Simple design criteria and efficiency of hydrodynamic vortex separators

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ABSTRACT

Vortex separators still draw attention from specialists investigating the process of removing particles suspended in liquids. The devices are locally applied for waste water treatment in different systems – from storm waste water sewerage to water circulation in fish ponds. However, the methods for separator design presented in the literature are questionable. The paper presents two simple and functional criteria that were employed to construct a laboratory test stand. The test results gave positive feedback on the efficiency of vortex separators.

Key words | centrifugal force, design, efficiency, storm waste water, vortex separator

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INTRODUCTION

Centrifugal separators can be divided into two categories of device: cyclones and vortex separators that are both characterised by an inlet tangential to a cylindrical chamber and an outlet located in the axis of the object. Cyclones originate from the beginning of the 20th century (White 1932) and are mainly used as devices for removing dust from air, as well as for water treatment (hydrocyclones). Basic research on hydrodynamic vortex separators (HDVS) designed to remove suspensions from waste water was described by Smith (1959). A more detailed study on HDVS devices (Figure 1) was launched in the 1960s, yielding solutions such as the US Environmental Protection Agency's Swirl Concentrator or Storm King (Andoh & Saul 2003).

In spite of having similar construction, cyclones and vortex separators have different levels of efficiency in practical applications, which results from their different dynamics. For instance, the centrifugal force generated by relatively small cyclones that treat air and work under pressure is stronger than that produced by bigger HDVS that work gravitationally and treat waste water.

Nevertheless, vortex separators still attract attention as they can make better use of their cubic capacity. In HDVS, dead zones inside the chamber are reduced due to circulation of the liquid (Andoh & Saul 2003). Veerapen *et al.* (2005) made a significant contribution to the research on HDVS. After performing a series of experiments and calculations using computational fluid dynamics (CFD), they arrived at a concluded that the 'two fundamental processes affecting separation in the swirl separator are sedimentation and turbulent dispersion', and that influence of the centrifugal force could be neglected. These statements led to the formulation of a theoretical description of separator operation based on advection-dispersion suspension mass balance.

However, the possibility of practical application of the description proposed by Veerapen *et al.* (2005) is disputable. First, a one-dimensional model of dispersion can only be employed provided that the length of the liquid stream under consideration is greater than the length of the advective subzone L_A. According to the author of the theory of dispersion, Taylor (1954), for a circular stream (flow along the horizontal axis of a separator with radius R) with average velocity v_z, the length of the stream L_A has the following form:

$$L_A = 0.07\frac{v_z R^2}{K_T} \tag{1}$$

Transverse dispersion coefficient K_T equals

$$K_T = 0.041\sqrt{\lambda} v_z \tag{2}$$

where the Nikuradse coefficient λ is calculated from the Darcy–Weisbach formula; accordingly, $\lambda = 0.04$ obtains $L_A = 8.6R$. Veerapen *et al.* (2005) considered two separator

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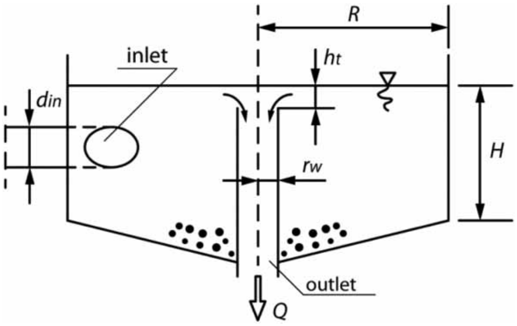

Figure 1 | Schematics of axial cross-section of HDVS.

radii: $R_1 = 0.31$ and $R_2 = 0.75$ m for $L_A = h_t$ (where $h_{t1} = 0.028$ and $h_{t2} = 0.75$ m, respectively) yielding the ratio L_A/R equal to 0.9 and 1.0. Such results indicate that condition (1) is not fulfilled and the dispersion model, although formally correct, cannot be accepted from a physical point of view. Second, the specifics of the suspension that is to be removed from the stream need to be taken into account. Veerapen *et al.* (2005) analyzed fish ponds where the density of the suspension ranged from 1,060 to 1,180 kg/m^3. However, vortex separators are designed for the removal of mineral suspension from storm waste water where suspended particles have a density of the order of 2,700 kg/m^3. With grit density being twice the value of fish excrement it would be expected that centrifugal force will be greater in magnitude and should be included in the model. This statement will be further elaborated during the course of the paper.

Finally, the fact that various manufacturers offer vortex separators in their product catalogues (Andoh & Saul 2003) means that the separator operation is accepted by the user. However, there are not many alternative solutions that employ centrifugal force to enhance the removal of suspension from storm waste water. Alternative devices include parallel plate separators in which separation is enhanced by lamella packs, and coalescence separators for the removal of oils and petroleum derivatives. Conversely, industrial waste water can be treated using numerous solutions from electromagnetic separators (removal of iron filings) to resilient separators that are similar to screens and filters. However, devices operating in stable manufacturing conditions cannot be compared with sewerage devices that lack a fully developed design method.

In conclusion, further research on HDVS devices is justified. This paper presents the results of research on the functional characteristics of vortex separators. The main emphasis was put on development of a functionally simple technical criterion that will allow quick evaluation of the technical parameters of the object being designed (or existing and operating).

METHODS

Quantitative description of vortex separator operation

Principle of vortex separator dimensioning

Every device employed for suspension removal from waste water comes with a set of proper design methods (from simple to complex solutions). The simplest methods are presented in various handbooks and manuals (for example, WEF Manual of Practice No. 8 1992). For instance, it is recommended that surface load in a vortex separator should equal circa 100 m^3/m^{2}h. Comprehensive (complex) methods are based on an equation of the motion of specific particles suspended in liquid. By solving this equation, it is possible to obtain formulas that describe particles trajectories. Their analysis enables the design of new objects, evaluation of the operation of existing ones or solving other technical problems.

Taking into account the characteristics of the motion of particles forming the suspension (small size and low acceleration), the equation of motion acquires the following form (Soo 1969; Slattery 1999; Gronowska 2012):

$$\rho_c V_c \frac{d\mathbf{v_c}}{dt} = (\rho_c - \rho) V_c \mathbf{g} + \alpha_s \rho V_c \frac{d(\mathbf{u} - \mathbf{v_c})}{dt} + C_D F_C \frac{\rho |\mathbf{u} - \mathbf{v_c}| (\mathbf{u} - \mathbf{v_c})}{2} + \mathbf{F_C} + \mathbf{F_{TD}} \quad (3)$$

where C_D is drag coefficient; $\boldsymbol{F_c}$ is centrifugal force; $\mathbf{F_{TD}}$ is transversal drift; $\mathbf{g}$ is gravity acceleration; t is time; $\mathbf{u}$ is liquid velocity; V_c is particle volume; $\mathbf{v_c}$ is particle velocity; α_s is associated mass coefficient; ρ is liquid density; ρ_c is particle density.

In relation (3) three forces were neglected: the Basset, Saffman and Magnus forces. These forces describe the change of particle motion conditions in time, liquid velocity gradient around the particle, and the possible rotary motion of the particle (if it occurs), respectively (Soo 1969). Taking into account limited acceleration inside the separator, the small dimension of suspended particles in comparison to the separator, and the relatively regular shape of particles, these three forces can be omitted. However, relation (3) should include two important factors: centrifugal force $\mathbf{F_C}$ and transversal drift (sometimes also called buoyancy) $\mathbf{F_{TD}}$. In vortex separators, centrifugal force acts along the axis of the device's chamber towards the outside wall, and its modulus is described by the relation

$$F_C = \rho_c V_c \omega^2 r = \rho_c V_c \frac{u_t^2}{r} \quad (4)$$

where r is distance from the axis of rotation (chamber radius); u_t is liquid tangential velocity; ω is liquid angular velocity.

Transversal buoyancy $\mathbf{F_{TD}}$ expresses radial change in pressure p related to the circulative motion of liquid. This force acts along the chamber radius; however, in the case under consideration it is directed towards the centre. In order to calculate its modulus, it is necessary to determine pressure distribution as this force is described by the relation (Soo 1969)

$$F_{TD} = -V_c \frac{\partial p}{\partial r} \quad (5)$$

When supplemented with a velocity field model chosen adequately for the real flow, relation (3), which describes force balance, it can be used as a basis to simulate motion of a characteristic suspended particle. Conversely, it is possible to use a simple evaluation of whether a given particle will leave the separator chamber through the outlet pipe or not. The particle will stay inside the device (be removed from the waste water stream) provided that centrifugal force F_C at the outlet cross-section (for $r = r_w$, Figure 1) is not smaller than the sum of drag force F_N and transversal drift force F_{TD}, which directs the particle towards the centre

$$F_C \geq F_N + F_{TD} \quad (6)$$

There is a possibility that the particle will remain inside the chamber even though condition (6) is not fulfilled. In reality, many particles fall to the bottom of the separator due to the process of gravitational sedimentation, thus moving out of range of the outflow stream. Nevertheless, the proposed relation is functionally simple and provides a favourable margin of safety, especially for draft calculations.

Liquid velocity field in vortex separator

The velocity field of liquid flow in a vortex separator can be described in a number of ways. The most precise description is obtained by solving general equations of motion using CFD methods (Dyakowski *et al.* 1999; Martignoni *et al.* 2007). The solution can be further used in technical simulations, analyses and discussions of different variants of device construction and operation. However, engineers still seek mathematically simple flow models. This paper presents a synthetic model based on the balance of liquid mass and energy of the flow. In general, such an approach complies with methods described in the literature on the topic (Rhodes 2008). Moreover, the model was formulated using the results of the authors' own research, as well as those found in the literature (Stairmand 1951; Gronowska & Sawicki 2011; Sawicki 2004, 2012).

The model assumes that radial velocity u_r changes only with respect to chamber radius r and is given by a relation that is commonly applied to this type of device (Rhodes 2008)

$$u_r(r) = \frac{Q}{2\pi r h_e} \quad (7)$$

where Q is liquid discharge; h_e is thickness of flow active layer.

Thickness of the active layer of liquid circular flow h_e is equal to water elevation above the outlet h_t (Figure 1) for $r = r_w$

$$h_e = h_t \quad (8)$$

Liquid elevation h_t can be determined from classical methods of hydraulics (Nalluri Featherstone 2001) as the outlet pipe works like a shaft overfall or the 'morning glory spillway' (Camargo *et al.* 2006). Making use of Bernoulli's theorem makes possible

$$Q = \frac{4}{3} \mu_p \pi r_w \sqrt{2g} h_t^{3/2} \quad (9)$$

where discharge coefficient μ_p can be calculated from the empirical relation (Gronowska & Sawicki 2014)

$$\mu_p = \frac{0.245}{(h_t/r_w)^{0.87}} \quad (10)$$

Tangential velocity in the model is described by an irrational function. The shape of this velocity profile is analogical to the one presented by Stairmand (1951)

$$u_t(r) = B r^{-0.65} \quad (11)$$

According to Rhodes (2008) the value of the exponent should equal –0.50 instead of –0.65. However, thorough analysis of the results presented by Stairmand (1951) indicates that the latter better suits the chosen tangential velocity model.

Multiplier B was determined from the condition of equality of energy of circulative motion delivered by the inlet stream and energy dissipated inside the separator (Slattery 1999; Sawicki 2004, 2012)

$$B = 4.63Q\left[Hd_{\text{in}}^4\left(\frac{1}{r_w^{0.95}} - \frac{1.41}{R^{0.95}}\right)\right]^{-1/3} \quad (12)$$

Technical criterion of separator operation

Combination of the proposed velocity fields and condition (6) gives the first technical criterion of vortex separator operation.

Making use of the proposed velocity field, one can obtain the first technical criterion generally expressed by condition (7). Substitution of F_C from (4), F_N from (3) and F_{TD}, which according to (5), acquires the form

$$F_{TD} = -\rho V_c\left(\frac{u_t^2}{r} + \frac{Q^2}{4\pi^2 h_e^2 r_w^3}\right) \quad (13)$$

into (6), as well as taking into account the velocity field according to (7) and (11), yields the following inequality (for $C_D = 1.99$, cubical shape of particles):

$$\frac{0.0012 d_{\text{in}}^{8/3} H^{2/3}}{h_e^2 r_w^{1/3}}\left(\frac{1}{r_w} + \frac{4}{3d_c}\right) + 1 \le \frac{\rho_c}{\rho} \quad (14)$$

where d_{in} is inlet pipe diameter; H is water depth; d_c is particle diameter.

Assuming the radius of the inlet pipe is equal to 100 mm and the diameter of suspended particles is equal to 1.0 mm, the following relation is obtained:

$$\frac{1}{r_w} \ll \frac{4}{3d_c} \quad (15)$$

that allows simplifying (14) into

$$\frac{0.0016 d_{in}^{8/3} H^{2/3}}{h_e^2 r_w^{1/3} d_c} + 1 \le \frac{\rho_c}{\rho} \quad (16)$$

Relation (16) is the first technical criterion for vortex separators. It can be used to evaluate whether an existing object was properly designed or to choose characteristics of a new device so it will operate as desired. Substitution of (10) into (16), after some transformations, yields

$$\frac{0.0052 d_{\text{in}}^{2.7} H^{0.7} r_w^{5.6} g^{1.6}}{d_c Q^{3.2}} + 1 \le \frac{\rho_c}{\rho} \quad (17)$$

Relation (17) explains the difference in efficiency between separators treating air and water mentioned earlier in the paper. For sand particles with density $\rho_c = 2{,}700$ kg/m^3

$$\rho_c/\rho_{\text{air}} = 2700; \quad \rho_c/\rho_{\text{water}} = 2.7 \quad (18)$$

It can be clearly seen that criterion (17) is easier to fulfil in the case of air rather than water.

Moreover, it should be noted that the technical criterion (17) does not include the full set of characteristic geometrical dimensions of a vortex separator. This is a consequence of the physical basis of this relation, which describes only the flow conditions near the outflow. First, Equation (17) lacks the value of separator radius R. In order to include this parameter, the authors refer to the condition of inequality between particle retention time t_R and its sedimentation time t_S

$$t_R \ge t_S \quad (19)$$

Precise determination of particle retention time, which includes the influence of centrifugal force, can be acquired by solving the equation of particle motion (3). To retain the functional simplicity of the technical criteria, centrifugal force inside the separator chamber is negligible (besides the discussed outflow section). Analysis of relations (4) and (11) reveal that centrifugal force increases near the outflow cross-section. Therefore, a cylindrical chamber of height H and radius R obtains

$$t_R = t_{PF} = \frac{V}{Q} = \frac{\pi R^2 H}{Q} \quad (20)$$

where t_{PF} is plug flow time; V is separator volume.

As computational sedimentation time equals

$$t_S = \frac{H}{v_f} \quad (21)$$

comparison of Equations (20) and (21) yields the second technical criterion

$$R \geq \sqrt{\frac{Q}{\pi v_{\mathrm{f}}}} \tag{22}$$

where v_{f} is free sedimentation velocity.

Empirical determination of HDVS efficiency

Laboratory test stand

The first technical criterion (17) allows calculation of one out of five characteristic values (d_{in}, H, r_w, d_c or Q) of vortex separators, provided that the remaining four are known. For suspended sand particles: $\rho_c = 2{,}700$, $\rho = 1{,}000\ \mathrm{kg/m^3}$ and $g = 9{,}81\ \mathrm{m/s^2}$. Critical size of particle is the substitutional diameter $d_c = 0.10$ mm (Imhoff & Imhoff 1979). Taking into account technical conditions, it was assumed that $H = 0.30$, $d_{\mathrm{in}} = 0.03$ and $r_w = 0.015$ m. For such dimensions Equation (17) gave the lower limit of liquid discharge inside the separator

$$Q \geq 0.23 \cdot 10^{-3}\ \mathrm{m^3/s} \tag{23}$$

With reference to relation (6), with this value of discharge, the centrifugal force is strong enough to keep suspended particles inside the device. As free sedimentation velocity for sand particles 0.10 mm in diameter equals 0.0067 m/s (Imhoff & Imhoff 1979), the separator radius determined from condition (22) is $R = 0.15$ m.

To generate the circular motion of liquid inside the device, the inlet stream must be directed parallel to the outside wall. The laboratory stand was equipped with an inlet conduit perpendicular to the outside wall with an elbow fitting at the ending that directed water towards the wall. (Figure 2).

Sand was introduced to the device via a dispenser in the form of a vertical pipe 300 mm in diameter fixed on the inlet conduit to the chamber. The bottom part of the device consisted of a sedimentation funnel 0.15 m high, ending with a drain valve to remove sand from the chamber. The test stand was made of acrylic glass and PVC.

Course of measurements

Vortex separator efficiency tests were performed for six sand fractions defined by seven sieve sizes: 0.063, 0.1, 0.125, 0.2, 0.25, 0.5 and 2.0 mm. Dried sand was partitioned into fractions by means of standard sieve analysis equipment.

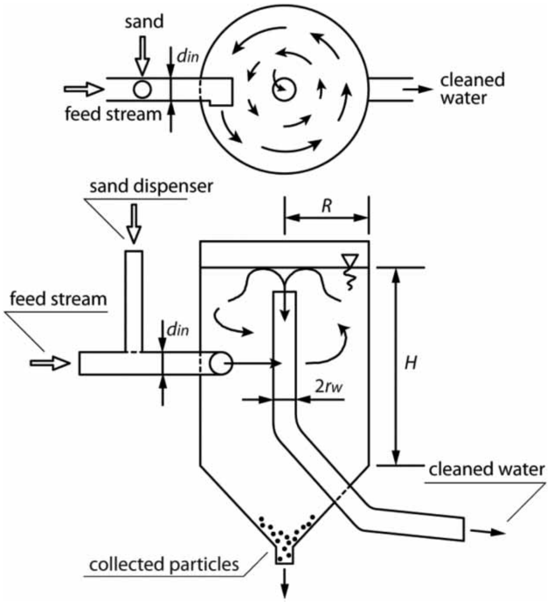

Figure 2 | Schematic of the laboratory separator.

Once liquid discharge had been set, the portion of sand mixed with water was introduced into the water stream by the dispenser pipe. Each sand portion weighed $M = 100$ g. When the sedimentation process inside the chamber finished, the accumulated sand was removed, dried and weighed. Separator efficiency e was calculated from the relation

$$e = \frac{M_{\mathrm{R}}}{M} \tag{24}$$

where M is mass of introduced sand; M_{R} is mass of removed sand.

Results and discussion

Results from measurements were presented on a histogram e (d_c). A sample histogram is presented in Figure 3 (for $Q = 0.0003\ \mathrm{m^3/s}$).

The design of devices for suspension removal is usually based on binary systems; the same is true for vortex separators. All particles larger than the particle of the chosen limiting size should be removed from the feed stream, whereas smaller ones may remain in the stream. The theoretical efficiency curve of such a model will be discrete in character. Comparison of the obtained results and the theoretical curve (Figure 3) indicate that the real course of the process is compatible with the binary model (for particle

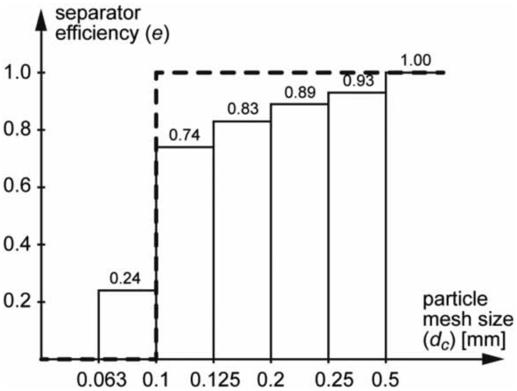

Figure 3 | Efficiency of the laboratory separator (solid line – measurements; dashed line – theoretical model).

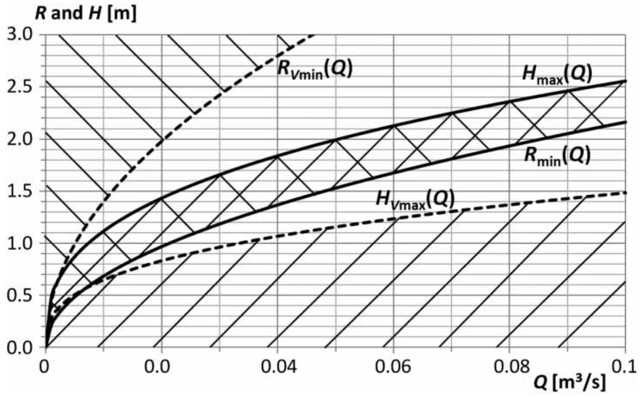

Figure 4 | Geometrical interpretation of simplified design criteria.

size $d < 0.1$ mm, only a small portion of particles is separated from the feed stream; for $d > 0.1$ mm, device efficiency significantly increases).

Results from measurements indicate that the efficiency of the laboratory separator is high. The rate of reduction of sand 0.1–0.2 mm exceeds 78% and for fractions bigger than 0.2 mm, it reaches 94%. Taking into account the fact that the laboratory stand was designed using a simplified method, the results are satisfactory (Imhoff & Imhoff 1979).

Although the laboratory model has small dimensions, it was designed as a self-contained object using the method proposed in the paper and not as a scaled-down laboratory model of an existing technical device. This fact ensures that a device of a technical scale designed by the proposed method will operate satisfactorily.

In light of the positive results from research on the laboratory test stand, the authors decided to analyse whether the developed design criteria would yield reasonable dimensions of devices applied in engineering practice. First, it is necessary to note that inlet and outlet diameters are dimensions of the order of 0.1 H. This fact allows reduction of the first criterion (17) to a relation of maximum allowable device height H [m] and discharge Q [m^3/s]

$$H \leq H_{\max} = 5.86Q^{0.36} \tag{25}$$

Furthermore, for assumed free sedimentation velocity $v_f = 0.0067$ m/s (Imhoff & Imhoff 1979), the second criterion (22) acquires the form (R [m])

$$R \geq R_{\max} = 6.84Q^{0.5} \tag{26}$$

Plots of both relations are presented in Figure 4. It can be seen that from the range of values of parameters H and R that fulfill the proposed design criteria (25), (26) is found between the curves. This range indicates the rational dimensions of the device.

For comparison, relations (17) and (22) were used to evaluate operation of the separator employed for treatment of waste water from fish ponds (Veerapen *et al.* 2005). In this case, suspended particles have a density of 1,100 kg/m^3 that means their free sedimentation velocity equals 0.0016 m/s. For such conditions, design criteria appear as follows (H [m], R [m]):

$$H_V \leq H_{V\max} = 3.4Q^{0.36} \tag{27}$$

$$R_V \geq R_{V\max} = 14Q^{0.5} \tag{28}$$

Plots of these functions are also presented in Figure 4. As seen on the graph, there is no common range of HV and RV values; thus, both design criteria cannot be met simultaneously. As a result, Veerapen *et al.* (2005) were unable to successfully apply the vortex separator to remove feed remains from waste water.

CONCLUSIONS

The scientific literature regarding vortex separators is extensive; however, it lacks a physically justified and practically convenient design method. This results from the fact that there is no reasonable description of waste water velocity readily available.

The mathematical model of the liquid velocity field in the considered device (7) and (11) presented in the paper allowed the determination of forces acting on a suspended particle. The developed design method included two quantitative technical criteria – balance of forces acting in the outflow cross-section (6) and comparison of the time of flow with the required sedimentation time (19). These criteria yielded two relations (17) and (22).

Correctness of the relations developed was then empirically verified by measuring efficiency of a physical model of a vortex separator that was designed based on the proposed criteria – computational discharge and separator diameter, and resulting technical conditions. Research conducted indicated that the laboratory model had relatively high effectiveness (Figure 3).

Furthermore, the authors showed that the developed design criteria can be simplified. Taking into account technically justified proportions between particular dimensions of the object, they obtained draft relations (25) and (26). These equations demonstrated that the design criteria applied for mineral suspension provide an available range of device parameters to choose from. Conversely, both criteria cannot be fulfilled simultaneously for particles of small sedimentation velocity. In either case, these draft relations can be useful in the initial stages of the design process.

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