Chapter

Performance Analysis and Modeling of Microplastic Separation through Hydro Cyclones

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Abstract

The filtering hydro cyclone is a solid–liquid separation device, generally conical in shape. The hydro cyclone allows the separation of microplastics from water, to facilitate micro-recycling. To test the capabilities of a hydro cyclone at separating microplastics from water, Rietema's standard sizes, mathematical and computational fluid dynamics (CFD) modeling were used. The results show that, even dough the mathematical model in unreliable when considering parameters out-side standard operation conditions, hydro cyclone microplastic separation can be achieved at 98% efficiency. Particles reach the outlet on average in 1.5 s for a flow velocity of 2 m/s, and denser microplastics end up in the underflow.

Keywords: hydro cyclone, water treatment, microplastics, filtration, separation

1. Introduction

Plastics are the most used and versatile material of the modern age, and inevitably global production of plastics has increased exponentially to meet demand. Of all the plastics ever produced it is estimated that 10% has been released into the ocean [1]. Furthermore about 33% of the plastic produced every year is designed to be single use and is discarded within a year [2]. Plastic waste has become a major issue in the last century, mostly damaging marine environments, and activists have taken action to neutralize this problem. Although microplastics are yet not considered as threatening as larger plastics, they are growing in importance. It is extremely important that both plastics and microplastics are collected from rivers, oceans and waste waters to be recycled to block the environmental disaster these are causing.

Microplastics are the product of mechanical, chemical and thermal degradation of plastic objects, varying in size between 1 μm and 5 mm [3]. These particles can be found on surface waters and land, and from fresh-water to deep ocean sediments, making them susceptible to environmental factors such as heat, erosion and extreme pressures that may degrade them at rates not yet well established [4]. Through degradation they can assume many different shapes and sizes that fall into the following 5 categories [3] (**Table 1**).

The density of microplastics can vary significantly from (10–2300 kg/m^3). The most common plastics like ABS (1030–1210 kg/m^3), PET (1300–1500 kg/m^3) and

Abbreviation	Type	Definition	Size
PT	Pellet	A small spherical piece of plastic.	2–5 mm [5]
FR	Fragment	An irregular shape piece of plastic.	0.2–5 mm [6]
FB	Fiber	A strand of filament of plastic.	1–5 mm [7]
FI	Film	A thin sheet or membrane piece of plastic.	1–5 mm [3]
FM	Foam	A piece of sponge, foam or foam like plastic.	1–5 mm [3]

Table 1.
5 categories of degradation characteristics for microplastics found in the environment.

PVC (1150–1700 kg/m^3) are all denser than fresh and sea waters (997–1025 kg/m^3), this allows for most of the microplastics present in water to be separated using gravity. Physical and chemical hazards related to ingestion of microplastics across a diverse range sizes and types have generated ecological concerns. Further, the impacts on human health of the chemical exposure to plastic debris from seafood consumption, and toxins that adsorb onto microplastic debris from the surrounding water, are currently unknown.

This paper proposes to use hydro cyclones to separate them from fresh and seawaters. Firstly, the paper briefly summarizes the functioning of hydro cyclones, secondly applies them to the microplastics separation, through mathematical and CFD models. And finally concludes that they could be very effective in separating up to 98% of the microplastics from the water.

2. Hydro cyclones

Cyclones are used in industry as dust separators; they isolate the dust from air using differential centripetal forces generated by fast circular flow in a cylinder that allow the denser material to flow outward and downward, while the lighter material to flow inward and upward. Hydro cyclones work by using the same principles as the normal cyclone. Hydro cyclones have a cylinder-conical shape which have a tangential feed inlet into the upper cylindrical section and two outlets along the axis at the top and bottom. Hydro cyclones operate vertically: the fluid enters horizontally through an inlet, tangential to the cylinder, that creates a circular flow into the cyclone. This, in turn, produces a vortex effect, where the denser particles circulate around the outer edge of the chamber reducing their kinetic energy through friction along the cylinder and cone walls and, thus, sinking downward and leaving through the spigot. The lighter particles, due to the small area of the spigot, are taken into the inner part of the vortex that flows upward exiting at the top of the cyclone. These two downward and upward cyclonic flows are called, respectively, underflow and overflow [8]. The product of the separation is at the underflow where the denser microplastics exit as a slurry (**Figure 1**).

Theoretical Advantages of using hydro cyclones to separate microplastics are [4]:

- Optimum separation characteristics at varying operation parameters.
- Long life time for appropriate material selection for each application.
- Simple operation.
- Modular design through basic connections and adaptors.

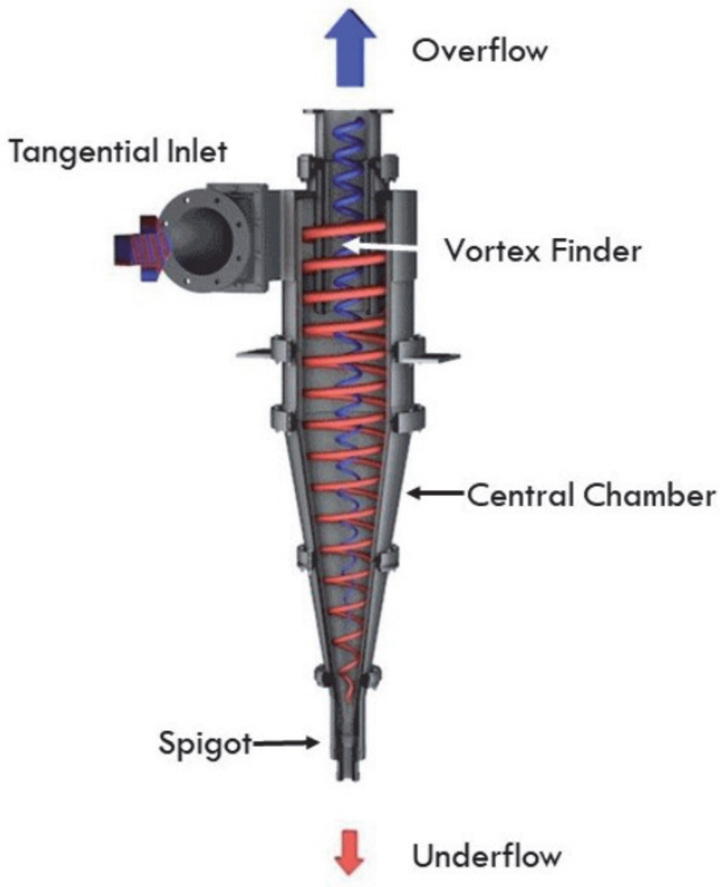

Figure 1.
Diagram of the behavior and characteristics of a hydro cyclone [4].

- Low weight.
- FDA approval.

3. Methodology

Latest investigations classify hydro cyclones based on the particle size of which 50% reports to the overflow and 50% to the underflow, or the so-called $D50_c$ point [9]. All equations used in Sections 3 and 4 have been taken from Richard A. Arterburn et al. [9]. Studies have shown that this classification remains persistent through a range of cyclone diameters and applications. The separation a cyclone can achieve can be approximated using the Eq. (1). The $D50_c$ (base) for a given diameter cyclone is multiplied by a series of correction factors designated by C_1, C_2, and C_3 (Eq. (1)).

$$D50_c(application) = D50_c(base) \times C_1 \times C_2 \times C_3, \tag{1}$$

where $D50_c$ (base) is the micron size that a standard cyclone can achieve under baseline conditions and $D50_c$ (application) is the filtering potential for a particular application.

$$D50_c(base) = 2.84\,xD^{0.66}, \tag{2}$$

where D is the cyclone diameter in centimeters.

The first correlation factor C_1 in Eq. (3) refers to the influence of the concentration of solids contained in the feed. The higher the concentration the coarser the separation. This correlation is a factor of slurry viscosity and particle size and shape. Variables such as liquid viscosity also affect this correlation.

$$C_1 = \left(\frac{(53 - \%_{solids})}{53}\right)^{-1.43}, \quad (3)$$

where $\%_{solids}$ is the percent solid by volume of cyclone feed.

The second correlation C_2 in Eq. (4) is for the influence of pressure drop in the cyclone, measured by taking the difference between feed pressure and overflow pressure. It is recommended that the pressure drop varies between 40 kPa and 70 kPa. This is to limit energy usage as well as equipment wear. As a result, a higher pressure drop would equate in finer separation.

$$C_2 = 3.27 \times \Delta P^{-0.28}, \quad (4)$$

where ΔP is the pressure drop in kPa.

The third correlation C_3 in Eq. (5) corrects the influence of specific gravity on the solids and liquid inside the cyclone. Stoke's law has been used to determine particle diameters which would produce the same terminal settling velocity for a particle of known specific gravity in a liquid.

$$C_3 = \left(\frac{1.65}{(\gamma_s - \gamma_l)}\right)^{0.5}, \quad (5)$$

where γ_s is the specific gravity for solids and γ_l is the specific gravity for liquids.

$D50_c$ (application) may be formulated as the product of the selected minimum size of separation and the associated multiplier for the percentage of solids passing through the overflow (Eq. (6)).

$$D50_c(application) = micronsizexmultiplier, \quad (6)$$

where the multiplier is defined form the **Table 2** below, taken from [9]. The result is that for a identified $D50_c$ (application) micron size, all the particles less than that will go into the overflow and all the particles bigger that that size will discharge to the underflow.

% of solids passing through overflow	Multiplier
98.8	0.54
95	0.73
90	0.91
80	1.25
70	1.67
60	2.08
50	2.78

Table 2.
% of solids passing through overflow and the correspondent multiplier.

Standards	Di/D	Do/D	L/D	Angle
Rietema	0.28	0.34	5.00	20°
Bradley	1/7	1/5	6.8	9°

Table 3.
Rietema and Bradleys standard relations for hydro cyclone dimensions.

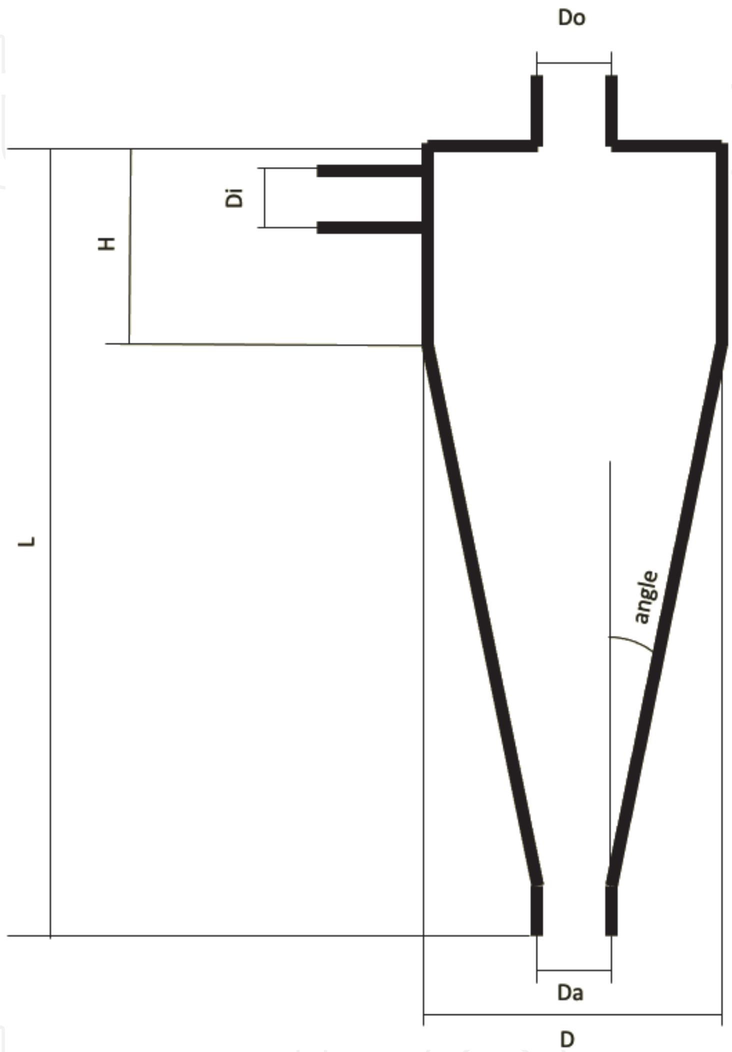

Figure 2.
Hydro cyclone dimension nomenclature and position.

Other cyclone geometric variables such as Di, Do, L and angle, have been found through the standard cyclone dimension relationships of the Rietema and Bradley hydro cyclones [8]. **Table 3** shows the correspondent relations (**Figure 2**).

4. Modeling

In order to create a model of a hydro cyclone that provides an good representation of its behavior and dimensions is critical. The minimum size of microplastics was assumed to be 5 μm; the density of the plastics going inside the hydro cyclone was assumed to be 1500 kg/m^3 (which is the average of densities between the most common plastics and the % that are present in the environment); the % volume of solids (microplastics) in the fluid (water) going inside the hydro cyclone; the pressure drop was considered to be 50 kPa as it is standard for most hydro cyclones;

the % of solids passing through the overflow which relates the multiplier; the Rietema standard cyclone dimension relations where chosen because considered a better fit for the application (**Table 4**).

Initial variables were calculated using the subsequent equations:

$$\rho_{average} = (\rho_{solids} + \rho_{water})/2 = 1248.5\, kg/m^3, \tag{7}$$

$$\gamma_s = \frac{\rho_{solids}}{\rho_{water}} = 1.50, \tag{8}$$

$$\Delta P = P – P_{drop} = 51 kPa, \tag{9}$$

$$D50_c(application) = d_{solids} x Multiplier = 13.9\ \mu m, \tag{10}$$

$$C_1 = \left(\frac{(53–\%_{solids})}{53}\right)^{-1.43} = 1.03, \tag{11}$$

$$C_2 = 3.27 \times \Delta P^{-0.28} = 1.09, \tag{12}$$

$$C_3 = \left(\frac{1.65}{(\gamma_s – \gamma_l)}\right)^{0.5} = 1.81, \tag{13}$$

$$D50_c(base) = \frac{D50_c(application)}{C_1 \times C_2 \times C_3} = 26.60, \tag{14}$$

$$D = \left(\frac{D50_c(base)}{2.84}\right)^{\left(\frac{1}{0.66}\right)} = 29.65\, cm, \tag{15}$$

Using the Rietema relations the rest of the hydro cyclone dimensions can be calculated.

$$Di = D \times 0.28 = 8.30\, cm, \tag{16}$$

$$Do = D \times 0.34 = 10.08\, cm, \tag{17}$$

$$L = D \times 5 = 148.28\, cm, \tag{18}$$

$$Da = Do = 10.08\, cm, \tag{19}$$

The dimensions of the apex diameter (Da) are a result of investigations done by [8]. Which result in Da being the equivalent to Do. This is to optimize the flow in the hydro cyclone.

Name	Value	Unit
D_{solids}	5	μm
ρ_{solids}	1500	kg/m^3
$\%_{solids}$	1	%
$\%_{overflow}$	50	%
ρ_{water}	997	kg/m^3
P	101	kPa
P_{drop}	50	kPa
Multiplier	2.78	—
γ_l	1	—

Table 4.
First set of variables for average conditions for microplastic separation.

Name	Value	Equation
C_1	1.348	(11)
C_2	1.087	(12)
C_3	2.846	(13)
$D50_c$ (base)	31.91	(14)
D	39.07	(15)
Di	10.94	(16)
Do	13.28	(17)
L	195.3	(18)
Da	13.28	(19)

Table 5.
Results for particle density 1200 kg/m³.

If the density of plastics going into the hydro cyclone is assumed to be 1200 kg/m^3 (which is the average of densities between the most common plastics between 900 kg/m^3 and 1400 kg/m^3), to achieve the same performance as in the 1500 kg/m^3 case, the dimensions of the hydro cyclone would have to increase as it would take longer to separate the particles. The results are shown in **Table 5**. These show an increase in size for the diameter (D) of 50% and of 30% for the length (L). Although this may seem like a large increase the design can still be manufactured, as the dimensions are relatively similar.

5. Computational fluid dynamics

The CFD simulation was made for the purpose of understanding if the separation of microplastics could be achieved with a hydro cyclone, and in how much time this separation would happen.

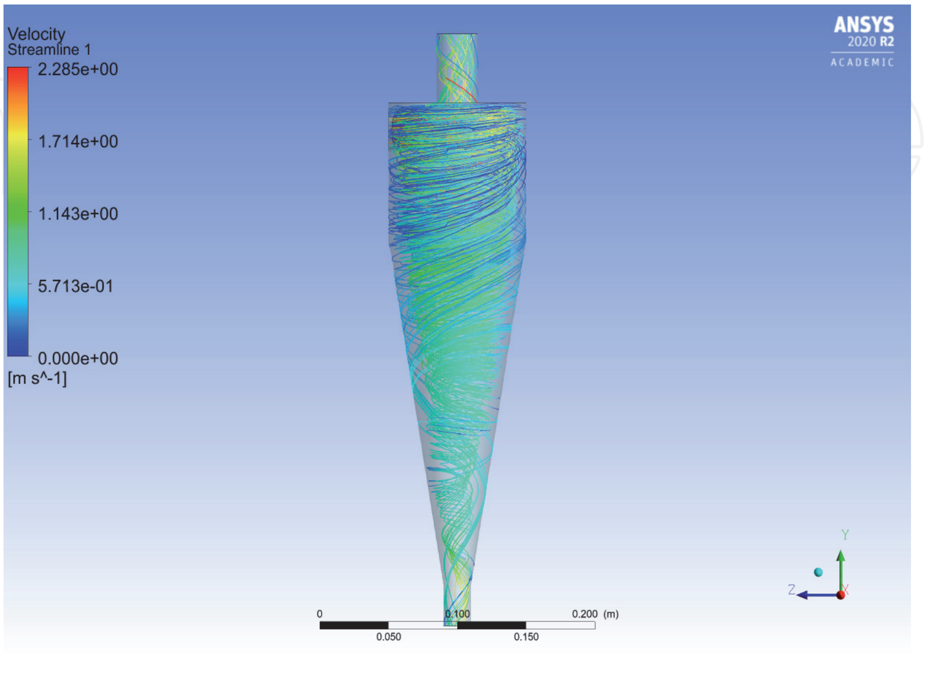

Figure 3.
Water flow simulation in a hydro cyclone through time.

Analysis though CFD was conducted assuming the dimensions indicated in the modeling section. Using Ansys Fluent software.

The CFD simulation was made for the purpose of understanding if the separation of microplastics could be achieved with a hydro cyclone, and in how much time the separation would happen. **Figure 3** illustrates the flow of water inside the hydro cyclone. It can be observe that both underflow and overflow collect water but that most of that exits through the overflow. Also visible is the inner vortex that forms because of the pressure difference.

Figure 4 shows the velocity inside the centre plane of the hydro cyclone. The big red spot on the top left is the velocity at inlet. The two outlets have increased velocities because of the pressure difference. Finally the inner part of the hydro

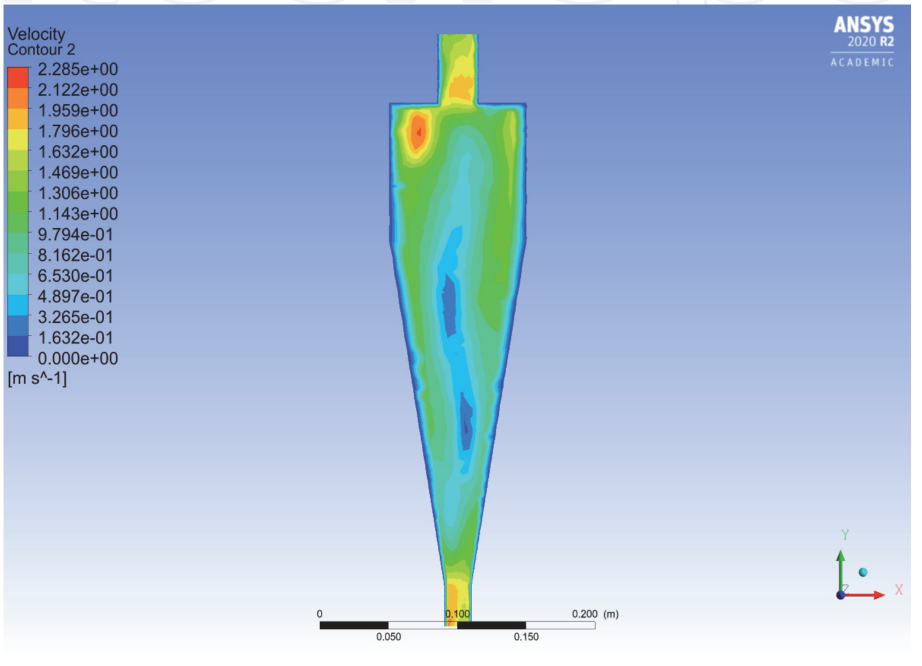

Figure 4.
Velocity gradient for water flow in a hydro cyclone.

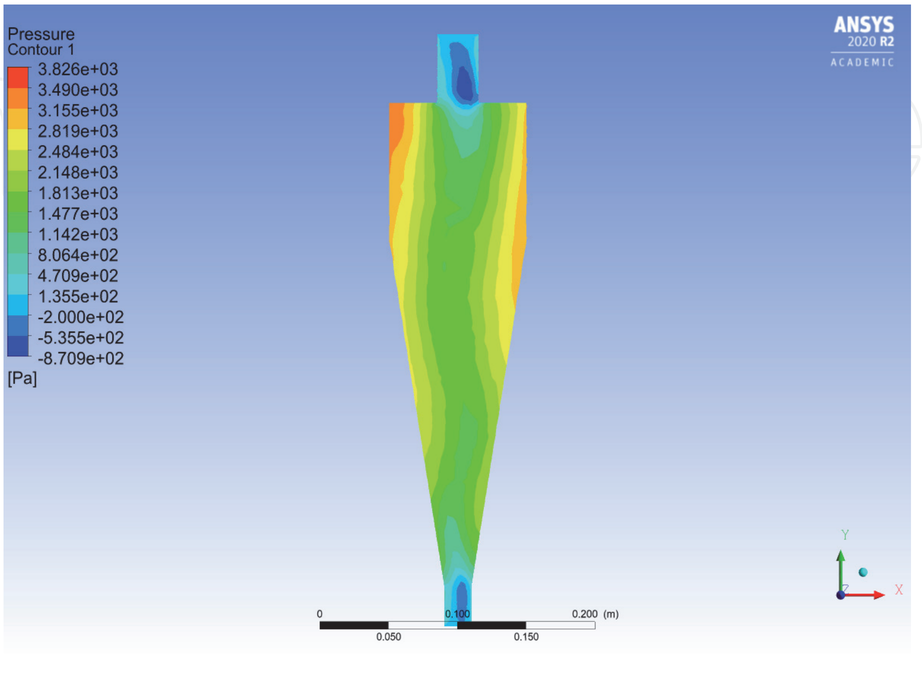

Figure 5.
Pressure gradient for water flow in a hydro cyclone.

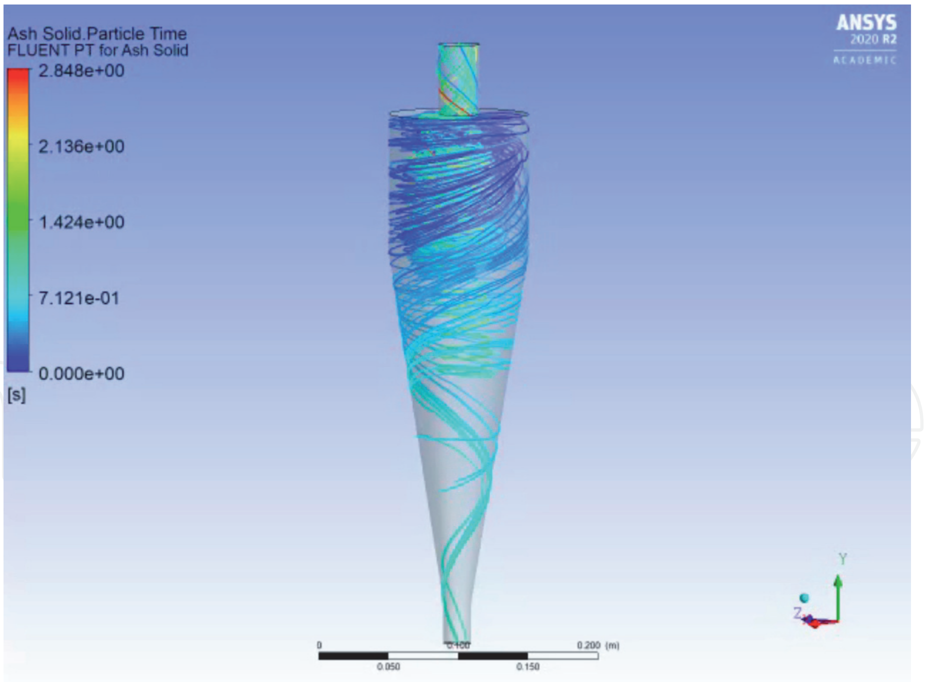

Figure 6.
Particle flow simulation in a hydro cyclone through time.

cyclone is under very low velocities because that is where the inner vortex flows and the velocities at the centre of it are close to 0 m/s.

Figure 5 shows the pressure inside the hydro cyclone and the difference that is created by the two outputs, where the pressure is negative.

Finally microplastic particles of the same physical characteristics where inserted inside a flow of water. **Figure 6** shows the result of this study where less denser plastics exit through the overflow and plastics that have greater density flow through the underflow. On average for a flow of 2 m/s a particle takes 1.5 s to reach any two of the outlets.

From CFD it can be seen that there is a lot of turbulence created near the inlet, where fluid coming inside disrupts the overflow vortex. To counteract this problem the design of the hydro cyclone would have to change to implement a sleave design for the overflow so that the inlet flow does not interact with the inner vortex.

6. Model results

Further studies were made to understand the behavior of some parameters used in the mathematical modeling using Rietema's correlations. The influence of particle dimensions was studied to see the impact on the cyclone diameter (D). **Figure 7** shows this relationship, and it can be deduced that the curve is close to exponential. This means that for particles smaller than 1 μm, the dimensions of the cyclone would be too small to be effective. If the minimum particle size is above 10 μm cyclone dimensions become exponentially bigger, which result in extremely big diameter (D) values. The problem is that Rietema's model used to produce the dimensions is not consistent for larger particle dimensions.

The second study related the % of solids inside the fluid, with the cyclone diameter (D) (**Figure 8**). The relation is linear for values of % solids between 1% and 21% and the change in diameter decreases as the particles increase.

The third study compered the solids density inside the fluid (Graph 3). The result, shown in **Figure 9**, conclude that for densities less then 1100 kg/m^3, the

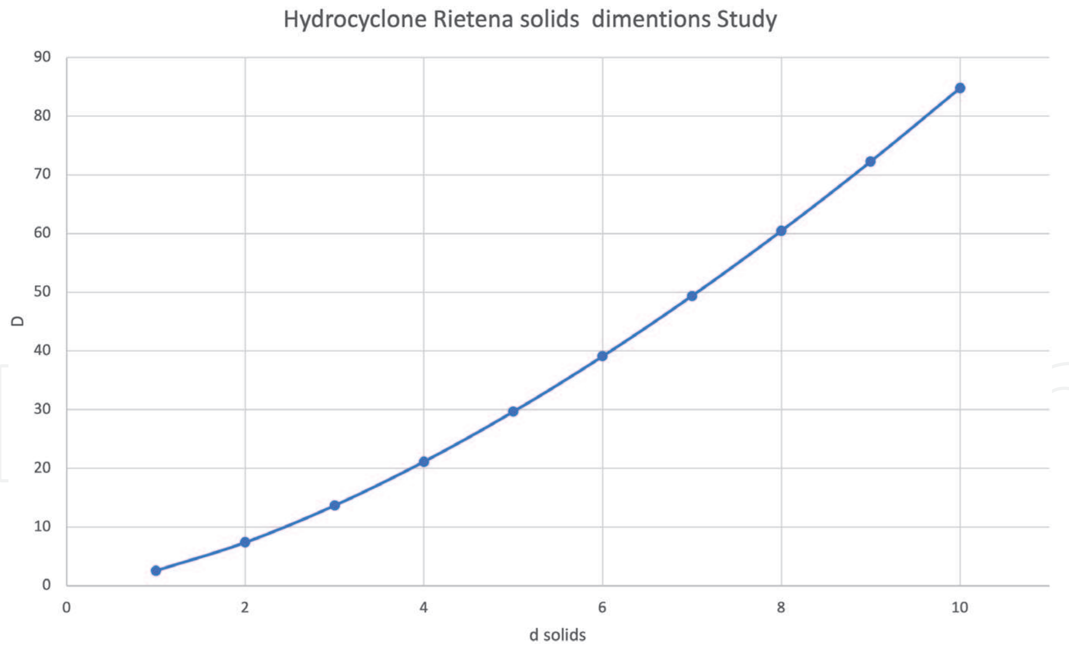

Figure 7.
Hydro cyclone Rietema model, solids dimensions study.

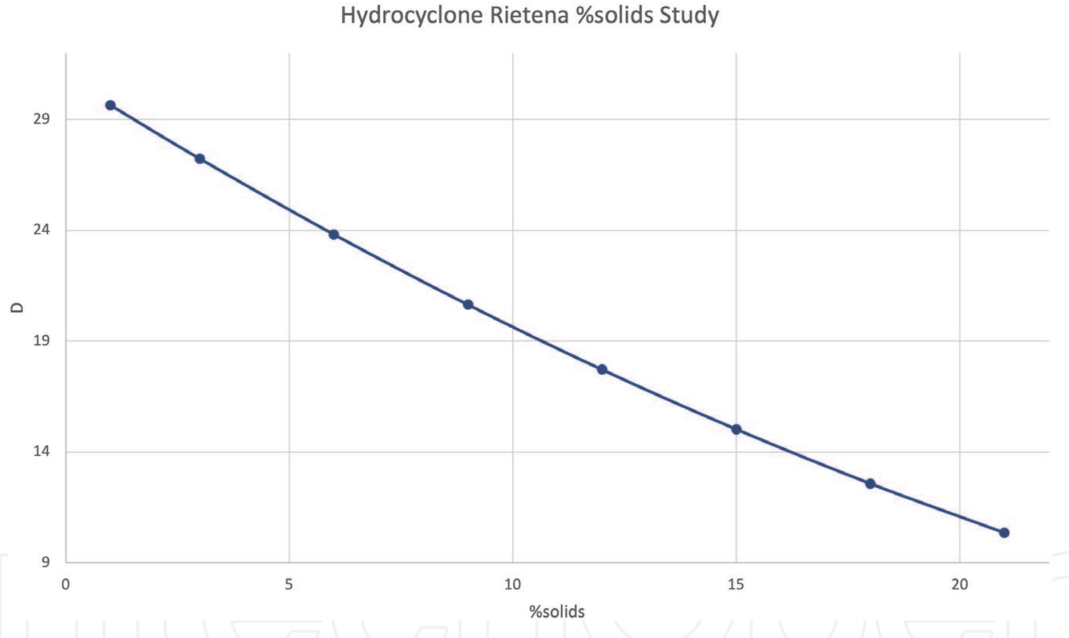

Figure 8.
Hydro cyclone Rietema model, %solids study.

dimension of the diameter (D) become unreliable. For bigger densities the diameter slightly decreases but the variation will become close to none. It can be seen that already from densities of 1200 kg/m^3 the model starts to get defective.

7. Conclusions

The results obtained through analysis and modeling of microplastic filtering hydro cyclones, under standard operational conditions, allow the following conclusions to be drawn.

Rietema's model offers the most consistent results throughout various tests, although becoming unreliable for values that exceed standard conditions. CFD

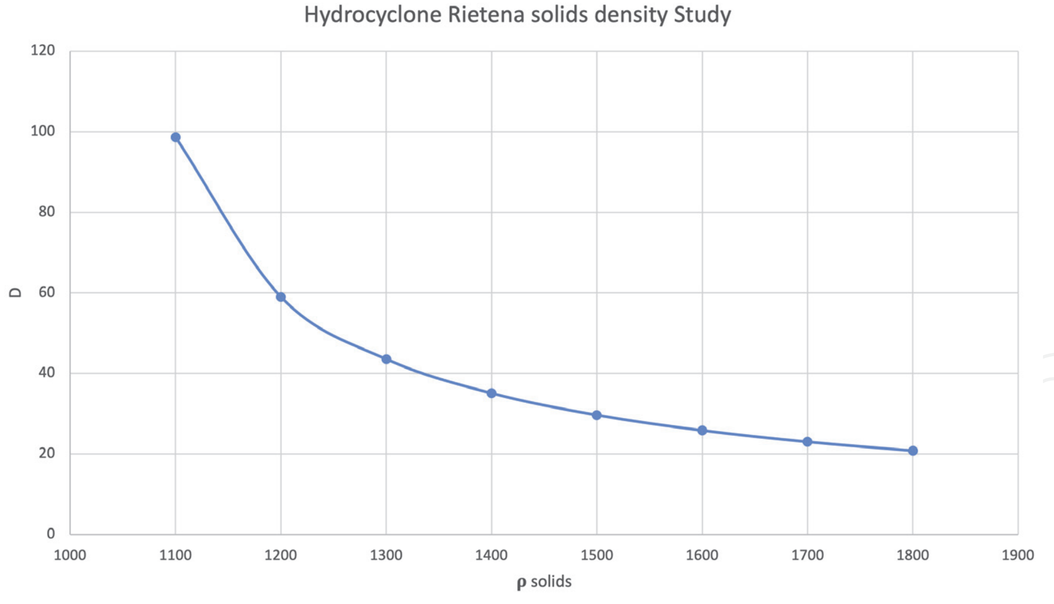

Figure 9.
Hydro cyclone Rietema model, particle density study.

models show that the correct design and dimensioning of the hydro cyclone can separate the flow consistently at a rate of 50% underflow and 50% overflow and the that on average particles take 1.5 s to reach any of the two outlets. The denser microplastics separate before and these reach the underflow in the least amount of time. Particles that reach instead the overflow could be captured by another hydro cyclone to be separated to a greater precision.

Future development could introduce an experimental apparatus to test the theories proposed in this paper. Implementation of this technology could be very useful in cleaning rivers and surface sea water from microplastics and other pollutants without damaging the aquatic flora and fauna. Hydro cyclones could be also mounted on water engine cooling and ballast water tank systems on cargo ships to purify water and prevent corrosion.

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Nomenclature

angle	Cyclone cone angle	°
C_1	First correlation	-
C_2	Second correlation	-
C_3	Third correlation	-
D	Upper cyclone diameter	cm
Da	Diameter of underflow	cm
Di	Diameter of inlet	cm
Do	Diameter of overflow	cm
$D50_c(application)$	Filtering potential for application	-
$D50_c(base)$	Minimum size of particles	μm

d_{solids}	Dimension of solid particles	kg/m^3
$Multiplier$	50 % separation multiplier	-
L	Hydro cyclone height	cm
P	Inlet pressure	kPa
P_{drop}	Pressure drop inside the cyclone	kPa
$\rho_{average}$	Average density	kg/m^3
ρ_{solids}	Particles density	kg/m^3
ρ_{water}	Water density	kg/m^3
γ_s	Specific weight of particles	-
γ_l	Specific weight of liquid	-
ΔP	Difference in pressure inside the cyclone	kPa
$\%_{solids}$	Percent of solid particles inside the fluid	%

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