

An efficiency formula for a hydrodynamic vortex separator

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INTRODUCTION

Hydrodynamic vortex separators (HDVSSs) are low energy solid-liquid separation systems. They have been applied for a number of duties including wastewater treatment, combined sewer overflow treatment and storm water treatment. Such systems operate whereby solids settle due to the force of gravity and sufficient residence time for this to take place is provided by the rotary nature of the path of the fluid through the separator. Figure 1 shows a schematic of a Grit King®, a form of HDVSS, analysed in this study¹. The fluid enters the HDVSS through a tangential inlet, marked in Figure 1 by 'A', and upon entering the main chamber strikes a deflector plate 'B'. The fluid tends to take a path through the HDVSS such that it rotates down around the outer part of the separator and upon reaching the bottom of the cone 'F' the fluid rotates up through the central region between the dip plate 'E' and the central shaft 'G' before leaving through the overflow 'J'. The vent box 'C' allows air trapped between the dip plate and the vessel wall 'D' to escape when the fluid level within the device fills the separator. Separated solids collected in the grit pot 'H' may be removed by an underflow component through the central underflow 'I' or by the use of a submersible pump. These systems tend to be more effective and less expensive to construct, operate and maintain than other types of system. In this study, the HDVSS is considered operating without an underflow component which may be the case in practice, for example, where collected solid material is removed on a batch basis.

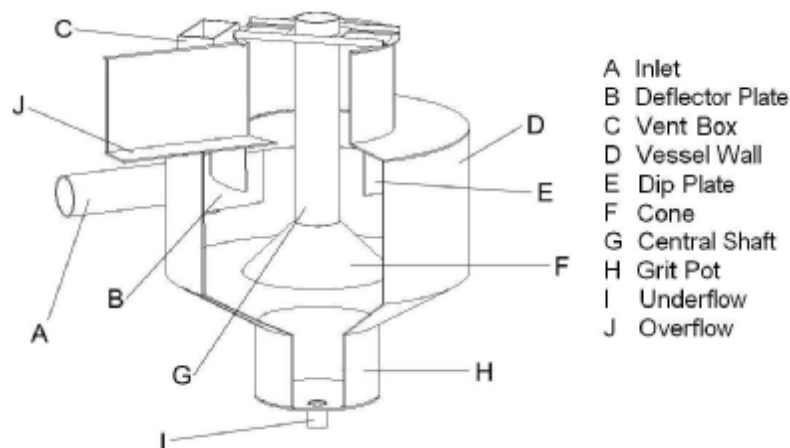


Figure 1. Schematic of a 0.75m diameter Grit King®

The operation of these systems has to date been difficult to quantify such that a single equation may be applied to predict the separation performance of such a device operating without an underflow.

EXPERIMENTAL TESTING

The rig used for testing the separator was custom built and included a header tank for maintaining a constant flowrate. Another feature was an inlet length of straight pipe of 45 diameters so that the

¹ Grit King® is the trade name of a type of HDVSS developed and supplied by Hydro International plc (UK). Related systems are available in Japan from JFE Engineering under a license agreement.

velocity profile at the inlet to the HDVS was reasonably developed, and the rig allowed the particles to be released into the system at the header tank, thus, the particles were allowed to settle along the length of the inlet pipe which allowed them to enter the HDVS at a realistic position which may not have been the case had a stand pipe been used which would be positioned relatively close to the HDVS. The trade names of the particulates used in testing the HDVS are Styrocell and Purolite. Styrocell is a pre-expanded polystyrene and Purolite is an ion exchange resin used for removing high molecular weight organic material from the influent water. Both types of particles are generally spherical and hence, a sphericity of 1 can be assumed. The sphericity is defined as the surface area of a sphere with the same volume as the particle divided by the surface area of the particle' [1]. Although the density is supplied by the manufacturer/supplier of the particles, the figure is not exact. In the case of Styrocell, pores of air may be trapped in the particle during the manufacturing process, which would explain why a fraction of particles float in water, despite the density being stated as being in the range 1020-1050kg/m³. Purolite expands when wet, and because it is an ion exchange resin, the density depends upon what ions the particles have come into contact with. The particles were therefore characterised by taking dry samples which were sieved to reduce the size range. The volume of particles used in retention efficiency testing ranged from 100ml to 900ml, depending on the volume of particles available after sieving. Since Purolite expands when wet, it was left in water for approximately a week after sieving. Settling velocity tests were then carried out on a random sample of typically 50 individual particles in a sieved size range. The diameter of the settling column used was 0.25m and the maximum particle diameter can be assumed to be 5.6mm from the sieve sizes used. Hence, from a figure adapted from Fidleris & Whitmore [2] which accounts for wall effects on the terminal settling velocity of a particle, the diameter of the settling column is sufficient to be able to neglect these. The temperature of the fluid was taken before and after the settling tests so that the density and viscosity of the water could be determined. Each settling test allowed the particle to settle an adequate distance to allow the terminal settling velocity to be achieved. Using a stop watch, the particle would then be timed to fall a pre determined distance. The diameter of a random sample of typically 50 individual particles in a sieved size range was also measured using Vernier Callipers, taking care not to squash the particle whilst taking its diameter. Ideally the diameter of all the particles in the sample used in the settling velocity tests would be taken, but due to the size of the particles, ease of handling did not allow this. Assuming the sphericity to be 1 and with the mean settling velocity and mean particle diameter, as well as the fluid density and viscosity, a mean particle density can be calculated. This involves calculating the particle Reynolds number, which is then used to calculate the drag coefficient from an equation proposed by Turton and Levenspiel [3]. The drag coefficient is then used in calculating the particle density from Equation 1. This has been done for all the particle sieve size ranges used in retention efficiency testing, and the results are presented in Table 1.

$$V_s = \sqrt{\frac{4dg(\rho_p - \rho_f)}{3C_d\rho_f}} \quad (1)$$

V_s = Particle settling velocity, m/s d = Particle diameter, m ρ_f = Fluid density, kg/m³
 g = Acceleration due to gravity, m/s² ρ_p = Particle density, kg/m³ C_d = Drag coefficient

Table 1. Particle properties

Particle type and sieve size range	Mean settling velocity, / m/s	Mean diameter, / m	Mean density, / kg/m ³
Purolite 500-600microns	0.02627	0.5678×10 ⁻³	1372
Purolite 500-710microns	0.00686	0.5468×10 ⁻³	1064
Purolite 710-1000microns	0.00966	0.7158×10 ⁻³	1057
Styrocell 1.4-2.0mm	0.02087	1.7369×10 ⁻³	1036
Styrocell 2.0-2.8mm	0.02925	2.2774×10 ⁻³	1037
Styrocell 2.8-5.6mm	0.03429	2.8026×10 ⁻³	1036

Faram et al. [4] have shown through experimentation that the efficiency of such devices is time dependant as particles captured in the grit pot may be re-entrained into the flow. Each retention efficiency test was therefore carried out for a duration of 10 minutes and the temperature of the fluid was taken at the start and end of each test. At the end of each test the butterfly valve was closed before switching off the pump to prevent particulates remaining in the HDVS from being flushed out by water remaining in the header tank. The HDVS efficiency is defined as the volume of particles remaining in the HDVS after 10minutes expressed as a percentage of what was released into the HDVS. Measuring the volume of particles instead of mass was justified by the fact that excess water held between the particles by surface

tension would be included in the measured mass and would therefore be erroneous. Drying the particles after each test would have been time consuming. Comparisons of efficiency using different volumes of particles in the samples available have been made and it has been determined that for the volumes used in testing, that the efficiency is independent of the particle loading.

RESULTS

Plotting the retention efficiency against the inlet flowrate gave a series of efficiency cusps and the repeatability of the data is consistent. The data for the Purolite 500-710micron range was not repeated once an efficiency cusp had been established due to the time required to collect all the particulate. Efficiencies for Styrocell 1.4-2.0mm below 4.25 litres per second cannot be achieved because at lower flowrates, the particles tend to flocculate and begin to float. At higher flowrates, the turbulence in the flow prevents the flocs forming. Flowrates higher than 12 litres per second cannot currently be achieved due to the limitation of the pump. Initially the trend in the efficiency cusps appeared to be with settling velocity of the particles but it was found that Purolite 500-600microns gave the highest efficiency despite having a settling velocity lower than Styrocell 2.8-5.6mm, as detailed in Table 1. In an attempt to reduce the efficiency cusps to a single curve, the efficiency was plotted against different dimensionless

groups as used by previous researchers such as $\frac{V_s}{U}$, [5] where U is the inlet velocity, $\frac{V_s C_d^{0.5}}{U}$, [6] and Froude number, none of which resulted in a satisfactory curve. A different approach was therefore taken by plotting efficiency as a function of $\frac{V}{Q}$, where V is the volume of fluid in the separator and Q is

the inlet flowrate which produced a series of efficiency cusps in the shape of an 'S'. An 'S' curve may be described by the logistic function, Equation 2, which was developed for modelling population growth [7], [8].

$$f(x) = A \frac{1 + Be^{-Cx}}{1 + De^{-Cx}} \quad (2)$$

Equation 2 is a four parameter model, i.e. requires four constants to be specified, but by examination of the function, this may be reduced. Firstly, the term Be^{-Cx} applies negative growth in that as $B \rightarrow D$ the function approaches a straight line, therefore $B = 0$. Now, as $x \rightarrow \infty$, $f(x) \rightarrow A$. Therefore $A = 100$ as the efficiency obviously doesn't exceed 100%. The function can now be written as

$$\eta = \frac{100}{1 + De^{-Cx}} \quad (3)$$

Equation 3 is now a two parameter model. The coefficients that give the best fit in a two parameter model may be determined using an optimization technique by Guymmer, [9]. This involves determining the R_t^2 value [10] for a matrix of values of C and D and reducing the range between the constants that give the highest R_t^2 value until a satisfactory accuracy has been achieved for each. This has been done for each efficiency cusp when plotted against $\frac{V}{Q}$. It has been found by plotting various

quantities for the full range of particles used, that the quantity that appears to be controlling the efficiency is mass diffusion which is given by

$$m_d = d(\rho_p - \rho_f) \quad (4) \quad \text{Where: } m_d = \text{Particle mass diffusion, kg/m}^2$$

Hence, the larger the mass diffusion, the higher the expected efficiency. A function has been found between the constants in Equation 3 and the particle mass diffusion, and hence, a model for the efficiency has been determined, for which an example of the fit is shown in Figure 2. A limitation of the model is that the predicted efficiency is never 0%. However, the offset is fairly small and when sizing a separator the required efficiency tends to be of the order of 95%, where it can be seen that the model gives an adequate prediction. The functions that best fit the constants in Equation 3 are polynomials and the model is only valid for particles with a mass diffusion within the range used in testing as extrapolation results in unlikely values for the constants. Further work is required to attain a more complete relationship for these.

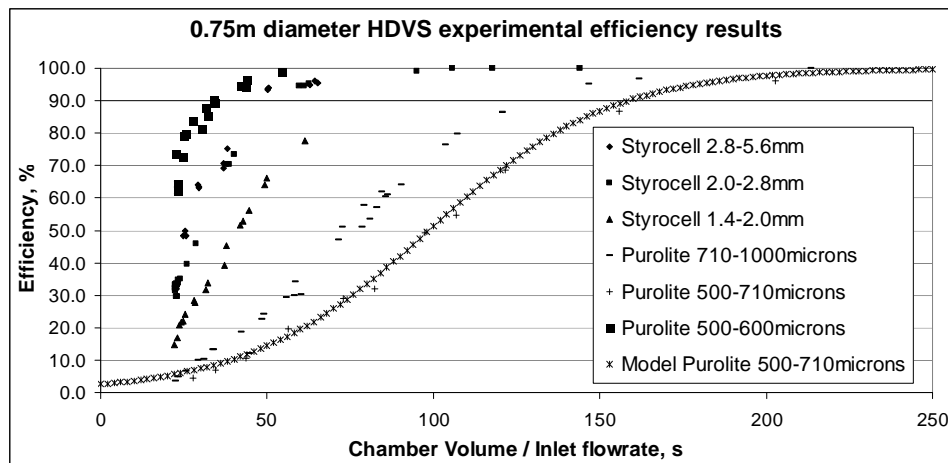


Figure 2. Comparison of the model and experimental retention efficiency results

CONCLUSION

Plotting retention efficiency as a function of dimensionless groups used by previous researchers has not resulted in a satisfactory single efficiency cusp. The efficiency has therefore been defined by the logistic function, where the constants are described as a function of the particle mass diffusion.

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