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# Removal of particles from highly viscous liquids with hydrocyclones

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## AUTHOR-HIGHLIGHTS

- Quality performance-data for a hydrocyclone acting on viscous liquids are given.
- Liquid viscosity effects on hydrocyclone cut size and pressure drop are elucidated.
- A model, predicting the performance well, is given in full.
- CFD simulations show that viscosity effects can be simulated reasonably with LES.

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## ABSTRACT

In this paper the performance characteristics, expressed as cut-size, grade-efficiency curve and pressure drop, have been determined for a hydrocyclone acting on highly viscous liquids. These results are of high quality and can serve as a benchmark for simulations and model predictions. To understand the results, CFD, large-eddy simulations of the flowpattern and pressure drop have been carried out, among other things to determine the vortex intensity as a function of liquid viscosity. A version of a main-stream cyclone model has been identified that predicts the trend in hydrocyclone performance with liquid viscosity well, both in terms of separation efficiency and pressure drop. This model is given in full, providing a valuable tool in evaluating the potential of hydrocyclone technology for new and unconventional separation duties.



## 1. Introduction

It is hugely advantageous to use hydrocyclone technology for a solid–liquid separation where-ever possible. Hydrocyclones are easy and cost-effective to construct, they may be applied in very aggressive environments and they contain no moving part, making them very robust and eminently suited for sub-sea or even down-hole separation.

It would therefore be beneficial for e.g. the oil and gas exploration industry to extend the use of cyclone technology to a wider range of applications than the present one. At present hydrocyclones are mainly used for water–sand separation, while many of the liquids to which they could potentially be applied are much more viscous than water. Another case for extending the use of hydrocyclones is that gravity sedimentation often fails to separate the fine particles required by today's increasingly stringent regulations.

### 1.1. Effect of viscosity on the cut size

The effect of viscosity on the cut-size of a cyclone is, in principle, predicted by the classical cyclone performance models (Hoffmann and Stein, 2008). One is as the model of Barth:

$$d_{50}=\sqrt{\frac{v_{rCS}9\mu D_x}{(\rho_s-\rho_l)v_{\theta CS}^2}} \tag{1}$$

where the subscript $CS$ denotes the velocity in the cylindrical surface obtained by prolonging the wall of the fluid outlet tube, or vortex finder, to the bottom of the cyclone indicated in Fig. 1 below. $d_{50}$ is the cyclone cut size, $\mu$ is the fluid viscosity, $D_x$ is the vortex finder diameter, $\rho_s$ and $\rho_l$ are the particle and liquid density, respectively. $v_r$ and $v_\theta$ are the radial and tangential velocities in a cylindrical coordinate system with axis in the cyclone axis. Eq. (1) is the so-called "equilibrium orbit" model. The equation is the result of a force-balance on a particle rotating in the surface CS, the forces being (a) the "centrifugal force" and (b) the drag force acting from the fluid flowing from the outer part of the (hydro)cyclone to the inner part across CS on its way to the exit(s). This radial flow is in the model assumed to be axially uniform.

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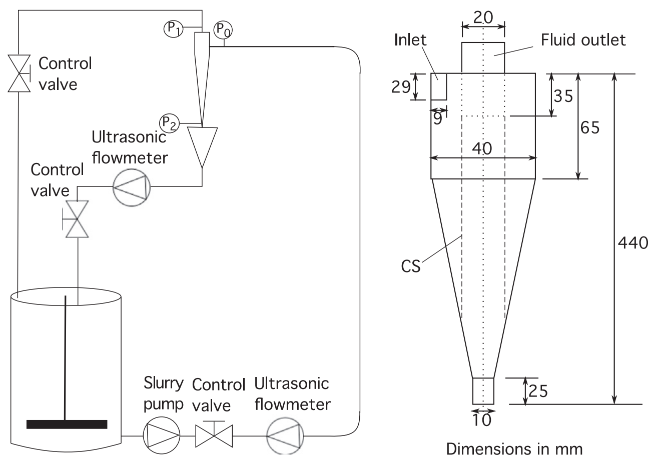


**Fig. 1.** Left: schematic of the experimental set-up. Right: detail of the cyclone with the dimensions given in mm.

Another model is that of Rietema (1959):

$$\frac{d_{50}^2(\rho_s-\rho_l)}{\mu}H\frac{\Delta p}{\rho_l Q}=3.5, \tag{2}$$

where $\Delta p$ is the cyclone pressure drop, $H$ is the total cyclone height and $Q$ is the volumetric flowrate through the cyclone. This is the so-called "time-of-flight" model, wherein the radial fluid flow is neglected and it is considered whether a particle, injected in the middle of the tangential inlet, has the time to reach the cyclone wall and be collected before reaching the bottom of the cyclone, where it is assumed to be swept into the inner part, upward flowing, of the vortex and lost.

Both of these models have—in spite of having been derived based on very different concepts—been shown to be robust and in rough agreement with a wide range of experimental results. Eqs. (1) and (2) show that both models predict that the cut size, all else being equal (including the flowpattern in the cyclone), increases with the square-root of the viscosity. However, the viscosity of the liquid may influence the flowpattern in the cyclone, specifically the vortex intensity and therefore $v_\theta$. If $v_{\theta CS}$ is reduced with increasing viscosity this might cause the cut-size to increase with the viscosity with a power higher than 0.5. $v_r$, on the other hand, is assumed axially uniform in equilibrium-orbit models and will remain unchanged at like volumetric flowrate.

Since most applications of hydrocyclones involve water as the liquid, there is limited experimental information about the effect of the liquid viscosity on the literature. Lately the hydrocyclone research has concentrated on CFD modeling, a review of this literature is given by Nowakowski et al. (2004).

Nageswararao et al. (2004) and Silva et al. (2012) review some of the most accepted and used models for hydrocyclone cut size. The well-known purely empirical expression for $d_{50}$ of Plitt (1976) was extended by himself Plitt et al. (1980) to include the effect of liquid viscosity as a factor raised to the power of 0.5. A later extension to this expression of Flintoff et al. (1987) also includes the effect of liquid viscosity as a factor $\mu^{0.5}$.

Ren et al. (2007) studied the fluid flow fields and the separation of sand in water and highly viscous oil/water emulsions in conventional and "rotary" hydrocyclones using CFD. In the rotary cyclone the cyclone wall was brought to rotate with the fluid. They found that the conventional cyclone was able to separate sand from water, but it could not separate sand from emulsions effectively, the rotary hydrocyclone did this much better. No experimental verification is offered in the paper.

Guo et al. (2006) and Wang et al. (2006) performed a series of experiments to study the dependence of the separation efficiency of a hydrocyclone on the inlet velocity and the oil/water ratio in a series of oil/water emulsions with water volume fractions of 0.4–1.0. They drew a number of conclusions about the influence of the viscosity of the oil/water emulsions, all quite consistent with expectations.

Agar and Herbst (1966) measured hydrocyclone efficiency for containing various concentrations of sucrose, a much-used agent for varying the viscosity of aqueous liquids. Due to the very high concentrations of sucrose also the density of the solutions varied somewhat. They fitted their results to a product-of-powers function to find the empirical relationship:

$$d_{50}=K_1\frac{D^{1.4}}{Q^{0.55}}\frac{\mu^{0.58}}{(\rho_s-\rho_l)^{0.5}} \tag{3}$$

Note that the constant $K_1$ in Eq. (3) is dimensional. $D$ is the cyclone diameter. They thus found that the viscosity should be raised to a power of 0.58 rather than 0.5 to reflect its influence on the cut size accurately.

One application wherein the density and also viscosity of the carrier liquid on hydrocyclone performance is important is classification in so-called dense media hydrocyclones, often used in e.g. the mining industry. Here the carrier "liquid" is a suspension of fine particles, the fine particles having been added to modify the apparent density of the medium to lie between the densities of two material fractions, consisting of larger particles, to be separated in the hydrocyclone. Suresh et al. (2010) have recently published in this area, the group using an experimental rig similar to the one used in this paper (Dwari et al., 2004; Suresh et al., 2010).

As also mentioned in the paper by Kawatra et al. (1996) about the influence of slurry viscosity on the cut size of hydrocyclones, the book reported by Bradley (1965) lists 8 different relations for the cut size in hydrocyclones, mostly empirical or semi-empirical. These relations feature the liquid viscosity to a power between 0.5 and 0.6. Note in passing that the effect of the viscosity of the slurry on the separation of the particles making up the slurry itself is not quite the same problem, since effects such as the so-called "solids loading" effect and hindered settling may come into play.

### 1.2. Effect of viscosity on the pressure drop

The variation of the pressure drop in (hydro)cyclones with the physical parameters is not so simple, and sometimes counter-intuitive. An example is the effect of roughening the cyclone walls. In pipe flow, roughening will lead to an increase in the pressure drop through the pipe. In cyclones, in contrast, the increased transport of momentum-deficit into the separation space due to a roughened wall leads to a less intensive vortex, such that the vortex converts static pressure in the outer part to dynamic pressure in the inner part less efficiently. The dynamic pressure in the inner part of the vortex flowing out of the cyclone is dissipated in the vortex finder (where 9/10 of the loss in total pressure is normally assumed to take place) with only very little recovery of static pressure, and thus the pressure loss is smaller in a cyclone with a less intense vortex. A more complete discussion of these issues is given in Hoffmann and Stein (2008).

Emami et al. (2010) investigated the classification of some organic particles in water and isopropyl alcohol with densities of 998 kg/m$^3$ and 785 kg/m$^3$ and viscosities of 0.00243 Pa s and 0.00099 Pa s, respectively. They operated at like cyclone pressure drop for the two fluids, and found that the flowrate of the isopropyl alcohol was the higher, which would indicate that the pressure drop falls with increasing viscosity.