressure gradient (outward), however, this
297 pushing force was not expected to have strong influences on particle settling.

298 3) Vortex-generated additional vertical forces can have both additive and subtractive forces
299 on suspended particles in a vortex, depending upon the region, so it becomes difficult to
300 assess the cumulative effects on particle settling.

301 Inconsistent support for the benefits of using vortices to enhance suspended particle settling
302 suggests that these devices may not be able to target the smaller, lighter particles, which tend to
303 carry the greatest burden of pollutants. This study provides a useful method to examine the flows
304 in more detail, understand the principles involved and this approach can be used in other studies.

305 **Notation**

306
307 The following symbols are used in this paper:

308 a = a constant;

309 g = the gravitational acceleration;

310 h = the elevation;

311 p = the pressure;

312 z = the vertical distance from the datum to the free surface minimum (taken as z_0);

313 R = the distance from the center;

314 V = the velocity of the flow;

315 V_t = flow tangential velocity;

316 ω = the flow rotation angular speed;

317 ρ = the density of the flow;

318 **Data Availability Statement**

319 Some or all data, models, or code that support the findings of this study are available from the
320 corresponding author upon reasonable request.

321 **Acknowledgement**

322 The present study was financially supported by the Great Lakes Action Plan (GLAP) with
323 funding by Environment and Climate Change Canada. Thanks are offered for the support from
324 the Engineering Branch at the National Water Research Institute for providing very valuable
325 advice and helping to build the physical model.

326 **References:**

327 Andoh, R.Y.G., and Smisson, R.P.M. (1994). “High Rate Sedimentation in Hydrodynamic
328 Separators.” Proc. of 2nd International Conf. On Hydraulic Modelling Development and
329 Application of Physical and Mathematical Models, Stratford, UK, pp. 341 – 358.

330 Andoh, R.Y.G., Hides, S.P. and Saul, A.J., (2002). “Improving Water Quality Using
331 Hydrodynamic Vortex Separators and Screening Systems.” 9th International Conference on Urban
332 Drainage, Portland, Oregon, USA, 8-13 September.

333 Andoh, R.Y.G., and Saul, A.J. (2003). “The use of hydrodynamic vortex separators and
334 screening system to improve water quality.” Water Science and technology, 47(4) 175-183.

335 Arnett, C. J. and Gurney, P. K. (1998). “High rate solids removal and chemical and non-chemical
336 UV disinfection alternatives for treatment of CSO’s.” Innovation 2000, Conference on Treatment
337 Innovation for the Next Century, Cambridge, UK.

338 Averill, D., Mack-Mumford, D., Marsalek, J., Andoh, R. and Weatherbe, D. (1997). “Field
339 Facility for Research and Demonstration of CSO Treatment Technologies.” Water Science &
340 Technology, 36 (8-9), 391 – 396.

341 Davidson, J. and Summerfelt, S.T., (2005). “Solids removal from a coldwater recirculating
342 system—comparison of a swirl separator and a radial-flow settle.” Aquacultural Engineering, 47-
343 61.

344 Faram1, M.G., Andoh, R.Y.G. and Williams, C.A. (2005). “Innovative approaches to urban
345 stormwater management.” 10th International Conference on Urban Drainage,
346 Copenhagen/Denmark, 21-26

347 He C. and Marsalek J. (2009). "A Vortex Plate for Enhancing Particle Settling Journal of
348 Environmental Engineering." ASCE, 135(8), pp. 627-635.

349 He, C. and Marsalek, J., (2014). "Study of Enhancing Sedimentation and Trapping Sediment with
350 Bed Grid Structure." Journal of Environmental Engineering, ASCE, 140(1), 21-29

351 He, C., Rochfort, Q. and McFadyen R. (2014). "Potential Errors and Error Propagation in Methods
352 Used to Determine Particle Removal Efficiency." Journal of Environmental Engineering, ASCE,
353 140(6), 21-29.

354 He, C., Scott, E. and Rochfort, Q. (2015). "Enhancing sedimentation by improving flow conditions
355 using parallel retrofit baffles." Journal of Environmental Management, 124(30), 40-50.

356 Lee, J. Y., Han and Kim, H.Q. (2011). "Study on the reduction of pollutant load from roads
357 using the modified hydrodynamic vortex filtration system (HVFS)." International Journal of
358 Urban Sciences 15(1), 35-45.

359
360 Michelbach, S., Wohrle, C. (1993). "Settleable Solids in A Combined Sewer System:
361 Measurement, Quantity, Characteristics.", Wat. Sci. Tech. Vol. 27, No. 5.

362 Milne-Thomson, L.M. (1968). "Theoretical Hydrodynamics" published by MACMILLAN & CO
363 LTD. London, 351-354

364 Okamoto, Y., Konugi, M. and Tsuchiya, H. (2002). "Numerical Simulation of the Performance
365 of a Hydrodynamic Separator." 9ICUD conference, Portland, Oregon, USA.

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

370 Tyack, J.N., Hedges, P.D., and Smisson, R.P.M. (1992). "The Use of Sewage Settling Velocity
371 Grading in Combined Sewer Overflow Design." NOVATECH 92, International Conference on
372 Innovative Technologies in the Domain of Urban Water Drainage, Lyon (France), November 3-
373 5.

374 Yu, J.H., Yu, H.X. and Xu, L.Q. (2013). "Performance evaluation of various stormwater best
375 management practices." Environmental Science and Pollution Research Vol. 20, 6160–6171

376

377 **List of Figure Captions:**

378 Fig. 1: Physical model of the studied HDVS with inlet pipes tangentially and perpendicularly
379 connected (perpendicular shown blocked in this figure).

380 Fig. 2: Schematic of experimental setup and structures dimensions. A-water pump, B-supply tank,
381 C-flow meter, D-control valve, E- particle capture screen.

382 Fig. 3: Results of comparison tests with the different inlet pipe connections and inflow rates: (1)
383 blue curves for empty tank, (2) green curves for inner cylinder added, (3) red curves for all
384 structures in the tank and (4) black curve is duplication test of red solid curve; solid lines for
385 tangential pipe and dashed lines for perpendicular pipe configurations

386 Fig. 4: Tested Empty tank with tangentially and perpendicularly connected inlet pipes.

387 Fig. 5: Tested HDVS with tangentially and perpendicularly connected inlet pipes and inner
388 cylindrical baffle added (no bottom structures).

389 Fig. 6: The bottom structures with two different slopes, (A) steeper slope (B) standard slope

390 Fig. 7: Top view of the captured particle distributions on the tank bottom: panels A and B for
391 inflow rate = 1.25 L/min and perpendicular and tangential inlet pipe, respectively, panels C and D
392 for inflow rate = 2.0 L/min and perpendicular and tangential inlet pipe, respectively.

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397 Figures:

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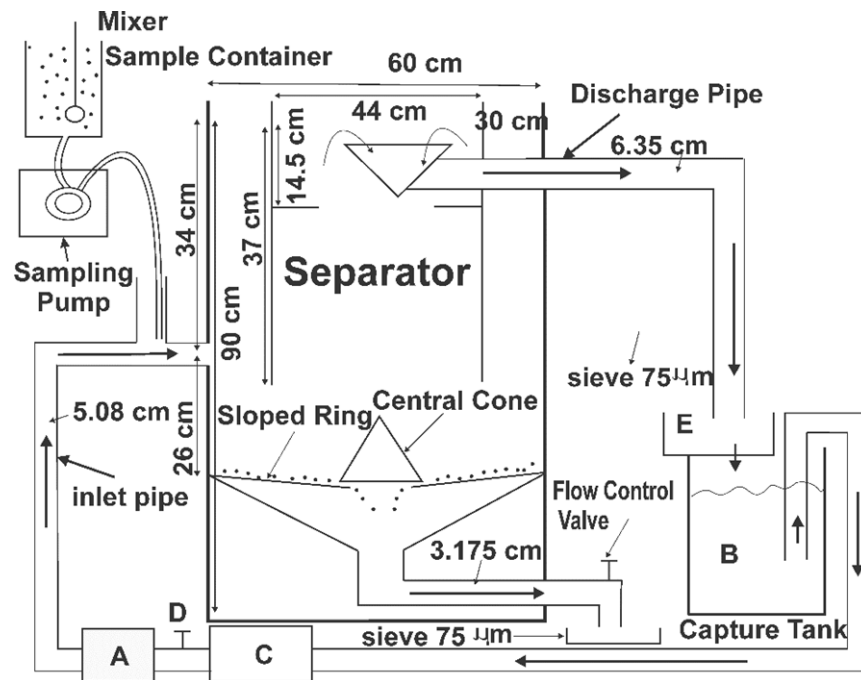
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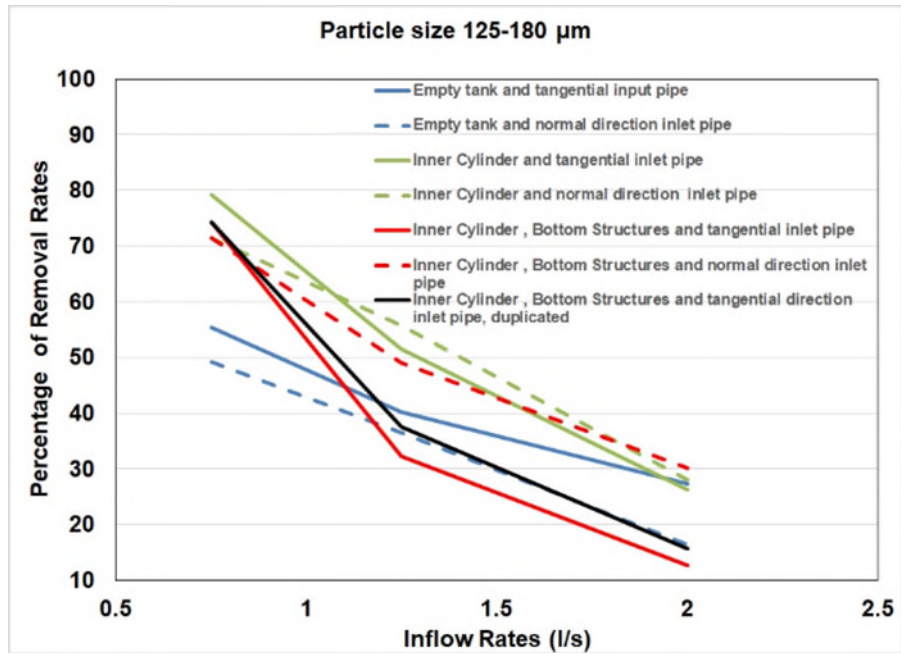
Fig. 1



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Fig. 2



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Fig. 3



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Fig. 4

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Fig. 5

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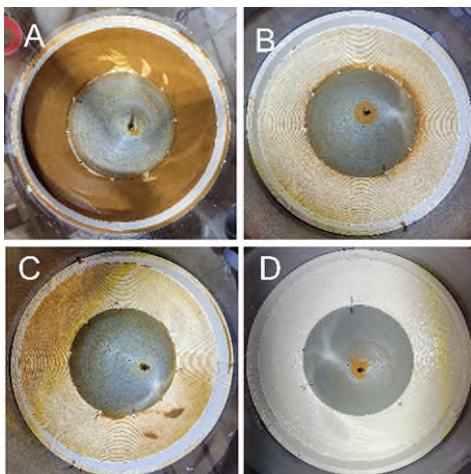


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Fig. 6

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Fig. 7