Proposing the most efficient and environmental safe hydrocyclone to depurate ballast water from ship hulls
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A proposal to select the most efficient and environmentally safe hydrocyclone to treat ballast water from ship hulls

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Abstract

Nowadays seas and oceans are exposed to serious threats such as land-based sources of marine pollution, the overexploitation of living marine resources, the physical alteration or destruction of the marine habitat and the horizontal transfer of marine species to new environments in ballast water. When marine species are introduced into new environments and the living conditions there are favorable to their reproduction, they may compete with native species and have economic and/or ecological impacts on the host environments and eventually cause severe human health problems. In order to prevent this kind of pollution, new maritime regulations have been introduced (Gollasch et al., 2007) which consist of a primary treatment to eliminate suspended solids and a secondary treatment to exterminate microorganisms.

The ballast water problem is caused by the introduction of invasive marine species into new environments by a ships' ballast water. A combination of methodologies including mass balance, granulometric analysis and Life Cycle Analysis (LCA) is applied here to optimize (in terms of environmental sustainability) the system for treating ballast water. The purpose of this system is to minimize maritime pollution so that the direct environmental impact is very low or even positive.

Keywords: Ballast Water Depuration, SL Separation, Hydrocyclones, Life Cycle Assesment

1. Introduction

Interest in ballast water treatment has arisen due to the dramatic ecological and economic impact caused by the introduction of species into new environments (nonindigenous organisms). The potential of ballast as a microorganisms transport vector lies in the fact that sediments and water can contain an assortment of metazoans and microorganisms that, thanks to global transport, may become invasive in new environments (Gollasch et al., 2007). Sediment accumulation in ships' holds can be appreciable, depending on the time that has elapsed since the ship was last dry-docked (Drake et al., .2007).

Hydrocyclones are inert devices that allow the separation or concentration of macrofluids as suspensions because of the difference between the inert forces that govern the movement of suspended solids in a liquid bulk. Unlike centrifuges, which use the same separation principle, hydrocyclones possess a number of advantages [Martínez et al., 2007a] such as the absence of moving parts, a high capacity, low maintenance requirements, low energy consumption and a short residence time. Due to these advantages they are ideal for application in a ship.

Life Cycle Assessment involves an analysis of the product from the stage of raw material recently extracted from the earth to the stage where the materials are newly disposed of. This is the so-called “cradle-to-grave” approach where the stages of manufacture, use and final disposal are analysed. The term “life cycle” implies that, for each operation, the inputs in terms of raw materials, resources and energy, and outputs in terms of emission to the air, water and solid waste, are calculated and then introduced into overall mass and energy balances (Arena et al., 2003).

This work is focused on primary treatment based on the removal of suspended solids by hydrocyclones. It highlights how the combination of conventional analytical techniques (mass balance, granulometric analysis) combined with Life Cycle Assessment (LCA) could provide a method for estimating the most environmentally friendly hydrocyclone.

2. Experimental set-up

Three hydrocyclone sizes (5, 10 and 18 cm internal diameter) were used to carry out the experiments described here and to compare the data (see Figure 1). They were designed according to the Rietema criterion (Castilho and Medronho, 2000). A scheme of the experimental apparatus is shown in Figure 1. This consists of a tank provided with a stirrer which is used to maintain the particles in suspension. The closed -circuit mode of operation means that the discharged underflow and overflow are returned to the feed tank, thereby maintaining the concentration at a constant value. Water is fed in at room temperature (15º C) by means of a 3 kW P050/30T centrifugal pump. It then passes through a by-pass that regulates the flow. The flow rate is controlled by a Khrone Aquaflux 090 K/D DN40 PN 40 electromagnetic meter. A set of three valves allows each single hydrocyclone to operate separately from the others in all the experiments.

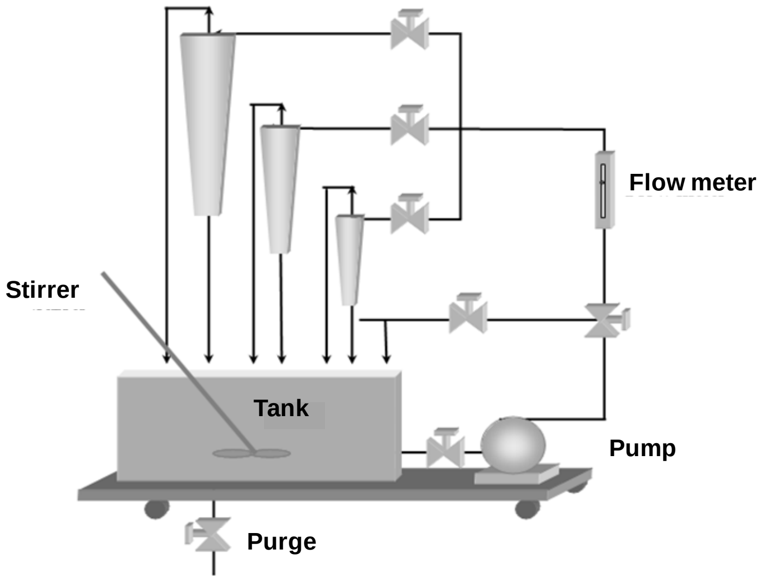
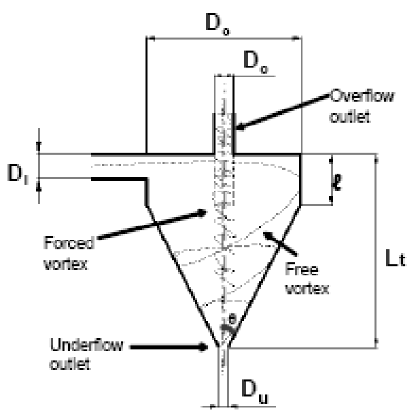


Figure 1. Experimental set-up

The morphology and dimensions of the hydrocyclones used is illustrated in Figure 2.



D_c	D_i	D_o	ℓ	D_u	$L_t - \ell$	θ
5 cm	1.4	1.7	4	1	21	11.4°
10 cm	2.9	3.4	8	2	42	11.4°
18 cm	5.4	6	12	3	63	16.3°
			30			
			42			
			60			

Figure 2. Hydrocyclone dimensions

3. Material and Methods

The feed sample was taken directly from the tank. Overflow and underflow samples were taken from the tank return lines. A granulometric analysis was carried out and the suspended solids (SS) concentration was measured for all the samples.

The mass of suspended solids was measured after a known volume was dried (at 105 C for a minimum of 6 h) and weighed by difference. The suspended solids tested were composed of $CaCO_3$. Particle size distribution (by volume percentage) was measured by using a laser granulometer MALVERN MASTERSIZER QS (small volume sample dispersion unit).

A Life Cycle Assessment was carried out to assess the damage caused to the environment at the different stages of the life cycle of the hydrocyclone. For this purpose SimaPro 6.0 software was used.

4. Results and discussion

In order to test the performance of the hydrocyclone, different combinations of operating parameters and geometrical characteristics were tried.

4.1. Selection of Hydrocyclone size

The most efficient and environmentally friendly hydrocyclone of those proposed in this study was selected by an efficiency calculation obtained from a mass balance study for different flow rates. The maximum efficiency was obtained at the maximum flow rate at which each hydrocyclone works.

The smallest hydrocyclone (5 cm internal diameter hydrocyclone) showed the highest efficiency. Because this value differs only slightly from the value of efficiency obtained for the 10 cm diameter hydrocyclone (see
Table 1), a LCA analysis is the perfect tool for choosing the most efficient as well as the most environmentally friendly hydrocyclone (Azapagic A., 1999).

LCA may assist both in defining the problem and in assessing the alternatives (Tillman, 2007; Basson and Petrie, 2007). This study is focused on choosing between three hydrocyclones in terms of efficiency and environmental sustainability. As pointed out above, the efficiency analysis does not distinguish between the 5 and the 10 cm hydrocyclone. Therefore a LCA analysis was performed to obtain some kind of evidence in favour of one of the other. In order to carry out the LCA analysis, three different impact categories were chosen: ecosystem quality, human health and sustainability of resources (Björn et al., 2006).

Table 1. Efficiency calculation for the maximum flow in each hydrocyclone size

Size (flow)	**Average Efficiency (%)**
5 cm (Q=3.5 m^3/h)	34
10 cm (Q=9 m^3/h)	33
18 cm (Q=23 m^3/h)	29

The results obtained by the LCA analysis, showed the same trend regardless of the impact parameter chosen (ecosystem quality, human health, resources). The ecosystem quality parameter is chosen (see Figure 3) for different operating conditions in order to study the influence of hydrocyclone size on the environment. It must be pointed out that for a given tank size to deballast in a fixed time (12 h of deballasting) different numbers of hydrocyclones are necessary. Because of this, deciding which hydrocyclone geometry should be used depends on the operating conditions, the *limiting* factors being material quantity and energy requirement.

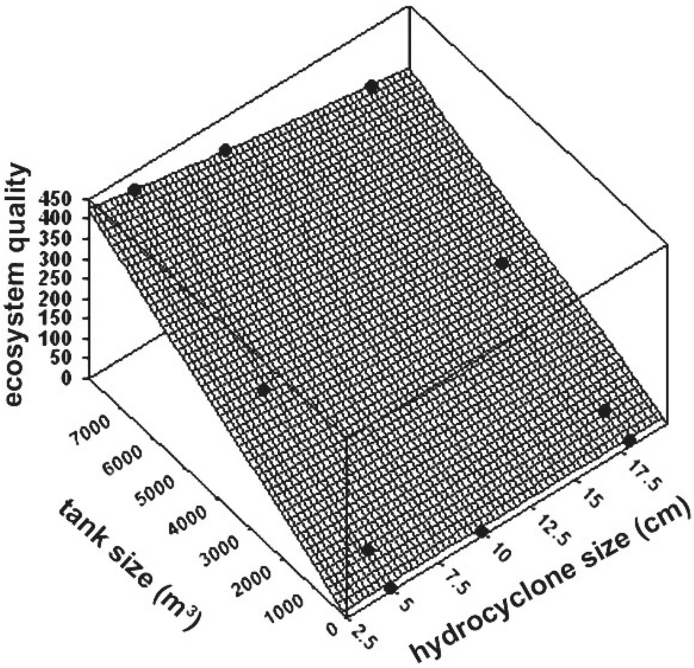


Figure 3. Comparison of the damage to Ecosystem Quality for the different sizes of hydrocyclone used to treat a small volume of ballast water

If the results obtained by the LCA analysis are multipled by the inverse of the results obtained from the efficiency analysis (see Figure 4), the 10 cm diameter hydrocyclone appears to be the most suitable (lowest values).

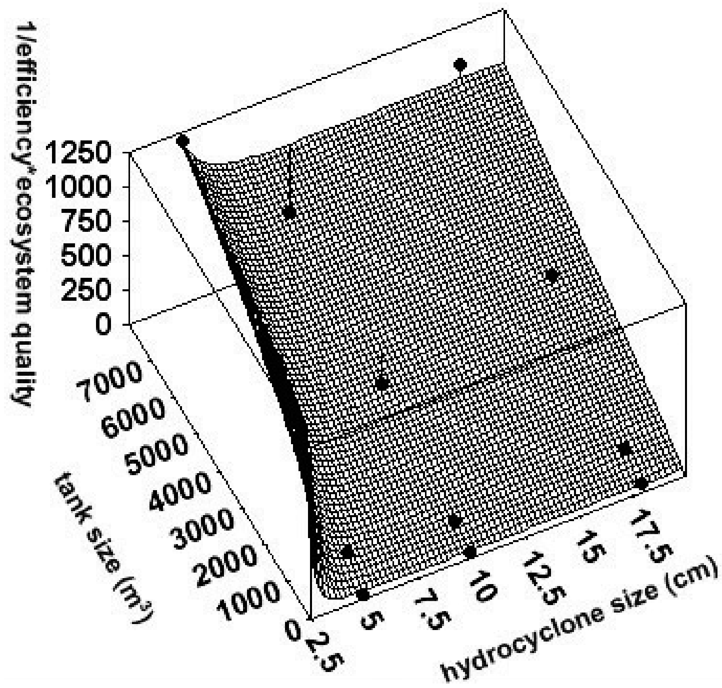


Figure 4. Combination of efficiency analysis and LCA methodology

4.2. Selection of the Vortex-finder length

Once the hydrocyclone size has been established its geometrical characteristics must be chosen in order to optimize the depuration process. One of the most important geometrical characteristics is the vortex-finder length /total hydrocyclone length ratio (Wang and Yu, 2007), as this parameter severely affects separation efficiency (Martínez et al., 2007b).

The insertion of the vortex-finder attempts to avoid the re-entrainment of particles in the overflow stream (Bradley, 1965). This step avoids a "short-circuit" occurring at the top of the hydrocyclone, close to the feed inlet and the overflow upper exit (Figure 5). Thanks to the vortex-finder, the particles are made to flow downwards guided by the outside wall. By increasing the vortex-finder length, more time is given for particle re-entrainment in the underflow stream and this, in turn, increases separation efficiency. Nonetheless, if the vortex-finder tip reaches the conical zone, some coarse particles may reach the return overflow stream instead of exiting through the apex, thereby causing a decrease in efficiency. Optimum length depends on the feed particle size and distribution. This should be determined preferably by experimentation.

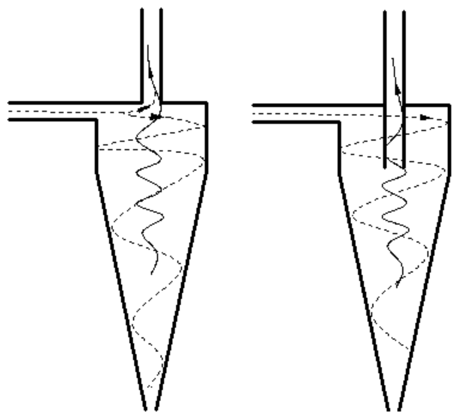


Figure 5. Elimination of a short-circuit by means of a vortex-finder.

Without the vortex-finder, the “short-circuit” generated in the upper part of the hydrocyclone impedes a clear separation. Similarly, when the depth of the vortex-finder is excessive, a substantial decrease in efficiency may be observed due to the swirls generated in the bottom of the hydrocyclone. The least efficient conditions occur when the vortex-finder depth is near to the junction between the cylindrical and the conical section due to the synergy of two phenomena: the change in trajectory from entering the conical part and the turbulence associated with the vortex-finder itself.

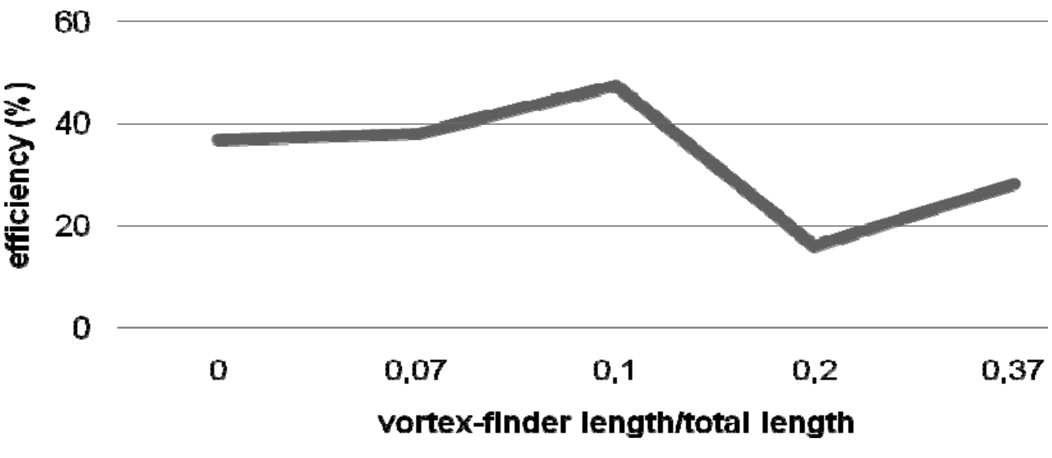


Figure 6. Efficiency vs. Vortex-finder length for the selected hydrocyclone (10 cm diameter)

Figure 6 describes the variation in efficiency for different vortex-finder length ratios. The most efficient vortex-finder length ratio occurs at about 0.1, the least efficient occurring at around 0.2 (junction between the conical and cylindrical regions), where heavy turbulences are generated due to the change in trajectory.

This result agrees with those obtained from a granulometric analysis, where, as Figure 7 shows, the highest particle recovery in the underflow is obtained for a vortex-finder length ratio of 0.1.

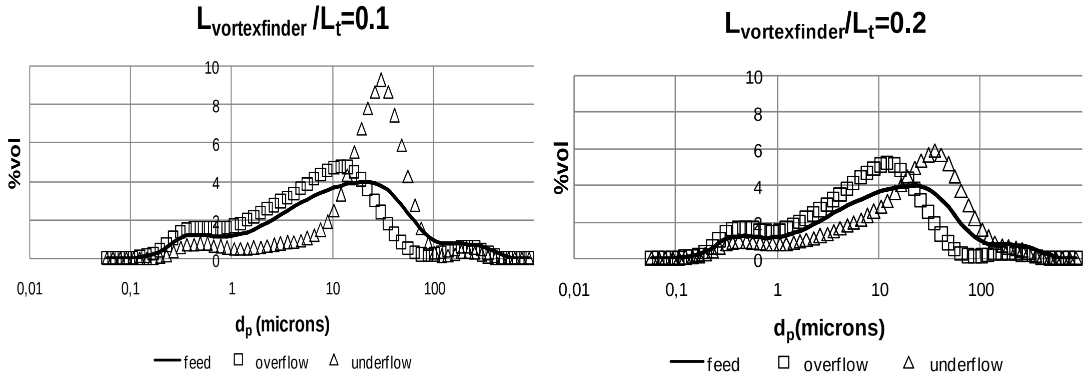


Figure 7. Granulometric analysis for the most and least efficient configurations for the 10 cm diameter hydrocyclone.

5. Conclusions

The following conclusions can be drawn from this study:

- Efficiency increases as the size of the hydrocyclone decreases and as the flow increases.
- A combination of the efficiency study and Life Cycle Analysis shows that the 10 cm diameter hydrocyclone is more suitable for carrying out ballast water disinfection in the range of operational conditions selected.
- Hydrocyclone efficiency vs. Vortex-finder length shows the same trend for the three hydrocyclones selected.
- The most efficient vortex-finder/total length ratio obtained from the efficiency calculation and granulometric analysis is around 0.1.

Acknowledgments

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