# An investigation into the factors that determine the efficiency of a hydrodynamic vortex separator

## Une étude sur les facteurs déterminant l'efficacité d'un séparateur hydrodynamique à vortex

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## SUMMARY

The performance of hydrodynamic vortex separators can be difficult to predict, and is thought to be affected by a great number of variables. In order to find an equation to accurately size a HDVS that could relate all these variables, a study using computational fluid dynamics (CFD) simulation has commenced. This will be complemented with experimental testing at a later stage. The paper presents the findings of an initial sensitivity analysis that looked at the effects of both physical variables and variables within the CFD code on predictions, such that accurate models can be created in the future. It has been found that the variables that most influence the predicted efficiency are the initial position of the particle in the inlet pipe, the particle characteristics (i.e. density, size and shape) and fluid viscosity.

## RESUME

La performance des séparateurs hydrodynamiques de vortex peut être difficile à prévoir, et on pense que celle-ci dépend d'un grand nombre de variables. Afin de trouver une équation pour déterminer précisément un HDVS qui pourrait relier toutes ces variables entre elles, une étude utilisant la simulation numérique en mécanique des fluides (CFD) a débuté. Celle-ci sera complétée par des essais expérimentaux ultérieurement. Cette publication présente les résultats d'une première analyse de sensibilité qui s'est attachée à regarder les effets à la fois des variables physiques et des variables du code CFD sur la prédiction, de telle manière que des modèles précis puissent être créés à l'avenir. On a constaté que les variables qui influencent le plus l'efficacité prévue sont la position initiale de la particule dans le tuyau d'admission, les caractéristiques de particules (c.-à-d. densité, taille et forme) et la viscosité du fluide.

## KEYWORDS

COMPUTATIONAL FLUID DYNAMICS, CFD, HYDRODYNAMIC VORTEX SEPARATORS

## 1. INTRODUCTION

Most older urban drainage systems consist of combined sewers which are used to carry foul sewage and storm water to wastewater treatment facilities. This can result in a large quantity of grit requiring removal at the preliminary stage of treatment, necessary to avoid damage to machinery such as pumps and valves, and accumulation in downstream process chambers (Gardner *et al*, 1996). One method of doing this is through the use of hydrodynamic vortex separators (HDVS), whereby grit settles due to the force of gravity. Sufficient residence time for this to take place is provided by the rotary nature of the path of the grit through the separator. HDVSs have advantages over more traditional methods of separating grit. They have no moving parts or power requirements, thereby minimising maintenance requirements, and tend to be more compact. This given, they are often cheaper to both construct and operate. Figure 1 shows the HDVS 'Grit-King®' which was modelled in this work. It consists of a number of parts such as the cone, dip plate and central shaft which Andoh *et al*, 1993, reported to induce 'highly stabilised flow patterns'. The grits enter through the inlet and are collected in the grit pot, from which they are periodically removed by gravity or pumped feed through the underflow. The overflow allows a constant stream of treated fluid to leave the device.

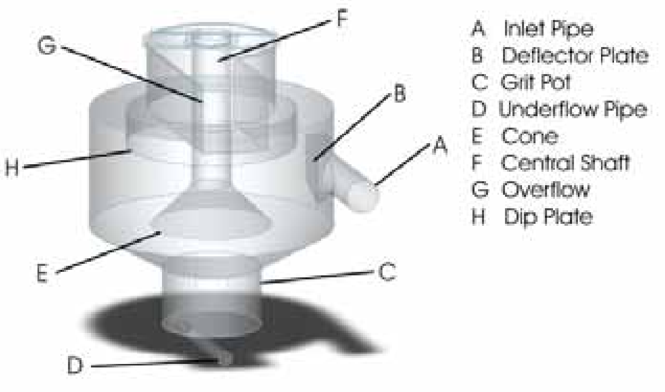

Figure 1. The Grit-King® hydrodynamic vortex separator

The performance of HDVSs, including the Grit-King®, based on a knowledge of influent particle characteristics, can be difficult to accurately predict, and is thought to be affected by a great number of variables. In order to find an equation to accurately size a HDVS, both experimental testing and CFD modelling approaches are valid. In the current work, a combination of these approaches will be applied. However, this paper focuses on an initial sensitivity study that has been undertaken to look at all the variables that could affect the predicted efficiency of a HDVS. This is imperative in order to have confidence in the CFD results when comparison with experimental data is limited to that for 'model' scale units (note – in practice, HDVSs have ranged up to 16m in diameter, at which scale performance characterisation would be both difficult and costly).

The CFD software FLUENT is one of the most popular commercial flow simulation codes and is used in many fields of engineering, such as the automotive, semiconductor and nuclear industries. The software has also been applied in the water industry. In using CFD to predict separator efficiencies, the flow field is computed and then the 'Lagrangian tracking routine' or 'Discrete Phase Model' (DPM), FLUENT Inc (2002), is implemented to inject particles into the HDVS and hence predict the efficiency. There are however a large number of variables and boundary conditions that can effect the predicted efficiencies when using the DPM.

There are many different ways of defining the efficiency for a HDVS as reported by Gardner *et al* (1996). However, in this work the efficiency is defined by equation 1.

$$Efficiency = \frac{\text{Number of particles collected}}{\text{Number of particles injected}}.100 \qquad (1)$$

## 2. LITERATURE REVIEW

### 2.1 Validation of Particle tracking

There is very little literature on sensitivity analysis of the variables pertaining to particle tracking within the CFD codes. Stovin *et al* (1998), have investigated a number of the variables available when tracking particles in storage chambers. As the application is different to a HDVS, not all the validation work that was carried out applies to modelling a HDVS.

Stovin *et al* (1998), found that when using the 'Stochastic turbulence model' 50 simulations were required before a 'deviation of ±2.5% from the population mean, at a confidence level of 99%,' was obtainable. With respect to the 'step length factor' they found that 'neither halving nor doubling the step length factor had any significant effect on the resulting efficiency prediction'.

Faram and Andoh (2000) and Faram and Harwood (2003) present general validation of HDVS efficiency predictions against experimental and semi-empirical model outputs, with generally positive conclusions, but do not consider the impact of model variables in any detail.

## 3. EXPERIMENTAL VALIDATION OF SETTLING VELOCITY

Many of the physical variables investigated are related to the equations used to predict the settling velocity of a particle, such as density, fluid viscosity etc, and hence separation efficiencies are often plotted as some function of particle settling velocity.

The first objective of this work was to ensure that FLUENT can predict the settling velocity of the simplest particle, a sphere, and compare the results with experimental data. Experimental testing was carried out by measuring the settling velocity of a variety of precision cellulose acetate balls through a distance of 1m in a 254mm internal diameter settling column. By comparing the particle-column diameter ratio with a figure adapted from Fidleris & Whitmore (1961), the diameter of the column was sufficient to say that wall effects were negligible. A distance of 300mm was provided for the ball to reach the terminal settling velocity. From a theoretical calculation of the settling velocity of the particle and knowledge of the particle and fluid properties, the number of time constants, derived from Newton's second law of motion applied to a sphere, can be calculated for the particle to reach 99.9% of the terminal settling velocity. Hence, an estimate of the distance required for the particle to settle before timing can be calculated. It was estimated that for the largest particle, a distance of 300mm was more than 5 times the distance required.

Using the FLUENT CFD simulation software, coarse and fine tetrahedral grids were used, as well as a grid aligned at 45° to the direction of the particle to see if grid alignment has any influence on the predicted settling velocity. The results comparing CFD with experimental data are presented in Figure 2. The only point in figure 2 not to compare CFD data with experimental is the point where the particle diameter is less than 0.001m. This is due to the difficulty in obtaining such small particles in practice.

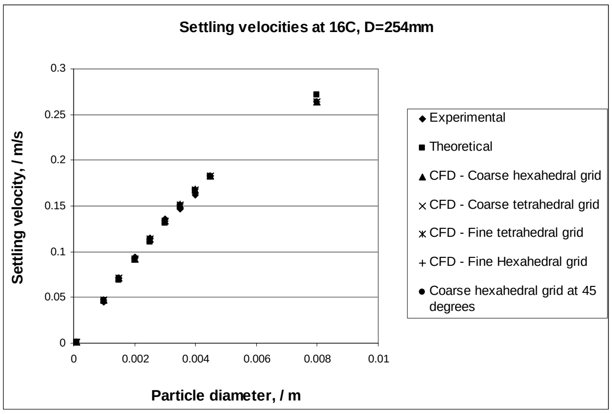

Figure 2. Comparison between CFD and experimental particle settling velocities

As can be seen from Figure 1, FLUENT CFD predictions compare very well with experimental results. However, one reason that the results are all very close is probably due to the fluid inside the settling column being stationary. If velocity gradients were present in the fluid, then one would expect grid resolution to influence the results. Despite this, the results do give confidence in the ability of CFD to accurately predict the settling velocity of a spherical particle.

## 4. FACTORS THAT INFLUENCE THE EFFICIENCY OF A HDVS

To produce an accurate model of a HDVS using CFD, it is necessary to investigate a range of variables that will affect the predicted efficiency. The variables investigated can be classed as either physical e.g. fluid viscosity, or numerical e.g. grid size. This sensitivity analysis was done by modelling a 4m diameter Grit-King® operating at a flowrate deemed to be 'typical', with a tetrahedral grid of approximately 500 000 cells where it had been determined that the results were grid independent. This investigation was also necessary to have confidence in results where experimental data under fully controlled conditions cannot be obtained where variables such as flowrate, fluid density and viscosity, particle shape, density and size are all known, e.g. separator efficiencies from a 5m device.

## 4.1 Model Variables

### 4.1.1 Comparison of results with and without a turbulent dispersion model

The turbulent dispersion model chosen was the 'Stochastic Tracking'. This was chosen because the particle trajectory is computed using the instantaneous value of the fluctuating velocity, as opposed to 'Cloud Tracking' which utilises statistical methods. Figure 3 shows the predicted efficiencies with and without the dispersion model.

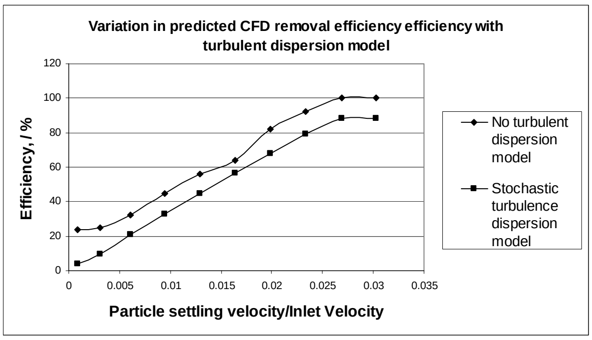

Figure 3. Comparison of predicted efficiencies with and without a turbulent dispersion model

There is a significant discrepancy between the two sets of results, and it is suspected that the results with the dispersion model will be the most accurate. This is because incorporating the fluctuating velocity component is a much more realistic representation of the flow field within the HDVS.

### 4.1.2 No turbulent dispersion model

To look at the effect of injecting particles without a turbulent dispersion model, five surface injections were carried out where the number of particles injected started at 135 and was increased in increments of 135 up to 675. A surface injection is such that a particle is released from each data point on the surface, in this case the inlet of the HDVS. The results were such that there was no variation in the efficiency. This is because without any dispersion of particles, each particle that is released from a data point follows the same path as the previous particle.

### 4.1.3 Length scale

The length scale 'determines the time step used to integrate the equations of motion for the particle'. (FLUENT Inc., 2002) Figure 4 shows how the predicted efficiency of a particle changes with length scale.

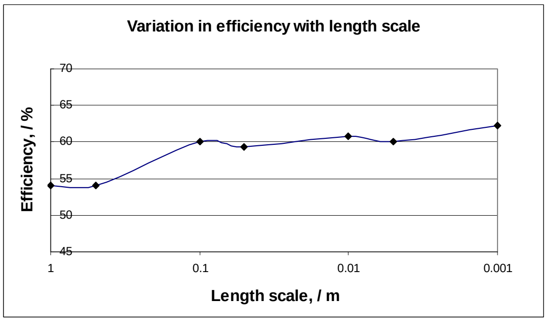

Figure 4. Change in predicted efficiency with length scale

It can be seen that there is quite a large difference in the efficiency at smaller length scales compared with those at larger values. This is most likely because at smaller length scales, the equations of motion for the particles are being updated on a much more frequent basis. Hence, the smaller the length scale, the more accurate the trajectory of the particle, and thus the predicted efficiency should be more accurate.

## 4.2 Physical Variables

### 4.2.1 Fluid temperature

The temperature of the fluid has a direct influence upon the viscosity, and hence the settling velocity of a particle. Figure 5 shows predicted efficiencies at 0.2, 16 and 25°C.

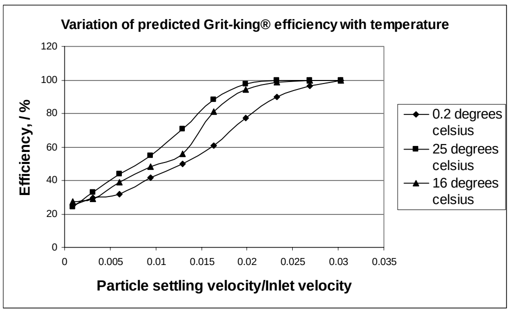

Figure 5. Efficiencies at 0.2, 16 and 25°C

As might be expected, at a higher fluid temperature the efficiency is greater due to the fluid having a lower viscosity, which means that the particle has a higher settling velocity.

### 4.2.2 Initial Particle Position

Two group injections were created where one was between two horizontal points in the top half of the inlet, and the other between two horizontal points in the bottom half of the inlet, as shown in Figure 6.

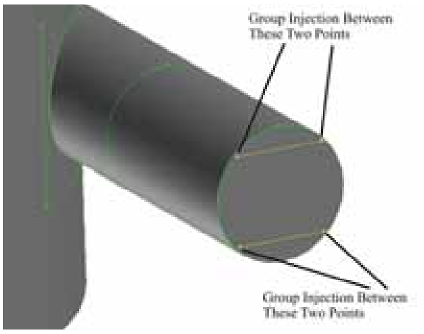

Figure 6. Position of two group injections on the inlet

Using stochastic tracking 2000 particles were released from each injection. The predicted efficiency for the top injection was found to be 54%, and the predicted efficiency for the bottom injection was 98%. Clearly from this result, the efficiency is dependent upon the initial position of the particle. Thus if the settling velocity of the particle was greater then the efficiency would be improved or alternatively, if the residence time for the particle was greater, then there would be a greater chance of the particle being separated.

### 4.2.3 Coefficients of restitution

Coefficient of restitution denotes the amount of potential energy that is retained or lost by a particle when it hits a wall. Figure 7 shows the difference between a model with the default values of restitution, which is one, and a model with values of zero.

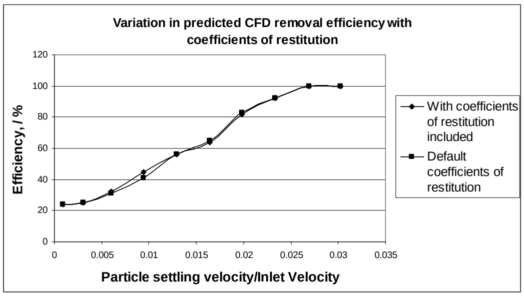

Figure 7. Comparison of predicted efficiencies with a coefficient of restitution of 0 and 1

As shown in Figure 7, coefficients of restitution have negligible effect. This is possibly because the only time a particle is most likely to strike a wall is when it enters the HDVS and strikes the deflector plate. This is shown in Figure 8 which shows the trajectory of a very small and light particle which tends to migrate towards the centre of the device.

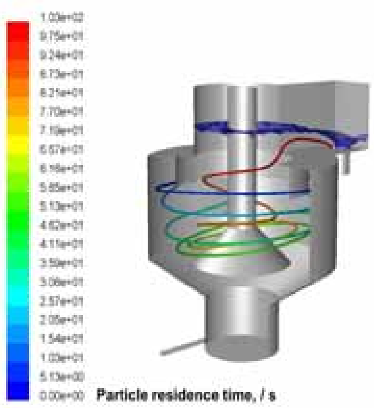

Figure 8. A particle trajectory through the Grit-King® HDVS, showing a plot of particle residence time

If the HDVS was biased towards a forced cyclone, then the particle would tend to travel along the outside of the device where it may come into contact with the outside wall, in which case the coefficient of restitution could be critical. However, this is not the case.

### 4.2.4 Shape factor

The shape factor of a particle has a direct impact on its settling velocity. Shape factor denotes the sphericity of a particle, with a value of one corresponding to a perfect sphere. The faster the settling velocity of a particle, the greater the chance of it being separated. Figure 9 shows predicted efficiencies of a range of particles, with four different shape factors.

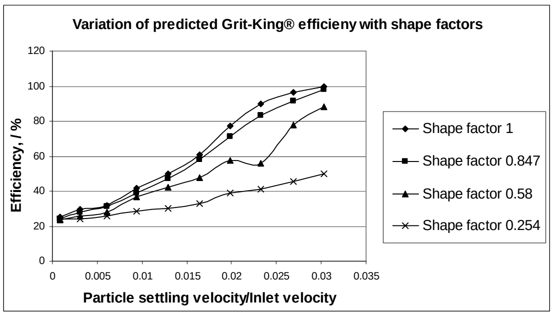

Figure 9. Comparison of predicted efficiencies for particles with four different shape factors

As the particle shape factor approaches zero there is less chance of it being separated. This is because as the shape factor approaches zero, the drag on the particle increases which reduces the settling velocity and reduces the chance of the particle settling into the grit-pot. This is important because grits are irregular in shape and so have a wide range of settling velocities, making predicting the efficiency quite a complex task.

## 5. CONCLUSION

It has been shown that FLUENT can accurately predict the velocity of a sphere in a stationary body of water, which is thought to be a crucial factor when determining the efficiency of a HDVS. It has also been shown that there are a number of variables that have a great effect on the efficiency of a HVDS including fluid viscosity, initial position of the particle and particle shape factor. Other variables are less significant such as coefficients of restitution and the inclusion of a turbulence model. The findings of this work will allow more accurate modelling of HDVSs when working on scaling laws.

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