Design Life Cycle of a 3-D Printed Hydrocyclone

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Abstract
In mineral processing solid-fluid mixtures are separated in various ways. Of these, hydrocyclones are found to be a simple and low cost technique for particle separation. Additive Manufacturing (AM) technology has the potential to improve the design and testing process for hydrocyclones. The aim of this study is to evaluate the effectiveness of using AM and surface treatments to optimise hydrocyclone design. The hydrocyclone used in these experiments is based on a commercial model used in practice. The hydrocyclone was manufactured with a common plastic material (ABS^+) and was fabricated by use a Rapid Prototyping Additive Manufacturing (RPAM) technique. This paper describes the 3-D design printing (3DDP) and manufacture of a hydrocyclone design based on a commercial design using RPAM and a surface protection process. Based on the results of this study, this process has the potential to reduce development time and cost to produce an optimal hydrocyclone design iteration.

Keywords
Additive Manufacturing, 3-D printing, Particle separation

1 INTRODUCTION

In the beverage, chemical, pharmaceutical, water treatment and mining industries separation of particles suspended in liquids has always been a major task [1,2,3]. Many devices have been developed for this purpose. Included in this area are filters – both active and passive – screens and classifiers [4]. Among the group generally called classifiers, hydrocyclones have been developed as they are known to be simple mechanical devices with low costs (both in production, usage and maintenance) used specifically in particle separation driven by size and density differences. They have in the past been made of plastics, metals, ceramics and even glass.

A typical hydrocyclone is shown in Figure 1. Despite the above-mentioned advantages, there are still substantial challenges in the development of new hydrocyclones. The ability to design a specific hydrocyclone is limited due to the complexity related to the nature of the linkage between the hydrocyclone separation efficiency and its energy related performance.

Since the development of the first hydrocyclones (more than a hundred years ago), several researchers have worked on improving the efficiency of separation in the hydrocyclones. These researchers [2,5,6,7,8,9,10] have contributed – albeit it in a somewhat haphazard manner – both by improving or modifying the basic design. This has been most obvious in the investigation of parameters that affect the separation efficiency according to a variety of theories [2,7].

Due to the material cost and manufacturing time related to hydrocyclone design changes, research into the effect of geometric, physical, operating and dimensionless parameters on hydrocyclones performance and efficiency has been limited to scale model tests of the final designs. It is postulated that the separation efficiency could also be affected by the hydrocyclone manufacturing process. In fact, AM technology may have the potential to improve the design and testing process for hydrocyclones more radically than for other products.

In this also, surface engineering treatments can minimize wear and extend the component life. In addition, surface finish may be a critical parameter

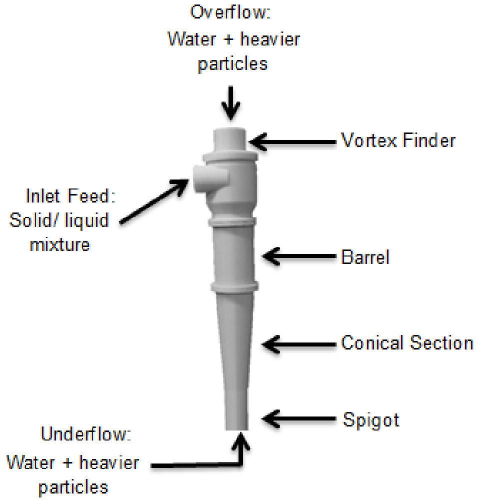


Figure 1 - 3-D Printed Typical Hydrocyclone

determining the practical performance life of the hydrocyclone. However, the effects of wear, especially on the inside wall of a hydrocyclone produced by AM has not yet been investigated. The aim of this paper is to evaluate the effectiveness of using AM and surface treatments to optimise hydrocyclone designs. The 3-D half scale hydrocyclone used in these experiments is based on a commercial model used in practice. The hydrocyclone was manufactured with a common plastic Acrylonitrile Butadiene Styrene (ABS^+) and was fabricated by use of a Rapid Prototyping Additive Manufacturing (RPAM) technique. Advantages of the RPAM are the rapid production, the relatively low cost and the ability to interactively address design changes in a short time. This paper describes the 3-D design and manufacture of an innovative hydrocyclone design based on a commercial design using RPAM and a surface protection process. This paper shows the analysis of the effect of using a 3-D printed hydrocyclone, for testing a hydrocyclone design, as opposed to the conventional design testing process for hydrocyclones with the aim to reduce development time and cost to produce an optimal hydrocyclone design iteration.

2 LITERATURE REVIEW

2.1 Design processes

Design processes have been studied for more than a century and have culminated in the classical work of Pugh [11]. Implicit in most such texts and research articles is that the design, evaluate paper design, prototype, evaluate prototype, make revisions process is expensive and of long duration.

Hague et al. [12] however, has the conception that integrating prototype production into the design phase itself started to be developed. They restricted their interest to impacts on the reduction of a complex assembly into a single complex object. This is in itself a radical notion for the period since they correctly understood that pre-AM era concepts around design from components upwards was now no longer a restriction.

2.2 Hydrocyclone design

Optimization is an advantageous method used to improve the design of a specific engineering device. The optimization of hydrocyclone design can lead to a decrease in the energy usage and maintenance in mineral processing industries. Many tools have been designed for the purpose of design optimisation. These tools consist of numerical simulation and experimental work. One of the tools used to simulate the flow within the hydrocyclone is computational fluid dynamics (CFD) [5,6,7,8,13,14,15].

Slack et al. [16], designed an automated process for CFD modelling of hydrocyclones. They have found that this method is not trivial. Even though CFD is time consuming (both computationally and physically) and expensive, many industries are still reliant on it to understand the complex fluid flow in hydrocyclones.

The most popular CFD models used to simulate the turbulent and multiphase flow (water-air-particles) in hydrocyclone are compared by Delgadillo et al [13]. They found that Large Eddy Simulations (LES) gives more accurate results than the Reynolds Stress (RSM) and renormalization Group (RNG) K-ε models. However, they did not validate the CFD results obtained. Hence, the design was not completely optimized. Another method called Lattice Boltzmann Method (LBM) used to simulate the flow in hydrocyclones was investigated by Bhamjee et al. [17]. They found that LBM could predict lower velocities than the Navier-Stokes model at a certain area; nevertheless, both models are in agreement. However, the low pressure values are not observed in the air core region. A review on hydrocyclone modelling for performance prediction can be found in [9].

Regarding these works an optimal hydrocyclone design cannot be fully optimised since the simulation results alone are not sufficient. They need to be validated using mathematical algorithms [18,19], or empirical formulae obtained via an experimental work [14,19]. The main factors that defined the optimal hydrocyclone design are performance (defined by the pressure drop) and separation efficiency [20]. For a (or many) given parameter(s) (geometrical or physical), the design is optimized on these two factors, tested and then validated. In general, the parameters are modified, simulated and tested. The cycle iterates until an optimal design is obtained. A schematic of the design optimization process is shown in Figure 2.

2.3 Rapid manufacture and design

The integration of design and prototype generation using a variety of RPAM techniques is well described in amongst others [12]. What is however not always clear is that the serious change to the whole design process that flows the ability to verify simple geometric questions, more complicated assembly issues and overall design issues by considering the printed design object.

Here we however, in Figure 2., wish to highlight the ability to further improve the design process's impact on the final design by the very tight integration of the physical object, the virtual object, the analysis using tools such as CFD and the rapid manufacture resulting in detail items.

It is in the confluence of advanced analytical tools (such as CFD) and rapid prototyping that the optimization of a product can proceed smoothly and in an organized and engineering sense.

2.4 Hydrocyclone performance

Generally, hydrocyclones performance and efficiency are studied from particle separation and fluid flow aspects. They can be affected by many variables: geometrical, physical and dimensionless, also by some variable related to the manufacturing process aspect.

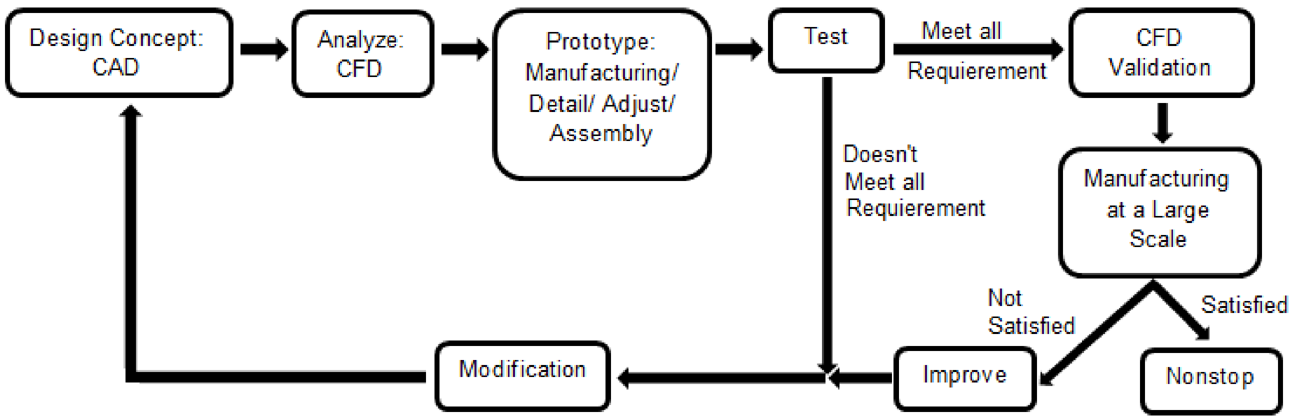


Figure 2 - Diagram of Design optimization of Hydrocyclones in Industries

Halls et al **[21]** have done an experimental study of particle separation using four cylindrical shaped micro-hydrocyclones (1 mm and 5 mm). These hydrocyclones were fabricated using micro-end milling and 3-D printing processes. The aim of her work was to compare the separation efficiency for both design processes used to fabricate the hydrocyclones. Unfortunately, the experimental works was only done for the 5 mm micro-milling hydrocyclone.

The study on the effect of surface roughness on the flow field of cyclone performance has been investigated by Kaya et al [22]. They have used experimental data and a mathematical model to validate the CFD simulations. They found that surface roughness due to corrosion and wear in the inner wall increases with a decrease of separation efficiency and performance of the cyclone. Unfortunately, this has not received much discussion for hydrocyclones. Since the surface roughness of a component depends on the material and/or manufacturing process used to fabricate it, then the material can have an effect on the total efficiency of separation.

3 DESIGN, ANALYSIS AND PROCESS

3.1 Why design changes and optimization

The normal procedure to design an engineering component requires a process not unlike Figure 2. However, from a realistic experience, the concept designs and assembly time is relatively shorter than the time to analyse the design. The design is optimized as described in section 2.2. But due to the complexity of the flow within the hydrocyclone, the turbulent and multiphase models used to simulate the flow require a large memory space. Therefore, the physical (real world) time is also long. By also taking into account the failures, discrepancies and corrections in the design modelling, meshing, solution set-up and calculations, the time to analyse is even longer. We can believe that it is possible to reduce the total design time and cost by skipping the numerical analysis of the model.

In most industries, metal hydrocyclones are used for testing– even if they are then mass produced using other materials. They are made through traditional manufacturing techniques such as casting, moulding, machining, forming or milling [23]. However, this method presents many constraints: the material, machining and tooling equipment costs are high [24]. Thus, the production, testing and manufacturing time can be very costly and time-consuming. All these reasons encouraged us to come up with the alternative method to produce a novel hydrocyclone prototype with the available AM technology: 3-dimensional design printing (3DDP).

3.2 3D Design / Print and Manufacture processes

3DDP is an energy efficient, environmental friendly AM technique in which parts are made by adding layers of material layer-by-layer at a very small scale [25]. It finds its applications in industries such as food and beverages, aerospace, medical, fashion, architecture and sculptures [24]. Among the benefits this technology presents, the greater are that 3DDP is a tool-less process which decreases excessive material cost and printing time [24,26]. The advantage of printing a component piece by piece in detail is that, if a part is broken or doesn't meet the requirement, it can be reprinted without the whole component being modified. 3DDP can be used by individuals at home or by big companies and 90% of the material is used during the process [23,26].

The process used to print the ABS+ hydrocyclone was Fused Deposition Modelling (FDM) [23,24]. It consists of extruding and heating the thermoplastic (ABS+) and any support material through a heated extruder layer-by-layer onto a build platform. A schematic of the 3DDP process for the hydrocyclone is given in Figure 3.

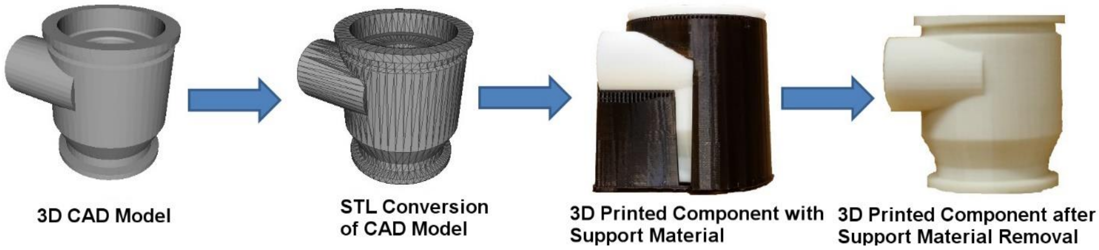


Figure 3 - 3-D printing process: From CAD model (left) to printed component (right)

The results obtained, in terms of development time, testing time and cost, will be compared with those of the conventional metal hydrocyclone.

4 EXPERIMENTAL SET-UP

In the set-up represented in Figure 4, for each test the sump was initially filled with water and all valves were opened except the hydrocyclone inlet line. The pump was primed and switched on and all the liquid was allowed to flow from the sump to the bypass line. This was done in the purpose of releasing the high pressure and eliminating the air bubbles in the water.

Thereafter, silicate powder of density 2650 kg/m^3 was introduced into the sump, and agitated via the bypass system. During the experimental runs, the inlet, underflow and overflow flow rates were collected and measured for a certain time using the gravimetric method.

5 RESULTS

The design related results obtained from the testing are presented in Figure 5. The effect of particulate feed concentration on the pressure drop and the separation efficiency is seen in Figure 5.

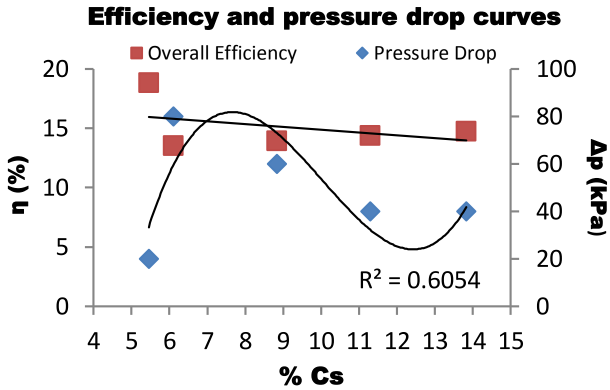
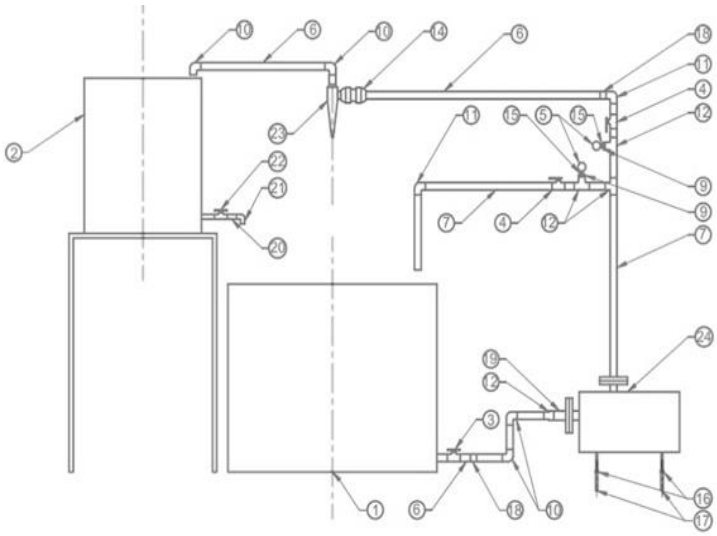


Figure 5 – Efficiency and Pressure Drop versus Solids Feed Concentration

In Figure 5, it can be seen that there is a non-linear relationship that makes direct analysis and simulation unlikely to determine the exact optimum design point. As demonstrated the expected pressure drop decreases with an increase of solids feed concentration. It is also important to note that the efficiency varies nonlinearly with the solids concentration. However, the errors in the results can come from the slurry pump, which had to be run and cooled down every time before proceeding with a variation in the testing parameters. Also the particles need to be continuously stirred to avoid silicate



24	1 OFF	PUMP
23	1 OFF	HYDRO CLYCLONE
22	1 OFF	Ø 25 PVC BALL VALVE
21	1 OFF	Ø 25 90deg BEND
20	100mm	Ø 25 PVC PIPE
19	150mm	Ø 50 STEEL PIPE
18	2 OFF	Ø 40 MALE-FEMALE
17	4 OFF	M10 CHEMICAL ANCHORS
16	4 OFF	VIBRATION DAMPENERS
15	2 OFF	Ø 8 NIPPLE
14	1 OFF	Ø 40 PVC CONNECTION
13	1 OFF	Ø 40 NIPPLE STEEL - PVC
12	1 OFF	Ø 50 - 40 REDUCER PVC
11	2 OFF	Ø 40 90deg BEND STEEL
10	4 OFF	Ø 40 90deg BEND PVC
9	2 OFF	Ø 40 - 8 REDUCER
8	3 OFF	Ø 40 STEEL T BEND
7	2650mm	Ø 40 STEEL PIPE
6	3500mm	Ø 40 PVC PIPE
5	2 OFF	PRESSURE GAUGE
4	2 OFF	Ø 40 BALL VALVE
3	1 OFF	Ø 40 GATE VALVE
2	1 OFF	Ø 700 TANK
1	1 OFF	Ø 1250 TANK

Figure 4 - Diagram of the experimental set-up [28]

crystallising quickly and settling at the bottom of the sump. Although the different challenges encountered during the testing, the 3DDP hydrocyclone presents many benefits that will be shortly discussed in the next sections.

5.1 Design benefits

From the nature of classical design from Pugh [11] it is clear that the process after the freezing of specifications is to some extent linear and allows only for revisiting previous steps in the case that specific design errors occur. In the present era however we must move beyond design changes required by errors to a more pro-active process where the changes during the final design phase and the physical testing phase merges into a more active design/test/revisit process that uses the nature of modern 3D printing and rapid manufacture to ensure, as shown in Figure 2, that design optimization becomes the norm rather than the exception. In the case where, as in hydrocyclones, there is still the need to use analytical tools that require calibration (such as CFD) the time involved in the design phase can be extended dramatically if optimal design is only achievable by repeated analyses with varying parameters. Then calibrating the analytical results at one or two parameter points using physical model testing allows a much more directed change in design parameters to enable optimal designs to be achieved. In Table 1, we attempted to illustrate a comparison of the time, cost and design benefits of the 3DDP and the other traditional manufacturing processes (milling, casting, etc.) use to manufature the metal hydrocyclones.

5.2 Time benefits

Often prototype development times are a serious constraint in the use of such devices in the design cycle. The prototype requires a more manual approach since the tooling and setups for production cannot be made for a single item. It is in this case that 3DDP is excellently suited to the problem of prototype development and testing in the design loop.

The total time for production of a suitable hydrocyclone was checked with two developers of such devices in the minerals beneficiation industry. The time from final design approval of the hydrocyclone to it being ready for testing varied from 12 to 26 weeks in general. The time involved in producing the prototype using the 3DDP process was slightly less than 2 weeks. This allowed a much more rapid transition to the testing phase and repeated testing of variants.

5.3 Cost benefits

Often prototype costs are a serious consideration in the use of multiple prototypes to test design changes since the costs of such handmade prototypes is typically substantially higher than for a production run version of a completed design.

Costs for a prototype of the hydrocyclone were checked with a physical producer of such devices and anecdotally it appears that the cost of a single prototype hydrocyclone for testing purposes could range from R15, 000 to R150, 000 for up to five design iterations [27]. The above cost is based on changing only one aspect of the hydrocyclone for example the cone design. The above data is based on a 100 mm diameter hydrocyclone and would be substantionally higher for larger hydrocyclones [27]. The full cost of a single iteration of the printed hydrocyclone was only R6, 000.

6 DISCUSSION

The final results of the design and testing can be summarized as follows:

1. Design using an integration of simulation, design and rapid prototype testing has shown an improvement in the hydrocyclone performance. Actual optimization can be achieved in minimal time and cost for complex systems that need some form of physical calibration.
2. Separation efficiency can be positively affected by the process in 1. Above beyond the levels that simulation using only CFD would allow.
3. 3DPP as a process allows substantial cost savings in a design situation where a large number of variables are involved in a nonlinear manner and the interaction of these variables is difficult to predict even using advanced simulations.

These results are summarised in Table 1.

Table 1. 3DDP compared to fabricated metal hydrocyclone testing process

	Design Testing Period	Cost
3DDP hydrocyclone	Less than 2 weeks	R6, 000
Fabricated metal hydrocyclone	12 to 26 weeks	R15, 000 to R 150, 000

7 CONCLUSIONS

The design and optimisation process proposed in this study has the potential to reduce development time and cost to produce an optimal hydrocyclone design iteration. The substantial cost and time savings, in the optimisation of a design, made using the process of leveraging 3DDP to produce and test several design iterations, provides a designer with an effective means of exploring a design situation where a large number of variables are involved in a nonlinear manner and where the interaction of these variables is difficult to predict even using advanced simulation software, such as in the case of hydrocyclones.

The nature of classical design relegates the process of benchmarking a design to the end of the design process, almost leaving it as an afterthought to the paper design. By ensuring a tighter integration between the design and testing process as well as analysis of the design, via the leveraging of 3DDP and analysis as in this study, design optimization may become the norm rather than the exception.

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