Design of an Energy-saving Hydrocyclone for Wheat Starch Separation

Växjö, May 2009
Thesis no: TD 052/2009
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Abstract (in English)

The nearly unlimited applications and uses of starch for food industry make this natural polymer a unique component; no other constituent can provide consistence and storage stability to such a large variety of foods. Starch can be extracted from agricultural produce through either chemical processes or physical separation. The latter involves the application of centrifugal forces by means of hydrocyclones. A hydrocyclone is a device which separates, through physical methods, two phases of different densities. There are three flows involved: the feed (mixture introduced in the hydrocyclone), the overflow (the least dense part) and the underflow (the densest part). Normally, the underflow part, or commonly known as "heavies", is the desirable part that companies keep, this is, the starch. Despite hydrocyclones are not very expensive devices, current-based hydrocyclones demand high energy rates. This work describes the design and testing of energy-saving hydrocyclones for extracting starch from wheat. Eight prototypes were built and tested at Larsson Mekaniska Verkstad AB (Bromölla, Sweden). This company makes process equipment for the starch industry and was the one with which the author collaborated during the elaboration of the Degree Project. Six of the eight hydrocyclones were built by Larsson; another was a commercial hydrocyclone and the last one was the one figured out after reading some literature and updates in the hydrocyclones field. The experiments consist of trying the eight hydrocyclones under different conditions, combining concentrations (153 g/L and 237 g/L) and pressures (500 Pa and 700 Pa). The experimental results proved the importance of geometry on hydrocyclone design, and showed the effect of geometrical parameters on the energy-saving properties of cyclones. Four of the eight new models behaved satisfactorily for low energy and high efficiency conditions, obtained with inlet pressures of 500 kPa and starch concentrations of 237 g/L.

Key Words Hydrocyclones, starch separation, wheat starch
Table of contents

Project data sheet ........................................................................................................ i
Table of contents ......................................................................................................... ii
List of appendices ....................................................................................................... ii
List of figures ............................................................................................................... iii
List of tables ................................................................................................................ iv

Chapter 1 : Introduction .............................................................................................. 1
Chapter 2: Theoretical design of a hydrocyclone for starch separation ................. 4
  2.1. Geometry and mechanics of hydrocyclones..................................................... 4
  2.2. Geometry of proposed hydrocyclone ............................................................ 7
Chapter 3: Materials and methods ............................................................................. 16
Chapter 4: Results and discussion ............................................................................ 28
Chapter 5: Conclusions .............................................................................................. 46
Chapter 6: Acknowledgements ................................................................................. 49
Chapter 7: References ............................................................................................... 50

List of appendices

Appendix I: MATLAB CODE FOR HELIX DESIGN: DESIGN OF FLAT SPIRAL .......... 51
Appendix II: MATLAB CODE FOR HELIX DESIGN: DESIGN OF SPIRAL (conical helix) .... 52
# List of figures

**Figure 2.1.** Basic geometrical parameters of a hydrocyclone (Grommers et al., 2004) .......... 4  
**Figure 2.2.** Three-dimensional drawing of a hydrocyclone (a) and flows inside it (b) .......... 6  
**Figure 2.3.** Internal spiral for proposed hydrocyclone ........................................... 9  
**Figure 2.4.** Basic parameters of helicoidal channel hydrocyclone .................................. 10  
**Figure 2.5.** Side (a) and front (b) view of helicoidal channel for hydrocyclone ............... 12  
**Figure 2.6.** Three-dimensional view of helicoidal channel for hydrocyclone .......... 12  
**Figure 2.7.** Final design for wheat starch separation hydrocyclone .............................. 14  
**Figure 2.8.** Prototype tested in the laboratory ............................................................ 15  
**Figure 3.1.** Testing bench used in the experiments ....................................................... 17  
**Figure 3.2.** Starch running through cyclones capsule ................................................. 18  
**Figure 3.3.** Detail of overflow disposal for every single cyclone tested ......................... 18  
**Figure 3.4.** Detail of pressure control panel ............................................................... 18  
**Figure 3.5.** Details of individualized cyclone capsule .................................................. 19  
**Figure 3.6.** Vortex (left side) and cyclone (right side) placed in the testing capsule ........... 19  
**Figure 3.7.** Schematic diagram of hydrocyclones testing bench .................................... 21  
**Figure 3.8.** Scale used to weight starch buckets .......................................................... 24  
**Figure 3.9.** Calculation block diagram for generating efficiency plots ......................... 26  
**Figure 4.1.** Efficiency curves for tested cyclones at 153 g/L (8 °Bé) of feed concentration and 500 kPa (5 bars) of delta pressure ................................................................. 29  
**Figure 4.2.** Curves for tested cyclones at 153 g/L (8 °Bé) of feed concentration and 700 kPa (7 bars) of delta pressure ................................................................. 31  
**Figure 4.3.** Curves for tested cyclones at 236 g/L (12 °Bé) of feed concentration and 500 kPa (5 bars) of delta pressure ................................................................. 32  
**Figure 4.4.** Curves for tested cyclones at 236 g/L (12 °Bé) of feed concentration and 700 kPa (7 bars) of delta pressure ................................................................. 33  
**Figure 4.5.** Efficiency curves for Hydrocyclone 1 at different conditions of concentration and delta pressure .................................................................................... 35  
**Figure 4.6.** Efficiency curves for Hydrocyclone 2 at different conditions of concentration and delta pressure .................................................................................... 36  
**Figure 4.7.** Efficiency curves for Hydrocyclone 3 at different conditions of concentration and delta pressure .................................................................................... 37  
**Figure 4.8.** Inlet spiral for hydrocyclone 3 ..................................................................... 39  
**Figure 4.9.** Efficiency curves for Hydrocyclone 4 at different conditions of concentration and delta pressure .................................................................................... 40  
**Figure 4.10.** Efficiency curves for Hydrocyclone 5 at different conditions of concentration and delta pressure .................................................................................... 41  
**Figure 4.11.** Efficiency curves for Hydrocyclone 6 at different conditions of concentration and delta pressure .................................................................................... 42  
**Figure 4.12.** Efficiency curves for Hydrocyclone 7 at different conditions of concentration and delta pressure .................................................................................... 43  
**Figure 4.13.** Efficiency curves for Hydrocyclone 8 at different conditions of concentration and delta pressure .................................................................................... 44


List of tables

Table 2.1. Geometrical parameters of the hydrocyclone shown in figure 2.1 ....................................... 5
Table 2.2. Key parameters for the theoretical hydrocyclone prototype ............................................. 15
Table 3.1. Legend corresponding to the elements shown in figures 3.1 to 3.5................................. 17
Table 3.2. Tested hydrocyclones ........................................................................................................ 27
Table 4.1. Efficiency ranking for the set of hydrocyclones tested (table 3.2) ................................. 34
Table 4.2. Hydrocyclones 1 and 3. Comparison of efficiencies for different conditions ............ 38
Table 4.3 Differences of efficiency between hydrocyclones 1 and 8.............................................. 45
Chapter 1

Introduction

An efficient separation of starch and protein in primary agricultural products is vital for the food industry. Many basic grains such as tapioca (Saengchan et al., 2009) or pin milled chickpea grain (Emami et al., 2005) require a good separation of starch and protein for its further use. There exist various physical methods for starch separation, and although Svarovsky (1984) has suggested the use of hydrocyclones for starch separation for more than twenty years, researchers are still investigating the benefits of cyclone technology for physical separation. One such recent study is brought by Emami et al. (2006), who compared the combination of hydrocyclone and centrifuge on one hand, with the coupling of a centrifuge and a sieve on the other, for separating starch and protein from chickpea flour. In this case, the process involving the hydrocyclone was more efficient extracting the starch, but it also included the aid of a centrifuge to achieve an acceptable separation rate. Saengchan et al. (2009), on the contrary, used only a hydrocyclone system instead of a centrifugal separator for tapioca starch separation; the optimum selection of process parameters enhanced separation efficacy. In spite of its economic importance, not only starch is the only application for hydrocyclone separators; Habibian et al. (2008), for example, employed the same technique for removing yeasts from alcohol fermentation broths. They concluded that viscosity was a crucial factor affecting separation efficiency, and because this technology could be applied to large molecules, starch appeared as a favorite candidate for hydrocyclone separation. This research proved that a multi-hydrocyclone system with low feed concentration is more efficient than one single hydrocyclone dealing with higher feed concentrations, although lab testing can be carried out with a single hydrocyclone (Emami et al., 2005).

The adequate geometry of a hydrocyclone, that is, its design, together with the proper choice of working parameters is the safest preparation for an efficient separation (Emami et al., 2006; Chu et al., 2000). According to
Grommers et al. (2004), small geometrical changes on the hydrocyclones have strong influences on the outcomes. The set of process parameters can be selected by pairs (Emami et al., 2005), or conversely by a threefold relationship (Chu et al., 2002b). It is important to design the hydrocyclone according to the target pursued (Chu et al., 2002a). The goal set by Chu et al. (2000) in their design was getting the highest savings on energy consumption. To do so, multiple parameter combinations were tested and graded based upon their influence on power conservation. They found that the most influenceable factors, sorted by relevance, were: central inserted parts, inlet pipes, cylindrical parts, vortex finders, cone parts and underflow pipes. Relevant information about hydrocyclones design has been reported in specialized journals; so, for example, pressures over 865 kPa may cause the appearance of undesirable particles in the underflow (Emami et al., 2005), and when the vortex finder length is about 10 % of the total length of the hydrocyclone high efficiencies can be reached (Fernández Martínez et al., 2008). An interesting phenomenon to consider is the formation of air cores (Gupta et al., 2008). The air core is a strip of air extended vertically throughout the whole axis of the cyclone provoked by the low pressures found in this place. Its effects can be reduced by introducing a rod inside the hydrocyclone.

The overall objective of this research is the design, study, and analysis of energy-saving hydrocyclones for wheat starch separation. This project took place under the Erasmus Program of international students exchange between Växjö University (Sweden) and the Polytechnic University of Valencia (Spain). The collaborative framework between industry and academia at Växjö University made possible the development of this investigation in the company Larsson M. Verkstad AB, located in Bromölla (Sweden). Design and literature search took place at Växjö University whereas the fabrication of the hydrocyclones and their testing happened in two facilities operated by Larsson in Bromölla and Linköping, both in Sweden. The duration of the project was limited by academic constraints, which approximately allocated the six month of the spring semester of 2009 to fulfill the goals set by both institutions. In addition to meeting the academic requirements for achieving an engineering
degree, this investigation was intended to help Larsson improve their current
designs of hydrocyclones for starch separation, paying attention to energy-
saving properties and separation efficiency. This *modus operandi* resulted in a
very fruitful collaboration between the graduating student, her academic
advisors, and Larsson staff.

The specific goals proposed and accomplished in this research project
were the following:

1. The technical study and scientific review of hydrocyclones
   geometry and starch separation techniques.
2. The proposal of a theoretical design of an energy-saving
   hydrocyclone.
3. Laboratory testing of the designed hydrocyclone in comparison
   with other models proposed by Larsson.
4. The enunciation of a set of recommendations for wheat starch
   separation cyclones.
5. The publication of the results found in the project at the Annual
   International Meeting held by the American Society of Agricultural
   and Biological Engineers in Reno (Nevada, USA) in June 2009.
Chapter 2

Theoretical design of a hydrocyclone for starch separation

2.1. Geometry and mechanics of hydrocyclones

Food industry hydrocyclones consist of several parts, schematically shown in figure 2.1, and described below. The fundamental geometrical parameters shown in figure 2.1 are listed in table 2.1.

Figure 2.1. Basic geometrical parameters of a hydrocyclone (Grommers et al., 2004).
Table 2.1. Geometrical parameters of the hydrocyclone shown in figure 2.1.

<table>
<thead>
<tr>
<th>Geometrical parameter</th>
<th>Symbol</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocyclone diameter</td>
<td>D</td>
<td>mm</td>
</tr>
<tr>
<td>Overflow diameter</td>
<td>D_o</td>
<td>mm</td>
</tr>
<tr>
<td>Vortex finder length</td>
<td>L_v</td>
<td>mm</td>
</tr>
<tr>
<td>Top side of inlet area</td>
<td>S_a</td>
<td>mm</td>
</tr>
<tr>
<td>Lateral side of inlet area</td>
<td>S_b</td>
<td>mm</td>
</tr>
<tr>
<td>Cylindrical length</td>
<td>L_cy</td>
<td>mm</td>
</tr>
<tr>
<td>Cone length</td>
<td>L_co</td>
<td>mm</td>
</tr>
<tr>
<td>Apex length or spigot</td>
<td>L_a</td>
<td>mm</td>
</tr>
<tr>
<td>Total length</td>
<td>L</td>
<td>mm</td>
</tr>
<tr>
<td>Underflow diameter</td>
<td>D_u</td>
<td>mm</td>
</tr>
<tr>
<td>Length from cyclone outlet to tip</td>
<td>L_{tip}</td>
<td>mm</td>
</tr>
<tr>
<td>Cone angle</td>
<td>α</td>
<td>°</td>
</tr>
</tbody>
</table>

Conventional hydrocyclones are formed by a main body divided in two sides: a cylindrical upper part and a conical bottom part. The cylindrical upper part, represented in figure 1 as $L_{cy}$, can be long, short or even inexistent, depending on the application. Its inner width is the hydrocyclone diameter length. The conical part ($L_{co}$) can vary in length and cone angle ($\alpha$ in figure 1). This conical part can also include a spiral carved inside to enhance efficiency in the hydrocyclone. A relevant parameter of cyclones is the hydrocyclone diameter ($D$). The cylindrical part diameter coincides with the hydrocyclone diameter until the conical shape. The inlet area is the entrance orifice of the fluid, and comprises two sides: top ($S_a$) and lateral ($S_b$). This part can be squared, rectangular or circular. The underflow orifice is one of the parts through which the fluid leaves the cyclone. This underflow diameter is represented as $D_u$ in figure 1. The apex length or spigot ($L_a$) is the small cylindrical part where the hydrocyclone ends. The total length of the cyclone ($L$) corresponds to the sum of the apex length, the cone length and the cylindrical length. The other part through which the fluid leaves the cyclone is the orifice of the overflow, whose diameter is indicated as $D_o$ in the figure. The vortex
finder length \( (L_v) \) is the part of the vortex assembled inside the cylindrical part of the cyclone. The total length from cyclone outlet to tip \( (L_{tip}) \) indicates the length from the end of the cyclone to the vertex where the cone part ends.

A three-dimensional representation of a hydrocyclone is displayed in figure 2.2a. The processing solution is injected tangentially through the inlet orifice, provoking a rotational motion in a spiral shape guided by the walls of the hydrocyclone and eventually getting out the cyclone through the underflow orifice. The solution, then, goes through a separation process after being divided in two flows: the descending flow exiting the cyclone through the underflow orifice; and the ascending flow moving upwards, changing the flow direction suddenly in the bottom part of the cyclone, near the underflow orifice, and going through the overflow orifice. This separation of the flows can be followed in figure 2.2b. The densest fraction (coarse fraction) goes through the underflow, while the suspension with smaller particles (fine fraction) goes through the overflow.

![Figure 2.2. Three-dimensional drawing of a hydrocyclone (a) and flows inside it (b).](image)
The actuating forces for a solid-liquid separation inside the hydrocyclone are of two types: centrifugal and drag forces. Gravitational forces can be neglected for small hydrocyclones, as those separating particles not bigger than 40 μm, like the wheat starch particles considered in this project. According to Eliasson (2004), wheat starch particles are approximately 22 μm. When centrifugal forces exceed drag forces, particles move outwards; in the opposite case, particles will generally move inwards (Saengchan et al., 2009). The separation principle of a hydrocyclone is based on inertial forces, because circular trajectories induce radial accelerations. Flow density also influences the separation success: if the solid fraction has a density higher than the fluid density, the particles move around the wall and eventually leave the cyclone through the underflow, but if the density of particles is lower than the fluid density, the flow leaves the cyclone through the overflow exit (Fernández Martínez et al., 2007).

2.2. Geometry of proposed hydrocyclone

The first design parameter to be determined is the hydrocyclone diameter $D_h$. Many choices have been suggested by specialized manufacturers. Larsson (Brömolla, Sweden), for example, features either 8 mm or 10 mm hydrocyclones. Wheat starch particles have an average size of 22 μm (Eliasson, 2004) and the potato starch particle average size is 40 μm. Due to that fact, a diameter of 8 mm should be suitable, as the common diameter for potato starch is 10 mm, but, tapioca starch particle is smaller than that of wheat starch and uses diameters of 10 mm, as well. Then, it was thought that would be adequate to assume a diameter of 10 mm for wheat starch adding the advantage to have higher capacity with that election. So, a diameter of 10 mm has been selected.

The second element of the hydrocyclone to be designed is the inlet area. This orifice can be squared, rectangular or circular in shape. The most efficient models reported in the market, mainly applied to potato or tapioca starch
separation, include a rectangular or squared inlet section, and therefore this was the shape chosen for the proposed design. However, a smaller size was preferred in order to increase flow pressure and in turns enhance efficiency. The final cyclone includes a square inlet section with a 2.1 mm side. The inlet area is located in the upper edge of the hydrocyclone. From this edge, a spiral carved inside the body of the cyclone can smooth the flow of starch and, in consequence, raise the cyclone efficiency. The basic equation for the proposed spiral is given in equation 1, where parameters $\alpha$ and $\beta$ are determined from the contour conditions shown in equation 2.

$$R = \alpha + \beta \cdot \cos \phi$$ \hspace{1cm} [Eq. 1]

$$\begin{align*}
\text{If } \phi = \pi & \Rightarrow R = R_{\max} \\
\text{If } \phi = -\frac{\pi}{4} & \Rightarrow R = R_{\min}
\end{align*}$$ \hspace{1cm} [Eq. 2]

Applying the conditions of equation 2 to equation 1:

$$R_{\max} = \alpha - \beta$$ \hspace{1cm} [Eq. 3]

$$R_{\min} = \alpha + \frac{\sqrt{2}}{2} \beta$$ \hspace{1cm} [Eq. 4]

Withdrawing equation 4 from equation 3, we can find $\beta$, and $\alpha$ can be obtained directly from equation 3 once $\beta$ is known. The final formula is given in equation 6:

$$\beta = 2 \cdot \frac{R_{\min} - R_{\max}}{2 + \sqrt{2}}$$ \hspace{1cm} [Eq. 5]

$$R = R_{\max} + \frac{2 \cdot (R_{\min} - R_{\max})}{(2 + \sqrt{2})} + \frac{2 \cdot (R_{\min} - R_{\max})}{2 + \sqrt{2}} \cdot \cos \phi \hspace{1cm} \phi \in \left[ -\frac{\pi}{4}, \pi \right]$$ \hspace{1cm} [Eq. 6]

The conditions for the proposed hydrocyclone will be $R_{\max} = 5.5$ mm and $R_{\min} = 5$ mm. and the equation for this specific case is as follows:

$$R = 5.5 - \frac{1}{(2 + \sqrt{2})} \cdot \frac{\cos \phi}{2 + \sqrt{2}} \hspace{1cm} \phi \in \left[ -\frac{\pi}{4}, \pi \right]$$ \hspace{1cm} [Eq. 7]
The spiral depicted in figure 1 has been generated when equation 6 is applied with $R_{\text{max}} = 5.5$ and $R_{\text{min}} = 5$. The Matlab® code for its generation is included in Appendix I.

\[ \text{Figure 2.3. Internal spiral for proposed hydrocyclone.} \]

The outer diameter, also known as the underflow diameter, is typically set around 2.8 mm in commercial cyclones for starch separation, such as Larsson’s or AVEBE’s. In the current design, the underflow diameter has been raised to 3 mm to help flow evacuate. Following the conventional designs for off-the-shelf cyclones, the spigot or apex length was fixed to 10 mm.

The calculation of the cylindrical part follows the recommendations made by Chu et al. (2000), in which the optimum length of the cylindrical part is twice the hydrocyclone diameter $D_h$. Therefore, the cylindrical part length is 20 mm. The total length of the proposed design, on the contrary, needs to be 87 mm due to manufacturing requirements.
The hydrocyclone cone length is a geometrical parameter determined by withdrawing the cylindrical and spigot lengths from the total length of the cyclone. Applying the specifications found above, the cone length for the proposed design is **57 mm**. Along the length of the cone part, it is possible to engrave a spiral creating a helicoidal channel. This channel can improve the cyclone’s efficiency. The mathematical determination of the helicoidal channel for the proposed cyclone is provided in full detail in the following paragraphs.

The basic parameters needed to formulate the helicoidal channel are:

- \( R_{\text{max}} \): maximum radius of the cone
- \( R_{\text{min}} \): minimum radius of the cone
- \( L_{\text{e}} \): Helix pitch
- \( L \): Total length of conical section of cyclone
- \([x,y,z]\): Cartesian coordinates as indicated in figure 2.4.

![Figure 2.4. Basic parameters of helicoidal channel](image)

The radius of the helix is variable and depends on the cone shape. It can be easily calculated with equations 8 and 9.

\[
\delta = R_{\text{max}} - R_{\text{min}} \frac{L - z}{L} \quad [\text{Eq. 8}]
\]

\[
R = R_{\text{min}} + \delta = R_{\text{min}} + \frac{R_{\text{max}} - R_{\text{min}}}{L} \frac{L - z}{L} \quad z \in [0, L] \quad [\text{Eq. 9}]
\]

\[ \text{~ 10 ~} \]
It can be checked with equation 9 that if \( Z = 0 \), \( R = R_{\text{max}} \); and similarly, if \( Z = L \), \( R = R_{\text{min}} \).

Before deducing the equation of the helix, or spiral, the number of loops \((n)\) needs to be obtained through the expression given in equation 10, where the function \( \text{int} \) forces \( n \) to be integer.

\[
    n = \text{int} \left( \frac{L}{L_e} \right) \quad \text{[Eq. 10]}
\]

The parametric equations of the three-dimensional helix are finally stated in equation 11:

\[
    \begin{align*}
    x &= \left[ R_{\text{min}} + \left( R_{\text{max}} - R_{\text{min}} \right) \frac{L - z}{L} \right] \cos(t) \\
    y &= \left[ R_{\text{min}} + \left( R_{\text{max}} - R_{\text{min}} \right) \frac{L - z}{L} \right] \sin(t) \\
    z &= \frac{L_e}{2\pi} \cdot t 
    \end{align*} \quad t \in [2\pi n^-] \quad x, y, z \text{ in mm} \quad \text{[Eq. 11]}
\]

The expression shown in equation 11 provides the Cartesian coordinates of a generic point \([x, y, z]\) belonging to the spiral, but the proposed hydrocyclone possesses very specific dimensions as described in the previous paragraphs. In particular, the following parameters have been determined for the calculated design: \( R_{\text{max}} = 5 \text{ mm} \), \( R_{\text{min}} = 1.5 \text{ mm} \), \( L_e = 5 \text{ mm} \), and \( L = 57 \text{ mm} \) \([z_{\text{max}}]\). After applying these figures to equation 11 the concrete helix to be traced inside the cone part is defined by equation 12 below.

\[
    \begin{align*}
    x &= \left[ \frac{285 - 3.5 \cdot z}{57} \right] \cos(t) \\
    y &= \left[ \frac{285 - 3.5 \cdot z}{57} \right] \sin(t) \\
    z &= \frac{5}{2\pi} \cdot t 
    \end{align*} \quad t \in \left[2\pi \right]^- \quad \text{[Eq. 12]}
\]

The helix determined by the expression of equation 12 was plotted with Matlab\textsuperscript{©} (code provided in Appendix II). A side view of the spiral is depicted in figure 2.3 (a), and its front view is given in figure 2.3 (b). The three-dimensional view of the helix is plotted in figure 2.4.
Figure 2.5. Side (a) and front (b) view of helicoidal channel for hydrocyclone.

Figure 2.6. Three-dimensional view of helicoidal channel for hydrocyclone.
The conclusions drawn by Fernández Martínez et al. (2008) with respect to the vortex finder, another key parameter in the design of hydrocyclones, establish the optimal length of the vortex as the 10% of the total length of the hydrocyclone. This simple calculation sets the searched length to **8.7 mm**.

The last parameter to fix before taking the designed model to the manufacturing lab is the overflow diameter. Even though Chu et al. (2000) suggest increasing the angle of the vortex, it was kept in 10° as the majority of commercial solutions because a wider angle would result in anomalous dimensions for the vortex. As a result, the overflow diameter was finally chosen to be **3.5 mm**. Other dimensions, such as the thickness of the walls, remained indistinct from the referenced design facilitated by Larsson. The definitive design for the hydrocyclone proposed is illustrated in the technical plots of figure 2.4. The set of parameters calculated or decided to define the hydrocyclone designed is specified in table 1.
Figure 2.7. Final design for wheat starch separation hydrocyclone.
Table 2.2. Key parameters for the theoretical hydrocyclone prototype.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocyclone diameter</td>
<td>10 mm</td>
</tr>
<tr>
<td>Inlet area</td>
<td>2.1 x 2.1 mm²</td>
</tr>
<tr>
<td>Underflow diameter</td>
<td>3 mm</td>
</tr>
<tr>
<td>Apex length</td>
<td>10 mm</td>
</tr>
<tr>
<td>Cylindrical length</td>
<td>20 mm</td>
</tr>
<tr>
<td>Total length</td>
<td>87 mm</td>
</tr>
<tr>
<td>Cone part</td>
<td>57 mm</td>
</tr>
<tr>
<td>Vortex finder length</td>
<td>8.7 mm</td>
</tr>
<tr>
<td>Overflow diameter</td>
<td>3.5 mm</td>
</tr>
</tbody>
</table>

Figure 2.8. Prototype tested in the laboratory.
Chapter 3

Materials and methods

The objective of the experiments proposed was to know the efficiency of each hydrocyclone especially designed to reduce energy costs; therefore, the first task to do was the design of the experiments and the selection of all parameters needed. An Excel™ file was prepared to process the data as the trials were being performed. The main parameters considered in the tests were: underflow pressure (kPa), feed concentration (g/L), delta pressure (kPa), feed volume (L), overflow volume (L), underflow volume (L), feed concentration (g/L), overflow concentration (g/L), underflow concentration (g/L), weight overflow (kg), weight underflow (kg), time overflow (s), time underflow (s), temperature (°C), feed flow (cm³/s), underflow flow (cm³/s), overflow flow (cm³/s), flow ratio (dimensionless) and efficiency (dimensionless). Once the main variables were chosen, the set of experimental hydrocyclones were introduced in an especially-built testing machine developed by Larsson, and represented in figure 3.1. The main components of the testing bench shown in figures 3.1 to 3.5 are indicated by numbers whose correspondence is included in table 3.1.
Table 3.1. Legend corresponding to the elements shown in figures 3.1 to 3.5.

### LEGEND FOR FIGURES 3.1 TO 3.5

<table>
<thead>
<tr>
<th>Number</th>
<th>COMPONENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electric Motor 1</td>
</tr>
<tr>
<td>2</td>
<td>Overflow flow(s) line(s)</td>
</tr>
<tr>
<td>3</td>
<td>Starch tray</td>
</tr>
<tr>
<td>4</td>
<td>Underflow pressure valve(s)</td>
</tr>
<tr>
<td>5</td>
<td>Underflow flow line</td>
</tr>
<tr>
<td>6</td>
<td>Hydrocyclone capsule</td>
</tr>
<tr>
<td>7</td>
<td>Electric Motor 2</td>
</tr>
<tr>
<td>8</td>
<td>Underflow pressure gauge</td>
</tr>
<tr>
<td>9</td>
<td>Inlet pressure gauge</td>
</tr>
<tr>
<td>10</td>
<td>Inlet flow line</td>
</tr>
</tbody>
</table>

Figure 3.1. Testing bench used in the experiments.
Figure 3.2. Starch running through cyclones capsule.

Figure 3.3. Detail of overflow disposal for every single cyclone tested.

Figure 3.4. Detail of pressure control panel.
Figure 3.5. Details of individualized cyclone capsule.

The procedure followed to run the experiments in the Larsson testing bench illustrated in figure 3.1 is described in the following paragraph. The first step done was the placement of the hydrocyclones inside their individual testing capsule, as figure 3.6 shows:

Figure 3.6. Vortex (left side) and cyclone (right side) placed in the testing capsule.
There are six cyclone capsules in the testing rig, what allows for trying six cyclones simultaneously; however, it was decided to run only three hydrocyclones at the same time in order to get suitable underflow pressures. Two electric motors were actuated to move the starch through the pumps: motor 1 (Strömberg, Finland) has a power of 2.2 kW, and motor 2 (EFACEC, Portugal) delivers 1.80 kW. Four different conditions were considered:

1) Starch concentration of $153 \text{ g/L} \ (8 \ ^\circ \B{e}) \text{ and } 500 \text{ kPa} \ (5 \text{ bars});$
2) Starch concentration of $153 \text{ g/L} \ (8 \ ^\circ \B{e}) \text{ and } 700 \text{ kPa} \ (7 \text{ bars});$
3) Starch concentration of $236 \text{ g/L} \ (12 \ ^\circ \B{e}) \text{ and } 500 \text{ kPa} \ (5 \text{ bars});$
4) Starch concentration of $236 \text{ g/L} \ (12 \ ^\circ \B{e}) \text{ and } 700 \text{ kPa} \ (7 \text{ bars});$

Figure 3.7 describes, schematically, how the flows are distributed in the testing bench for only one of the tested hydrocyclones, although the actual bench has six capsules, as shown in figure 3.1, and three cyclones were tested simultaneously every time. Once the three cyclones have been introduced in their respective capsules, the test starts by pumping the starch with the selected concentration. Thanks to the variable frequency generator, the feed pressure can be adjusted at the required level and the bench is ready to initiate the trials. The starch coming from the tank is the feed flow, and is pumped by pump 2 (Fig. 3.7) until it reaches the capsule through the inlet orifice represented in the diagram with number 1. The starch crosses the cyclone inlet and moves along a spiral engraved in it. When the starch reaches the bottom part of the cyclone, the physical separation takes place, and two different flows depart from the cyclone: the underflow leaves the cyclone through the underflow orifice, labeled as number 2 in the diagram, and the overflow exits the cyclone through channel 3 (Fig. 3.7). The coarse particles represent the starch, and are recovered in the underflow; however, as separation efficiency is not 100%, some small particles (fibers) are also carried in the underflow. The main function of the overflow is the collection of small particles, but accidentally it carries starch particles too. Nevertheless, the underflow is the desired product.
of the separation process. After the separation has occurred and both flows have been weighted and registered, underflow and overflow are merged again over a conveyor tray which pours the mix into pump 1. This pump closes the cycle and returns the solution to the tank for its use in the following tests.

The specific conditions for each test, according to the experimental design protocol, were assured after following this procedure: the required concentration of starch, either 153 g/l (8 °Bé) or 236 g/l (12 °Bé), was directly obtained from the facility’s starch transportation system by selecting the pipe with the appropriate concentration. Inlet pressure was initially set with the variable frequency generator, and continuously readjusted with a manual valve actuating over the feed flow (component 4 in figure 3.7). The overflow pressure was displayed in the manometer 6 of the flow diagram. Finally, the underflow pressure was also controlled through valve 5 and manometer 7.

Figure 3.7. Schematic diagram of hydrocyclones testing bench.
These experiments were carried out in a facility operated by Larsson at Reppe (Lidköping, Sweden). Two specific starch concentrations were determined for the set of experiments: 153 g/L (8 °Bé) and 236 g/L (12 °Bé).

The real value for the concentration of starch can be estimated in two different ways: using an aerometer or using a centrifuge machine. In these experiments, the latter method was employed because it is considered the most reliable. To get the concentration measurements, several test tubes of 10 ml volume were filled with the dissolution of water and starch especially prepared by the facility technician. The test tubes were introduced into the centrifuge machine and run for 5 minutes at 3750 rpm. After centrifuging them, three phases were separated: water, fibers and starch. The amount of starch found in the test tubes, expressed in millimetres, was registered, as well as the amount of starch plus fibers plus water, also in millimetres. The conversion from amount of millimetres into Baumé degrees is shown in equation 3.1.

\[
\text{Feed °Bé} = \frac{\text{Feed volume Starch (ml)}}{\text{Feed volume Total (ml)}} \cdot 15 \cdot 2.1 \quad \text{[Eq. 3.1]}
\]

The feed calculated through equation 3.1 was used to know the approximate value of the starch concentrations, but it was not employed in successive calculations. It was considered as a rough estimate of the concentrations. Before trying the cyclones, it was necessary to make sure that the required concentration of starch was available, together with the right inlet pressure. In this particular case, the value of delta pressure was almost the same as the inlet pressure, which was adjusted to 500 kPa (5 bars) or 700 kPa (7 bars) depending on the trial. The reason why inlet pressure and delta pressure can be considered the same is a consequence of the definition of delta pressure as the difference between the inlet (or feed) pressure and the overflow pressure. The overflow pressure was, in these tests, thirty centimetres of water column measured at the hydrocyclone capsule, which means that the overflow pressure is about 30 kPa (0.3 bars). These 30 kPa (0.3 bars) can be approximated to zero, and if the overflow pressure is considered to be zero, then the delta pressure is just the inlet pressure. The adjustment for the inlet
pressure was made with the help of a variable frequency generator and displayed in the inlet manometer (figure 3.4, number 9). Once these initial conditions were established, the underflow pressure for each hydrocyclone tested was set up. The underflow pressure was chosen arbitrarily; it started from low pressures and increased up to the point where it was still possible to get enough flow of starch. Before the end of each trial, the curve obtained was checked to assure that it had enough points to be represented. The underflow pressure values give a reference of where the X-axis points will be located. The underflow pressure was adjusted with a manual valve (fig. 3.5, number 4) and shown in the underflow manometer (fig. 3.4, number 8). For each pressure point tried and hydrocyclone tested, two samples of starch dissolution were analyzed. Two test tubes were filled with the starch dissolution: one with starch coming from the underflow flow, and the other with the starch dragged by the overflow current. This procedure was executed for the three hydrocyclones being tested at the same time. Concurrently, two test tubes filled with feed flow were measured to check that the inlet concentration was exposed to the same conditions every time. A 2 liter bucket was filled with underflow flow and another bucket of the same volume was filled with overflow flow. The time needed to fill up the buckets was registered in seconds. After taking several samples, the test tubes were put into the centrifuge for 5 minutes at 3750 rpm, separating the starch and leading to the calculation of millilitres of starch and total millilitres, that is, an estimate of the overflow and underflow volumes. The equations applied for the calculation of the overflow and underflow are equations 3.2 and 3.3 respectively.

\[
\text{Overflow } \text{oBé} = \frac{\text{Overflow volume Starch (ml)}}{\text{Overflow volume Total (ml)}} \cdot 15 \cdot 2.1 \quad \text{[Eq. 3.2]}
\]

\[
\text{Underflow } \text{oBé} = \frac{\text{Underflow volume Starch (ml)}}{\text{Underflow volume Total (ml)}} \cdot 15 \cdot 2.1 \quad \text{[Eq. 3.3]}
\]
The 2-liter buckets containing the starch dissolution were weighted with the electronic scale of figure 3.8. The weight of the buckets was input in the expressions of equations 3.4 and 3.5 to determine the overflow and underflow feed in L/h.

A look-up table was defined to convert the concentration of overflow and underflow given in degrees Baumé into grams per liter. The total value for the feed is given by equation 3.6 below:

\[
\text{Feed } F_r \text{ (L/h)} = \text{Overflow feed } O_f \text{ (L/h)} + \text{Underflow feed } O_f \text{ (L/h)} \quad \text{[Eq. 3.6]}
\]
The coefficient $R_f$, known as the flow ratio, gives an estimate of the quantity of flow that is running through the starch recovery channel (number 2 in the figure 3.7) respect to the total flow running through the inlet channel (number 1 in figure 3.7), and can be obtained through equation 3.7. This variable is represented in the abscissa axis of the efficiency plots depicted in the Results section.

$$R_f = \frac{\text{Underflow feed} \ U_f \ (l/h)}{\text{Feed} \ F_f \ (l/h)} \quad [\text{Eq. 3.7}]$$

It is important to distinguish the Feed $F_f$ from the Feed $C_f$. The difference between them is that the feed, $F_f$, is a flow, given in L/h, while feed $C_f$ is a concentration, given in g/L. The feed $C_f$ is therefore an important factor because it is the concentration fixed in advance, so the parameter that will guide the whole trial, and is defined by equation 3.8. Once the feed $C_f$ has been calculated in g/L with equation 3.8, it must be transformed back to degrees Baumé, since this is the most common unit used for starch context.

$$\text{Feed } C_f \ (g/L) = R_f \cdot \text{Underflow } C_u \ (g/L) + \text{Overflow } C_o \ (g/L) \cdot (1-R_f) \quad [\text{Eq. 3.8}]$$

The final efficiency, $E'_f$, for each hydrocyclone tested is obtained with equation 3.9, and represented in the Y axis of the efficiency curves of the cyclones.

$$E'_f = \frac{\text{Feed } C_f \ (g/L) \cdot \text{Overflow } C_o \ (g/L)}{\text{Feed } C_f \ (g/L)} \quad [\text{Eq. 3.9}]$$

The block diagram depicted in figure 3.9 summarizes the calculation flow from the initial data inlet pressure and feed concentration to the final outcome represented by the efficiency plot.
Figure 3.9. Calculation block diagram for generating efficiency plots.
The specifications for the eight hydrocyclones tested in Larsson’s bench are displayed in table 3.2.

Table 3.2. Tested hydrocyclones.

<table>
<thead>
<tr>
<th>No.</th>
<th>Hydrocyclone</th>
<th>Main features (in mm)</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inlet Ø</td>
<td>Overflow Ø</td>
</tr>
<tr>
<td>1</td>
<td>Usual standard cyclone Ø 10 mm</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Standard design 10 mm material, 20% PTFE</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Machined Ø 8 mm, version 1</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Machined Ø 8 mm, version 2</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Machined standard cyclone, Ø 10 mm</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Vortex 10 mm</td>
<td>10</td>
<td>2.7</td>
</tr>
<tr>
<td>7 *</td>
<td>SLA – geometry based cyclone</td>
<td>10</td>
<td>3.5</td>
</tr>
<tr>
<td>8</td>
<td>SLA – prototype standard design Ø 10 mm</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

*Prototype described in detail in Section 2.
Chapter 4

Results and discussion

The overall objective of this research was to modify the current design of hydrocyclones to improve efficiency, from the energy consumption point of view, when separating starch from wheat. The initial idea consisted of limiting pressure to 500 kPa (5 bars) while processing high concentrations of starch, resulting in a low energy profile but high separation rate, reducing energy and costs, which is the main goal of this study.

The efficiency curves of the hydrocyclones were built representing the flow ratio (Rf) values in the X axis and the Efficiency (E') values in the Y axis. Every graph depicts the efficiency curve of the eight cyclones tested for each specific testing condition of concentration and pressure. Consequently, the results of the experiments can be graphically represented in four different plots, one for each different condition. The four combinations of pressure and concentration were the following:

1) 153 g/L (8 °Bé) and 500 kPa (5 bars)
2) 153 g/L (8 °Bé) and 700 kPa (7 bars)
3) 236 g/L (12 °Bé) and 500 kPa (5 bars)
4) 236 g/L (12 °Bé) and 700 kPa (7 bars).

Every condition was applied to the set of eight experimental cyclones, and therefore, every efficiency plot includes eight curves, one for each cyclone. This procedure allows the fair comparison of the cyclones as testing conditions were exactly the same. Additionally, the individual performance of each cyclone for the four combinations of pressure and concentration tried is also plotted in separated figures. These curves show the best working conditions for each hydrocyclone proposed. The design goal for the cyclones is to find the best geometry to increase the pressure inside the cyclone without increasing inlet
pressure, maintaining, or raising, the separation efficiency without incurring in energy losses.

The technical specifications of the eight hydrocyclones tested are provided in table 3.2.

**Condition 1: Starch concentration 153 g/L (8 °Bé) and 500 kPa (5 bars)**

Figure 4.1 shows the curves of the eight hydrocyclones tested at 153 g/L (8 °Bé) of concentration and 500 kPa (5 bars) of pressure. It can be observed in the efficiency plot that cyclones 3 (Ø 8 mm, version 1) and 1 (Ø 10 mm, Larsson’s standard cyclone) provide the highest efficiency values in these conditions of concentration and pressure. Cyclones 2 (Ø 10 mm, new material) and 8 (SLA Ø 10 mm standard cyclone) also provide high efficiency. Cyclones number 5 (machined standard cyclone) and 7 (SLA, designed cyclone according to Chapter 2 directions) give the lowest efficiency points compared to the other hydrocyclones.

![Curves for tested cyclones at 153 g/L and 500 kPa](image)

Figure 4.1. Efficiency curves for tested cyclones at 153 g/L (8 °Bé) of feed concentration and 500 kPa (5 bars) of delta pressure.
Condition 2: Starch concentration 153 g/L (8 °Bé) and pressure 700 kPa (7 bars)

For the next condition tried, the inlet pressure was increased up to 700 kPa (7 bars). The results of the hydrocyclones in these new conditions are shown in figure 4.2. It can be observed that as the pressure increased so did the efficiency. This fact was expected given the direct relationship between pressure and efficiency (Svarovsky, 1984). Cyclones 1, 2, 3 and 8 were, again, the most efficient. A concentration of 153 g/L (8 °Bé) with the pressure of 700 kPa (7 bars) made the overall efficiency increase. In consequence, the curves were above the previous case. One reason for this outcome is the direct relationship between pressure and efficiency, but another cause can be found in the inverse relationship between efficiency and concentration (Svarovsky, 1984). At a “low” concentration of 153 g/L (8 °Bé; note that 153 g/L will be considered a low concentration hereafter compared to 236 g/L (12 °Bé), which will be considered a high concentration in this study), the efficiency is expected to be higher than at high concentrations of starch. The average efficiency for 153 g/L (8 °Bé) and 700 kPa (7 bars) when the Ri is over 0.4 is around 70 %. The relative comparison among cyclones also shows an advantage of 1, 2, 3 and 8 over 5 and 7. The highest value of efficiency reached in this testing condition was obtained for hydrocyclone 1, with a top value of 76 %.
Condition 3: Starch concentration 236 g/L (12 °Bé) and pressure 500 kPa (5 bars)

In Condition 3, concentration was increased to 236 g/L (12 °Bé) and delta pressure was set at 500 kPa (5 bars). According to the considerations made in this study, pressure is labeled low in this case and concentration high. A low pressure is preferable because it saves energy and reduces costs. High concentration is also preferable because the separation process is faster. Therefore, this study case initially presents more advantages than the rest, but the hydrocyclones need to respond accordingly yielding higher efficiencies.

The first apparent difference of the efficiency plot of figure 4.3, in comparison to figures 4.1 and 4.2, is the shape of the curves. All the curves for Condition 3 do not reach an efficiency peak after which they decrease again; the curve grows monotonically without reaching a local maxima. The peaks of the curves were limited by the settings of the underflow pressure valve. In this
particular test, the highest points of the curves were reached at the specific points of $R_f$ when the valve for controlling the underflow pressure was totally open, so the lowest underflow pressures and the highest flows to the underflow led to the maximum efficiency.

The hydrocyclone that reached the highest point of efficiency in these conditions of concentration and pressure was number 3 ($\varnothing$ 8 mm, version 1), with a value of 66 %. The second highest efficiency was found with cyclone 4 ($\varnothing$ 8 mm, version 2). These results prove that a smaller cyclone diameter has a positive effect on the energy-saving features of starch cyclones. The anomalous behavior of cyclone 5 was caused by a metal piece accidentally deposited in the inlet. Since there was no possibility of repeating the experiments after removing the metal part, no conclusions can be drawn for cyclone 5 under Condition 3.

![Efficiency curves for cyclones at 237 g/L and 500 kPa](image)

Figure 4.3. Curves for tested cyclones at 236 g/L (12 °Bé) of feed concentration and 500 kPa (5 bars) of delta pressure.
Condition 4: Starch concentration 236 g/L (12 °Bé) and pressure 700 kPa (7 bars)

The last testing conditions gave the efficiency plot of figure 4.4. When the starch concentration is 236 g/L (12 °Bé) and the delta pressure is 700 kPa (7 bars), cyclone 8 (SLA Ø 10 mm standard cyclone) reached the highest efficiency. The second highest efficiency was found with cyclone 5. This favorable result for cyclone 5 indicates its high potential for the previous conditions had the unfortunate metal part not ended up inside the inlet. This situation should be investigated in the future.

In general, low pressures produce more variability in the efficiency than high pressures, this is, the curves for low pressure conditions present a wider range of operation while high pressure curves are closer to each other, as shown in figure 4.4.

Curves for tested cyclones at 236 g/L and 700 kPa

Figure 4.4. Curves for tested cyclones at 236 g/L (12 °Bé) of feed concentration and 700 kPa (7 bars) of delta pressure.
The results of the experiments under the four conditions of concentration and pressure tested are summarized in table 4.1. One of the most important findings this table is showing is that hydrocyclone number 3 is the one that gives the highest efficiency even in low pressure conditions (500 kPa). As a result, this cyclone was the most appropriate for low pressures. Conversely, results were not so homogeneous when inlet pressure was set to 700 kPa. Given that one of the ways to reduce energy consumption is by keeping a low inlet pressure, and cyclone 3 performs well for both concentrations tried, the results of the experiments suggest that cyclone 3 operating at 500 kPa and 236 g/L is the most reasonable option of the set tried. Other cyclones with encouraging results which can be considered potential solutions are hydrocyclones 4, 1 and 8, in decreasing order of preference according to the desirable conditions of low pressure and high concentration. As hydrocyclone 2 also behaves acceptably for low pressures, it should be taken into account in the future as well.

<table>
<thead>
<tr>
<th>Concentration (g/L)</th>
<th>153</th>
<th>153</th>
<th>237</th>
<th>237</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta pressure (kPa)</td>
<td>500</td>
<td>700</td>
<td>500</td>
<td>700</td>
</tr>
<tr>
<td>1st position</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>2nd position</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3rd position</td>
<td>8</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>4th position</td>
<td>2</td>
<td>8</td>
<td>8</td>
<td>2 &amp; 3</td>
</tr>
</tbody>
</table>

**Individual performance of the hydrocyclones for all the conditions tested**

Once a hydrocyclone has been selected, it is very interesting to see how it behaves when working conditions vary. The following discussion takes this idea into account and bases its conclusions on the graphical representation of the efficiency for each cyclone when conditions change according to the directions given by table 4.1.
As we can see in figure 4.5, hydrocyclone 1 (Larsson existing standard cyclone Ø 10 mm) has the highest efficiency at the least desirable conditions: low concentration and high pressure. In fact, as shown in figure 4.2, cyclone’s 1 curve reached the highest efficiency point of all cyclones and conditions, with a value of 76%.

One of the strong points of this cyclone, apart from its high efficiency, is that it can operate at a wide range of pressures, as shown in figure 4.5. This feature makes cyclone 1 a good candidate when process conditions are not stable.

Figure 4.5. Efficiency curves for Hydrocyclone 1 at different conditions of concentration and delta pressure.

Figure 4.6 illustrates the efficiency curves for hydrocyclone 2 (20% PTFE, Ø 10 mm). The only difference between this cyclone and the first one is the material used in its construction; cyclone 1 is made of plastic PA66 whereas cyclone 2 has been constructed with plastic PA66 plus a 20% of PTFE. Being the material the only difference, we might expect a similar behavior, but results show that the responses of both cyclones are quite different, as seen
if figures 4.5 and 4.6 are carefully compared. The curves for low concentrations are not dissimilar but the curves for high concentrations are shifted; cyclone 2 gives the lowest efficiency at high concentration and low pressure whereas the worst efficiency for cyclone 1 is found at 700 kPa (7 bars). These surprising results, if properly validated by further experiments, provide a good recommendation in terms of ideal material for manufacturing new cyclones. Cyclone 1 is preferable to meet the goal of low pressure processes.

![HYDROCYCLONE 2](image)

Figure 4.6. Efficiency curves for Hydrocyclone 2 at different conditions of concentration and delta pressure.

Hydrocyclone 3 (Ø 8 mm version 1) features a diameter reduction of 2 mm. The corresponding efficiency curves are depicted in figure 4.7.
This hydrocyclone can also operate at a wide range of pressures, as shown in figure 4.7, thus, it could be suitable if unexpected variations of pressure occur.

According to figure 4.7, hydrocyclone 3 works well at low pressures and high concentrations of starch, which are the desired conditions. The curve corresponding to 236 g/L (12 °Bé) and 500 kPa (5 bar) reaches the highest value of efficiency in the plot. This outcome means that cyclone 3 can be fed with high concentrations (desirable to save time and money) and lower pressure (energy-saving condition) with an acceptable efficiency. These results place cyclone 3 as the favorite one so far to meet the project objectives. Table 4.2 compares the top efficiencies of cyclones 1 and 3 for the set of conditions programmed in the experiments.
Table 4.2. Hydrocyclones 1 and 3. Comparison of efficiencies for different conditions.

<table>
<thead>
<tr>
<th>Cyclone</th>
<th>Conditions</th>
<th>% of Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>153 g/L</td>
<td>500 kPa</td>
</tr>
<tr>
<td>Cyclone 1</td>
<td>67</td>
<td>77</td>
</tr>
<tr>
<td>Cyclone 3</td>
<td>68</td>
<td>72</td>
</tr>
</tbody>
</table>

The highest efficiency ever reached in the experimental phase of this project was found with cyclone 1, but that value was linked to the least desirable conditions of low concentration and high pressure. However, when setting low pressure (500 kPa or 5 bars) conditions, cyclone 3 reached higher efficiencies than cyclone 1, especially with starch concentrations of 236 g/L (12 °Bé), therefore cyclone 3 can operate efficiently at low pressures with high concentrations. It would be desirable to find an alternative geometrical design that could increase the efficiency for that particular case of high concentration and low pressure. Further research is needed to modify the geometry of the 8 mm cyclone in such a way that it can deliver even better efficiency at high concentrations and low pressures.

Cyclone 4 (8 mm-diameter cyclone, version 2) got the second best performance for 236 g/L (12 °Bé) and 500 kPa (5 bars), as shown in figure 4.9. This consistency hints at the fact that a diameter reduction results in better outcomes. Despite this desirable fact, the highest efficiency curves are still held by conditions of low concentration and high pressures (top curve). The set of curves for hydrocyclone 4 (Ø 8 mm, version 2) are represented in figure 4.9. Although this cyclone has the same diameter as hydrocyclone 3, there are significant differences in their efficiency. Values for cyclone 4 are not as high as for cyclone 3. The physical difference between both versions is in the inlet design: the inlet formula for hydrocyclone number 3 (Ø 8 mm, version 1) is shown in equation 4.1, and the inlet formula for hydrocyclone 4 (Ø 8 mm,
version 2) follows equation 4.2. The spiral generated with equation 4.1 and incorporated to the inlet area of hydrocyclone 3 is shown in figure 4.8.

\[
R (\text{mm}) = 6 - 1 + \cos (t \cdot 180) \quad t \in [0, 1] \quad \text{[Eq. 4.1]}
\]

\[
R (\text{mm}) = 6 - 2t \quad \text{[Eq. 4.2]}
\]

Figure 4.8. Inlet spiral for hydrocyclone 3.

As before, the efficiency for 153 g/L (8 °Bé), 700 kPa (7 bar) conditions has the highest value. According to the curve 236 g/L (12 °Bé) - 500 kPa (5 bar), it can be seen that efficiency is relatively high, but not high enough to consider this cyclone superior to number three in terms of energy-saving qualities.
Figure 4.9. Efficiency curves for Hydrocyclone 4 at different conditions of concentration and delta pressure.

The efficiency results for hydrocyclone 5, a machined standard cyclone of 10 mm diameter, are shown in figure 4.10. As mentioned before, the curve for 236 g/L (12 °Bé), 500 kPa (5 bar) was not valid because a metal part fell into the inlet body, spoiling the test data. Given that the rest of the curves show a positive behavior, good results are also expected for this situation. It would be recommendable to repeat the failed experiments as prospectives are favorable.
Figure 4.10. Efficiency curves for Hydrocyclone 5 at different conditions of concentration and delta pressure.

Figure 4.11 provides the efficiency curves for hydrocyclone 6, a vortex 10 mm cyclone. These curves follow the predicted trend: efficiency increases when pressure does, and decreases with increasing concentrations. Overall values of efficiency are acceptable, but cyclone 6 cannot be considered as a good cyclone for saving energy, which is the goal of the present study.
Figure 4.11. Efficiency curves for Hydrocyclone 6 at different conditions of concentration and delta pressure.

Hydrocyclone 7 was entirely designed for this study, unlike the other six cyclones which were built and developed by Larsson following their own experience-based specifications (the one missing was a commercial one). The details of the design process for cyclone 7 have been described in Chapter 2, and it follows the recommendations published in the specialized technical literature listed in Chapter 7. According to the results found in the experiments, and represented in figure 4.12, the new geometry proposed does not make cyclone 7 more efficient than the other ones. The fact that there was no specific information published about wheat starch can account for the low efficiency obtained. Yet, the shape of the curves was similar to the other cyclones’ curves and the efficiency no very much lower. With more opportunities for modifying and testing the initial prototype, as is usually done in R & D departments, the efficiency would surely improve after a few iterations. This study shows that the particular size of the particles traversing the cyclone is a key factor in the design of the cyclone. The geometrical
properties of hydrocyclones cannot be the same for potato starch, tapioca starch or wheat starch.

All cyclones, except number 7, have a maximum efficiency range between 64% and 76%. The maximum efficiency point for cyclone 7 is situated at 58%. The trials realized with cyclone 7 did not reach high underflow pressures. For that reason, it was difficult to have many points in the curve since the flow almost disappeared at middle values of underflow pressure. This disadvantage could be due to the resistance offered by the cone spiral, but this conjecture should be properly checked with carefully designed experiments. According to practical observations during the experiments, the low efficiency of cyclone 7 can be caused by either the shape of the vortex finder or the cone spiral.

The last cyclone tested was number 8, a prototype generated with SLA (Stereolithography) techniques and a diameter of 10 mm. Stereolithography is a 3D reconstruction method based on a UV laser that builds, layer by layer, a piece drawn with CAD techniques. The efficiency plots of cyclone 8 are

Figure 4.12. Efficiency curves for Hydrocyclone 7 at different conditions of concentration and delta pressure.
represented in figure 4.13. When comparing the maximum efficiency of each curve for this cyclone and cyclone 1, (current standard cyclone Ø 10 mm), manufacturing techniques do not seem to influence the final results significantly. Cyclones 1 and 8 have approximately the same efficiency range values, despite they have been fabricated following different ways. However, we can observe an interesting difference: for 236 g/L (12 °Bé) and 700 kPa (7 bars), cyclone 8 has higher efficiency than cyclone 1; nevertheless, the highest efficiency in cyclone 1 is found for 153 g/L (8 °Bé) and 700 kPa (7 bars). This fact is further detailed in table 4.3.

Figure 4.13. Efficiency curves for Hydrocyclone 8 at different conditions of concentration and delta pressure.
Table 4.3 Differences of efficiency between hydrocyclones 1 and 8.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Concentration g/L</th>
<th>153</th>
<th>153</th>
<th>236</th>
<th>236</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delta pressure kPa</td>
<td>500</td>
<td>700</td>
<td>500</td>
<td>700</td>
</tr>
<tr>
<td>Hydrocyclone 1</td>
<td>Standard cyclone Ø 10 mm</td>
<td>67%</td>
<td>76%</td>
<td>56%</td>
<td>62%</td>
</tr>
<tr>
<td>Hydrocyclone 8</td>
<td>SLA – prototype standard design Ø 10 mm</td>
<td>67%</td>
<td>71%</td>
<td>56%</td>
<td>66%</td>
</tr>
</tbody>
</table>

In the course of the experiments a hybrid hydrocyclone was accidentally assembled with the vortex of hydrocyclone 7 and the bottom part of the hydrocyclone 1. This combination did not lead to any advantage with respect to the set of cyclones already described. As a matter of fact, the efficiency was always lower, therefore, in light of these results, hybridization of hydrocyclones by swapping parts is not recommended at all. Nevertheless, these additional tests seemed to prove that the responsible for diminishing the efficiency might be the vortex rather than the cone spiral. In any case, no definite conclusions can be drawn with respect to the effects of cone spirals and vortices on efficiency unless more research is tackled.
Chapter 5

Conclusions

The main objective of this project was the improvement of hydrocyclone efficiency for wheat starch separation, and this overall goal has been reached. There is a hydrocyclone, out of the eight tested, that clearly meets the requirements to be considered an energy-saving hydrocyclone. This cyclone is the 8 mm cyclone (version 1) manufactured by Larsson Company. It worked better, not only for the desired pressure condition of 500 kPa, but also for the optimum combination of pressure and concentration given by 236 g/l and 500 kPa.

The Larsson Hydrocyclone version 2, also with a diameter of 8 mm, has the second highest efficiency for the desired combination of pressure and concentration. The standard 10 mm Larsson hydrocyclone is near the best efficiencies for the desired conditions and reaches the top efficiency for a pressure of 700 kPa and a concentration of 153. The 8 mm cyclone which yielded the best results was obtained by modifying this 10 mm version.

Another hydrocyclone evaluated in this project was the standard 10 mm Larsson cyclone, but manufactured applying Rapid Prototyping Stereolitography (SLA) techniques. This model had values of efficiency that were lower than those found for the standard 10 mm hydrocyclone. It seems that, according to experimental observations, the way of manufacturing hydrocyclones directly affects efficiency values, but definite conclusions cannot be drawn until more research is done.

The geometry-based hydrocyclone designed and developed over this project had low efficiency and could not operate favorably for a wide range of underflow pressures. The apparent reason for this outcome might be in the introduction of too many geometrical variations in one single cyclone, which complicates the discrimination of the individual effect of each parameter on the
final efficiency value. A better approach could have been followed by modifying the prototype step by step while registering the efficiency after each modification made. The only reason for not proceeding in that way is the scarcity of time for testing at a remote facility. The scheduled time for conducting all the experiments was one week, and some time was needed to check the testing bench. Despite the low efficiency values found for this hydrocyclone, it cannot be assured that these innovative modifications are not beneficial because if they had been individually evaluated, a more realistic assessment would have probably been realized. Therefore, the presence of a spiral in the conical part of the cyclone, the decrease of the overflow diameter, and the extension of the vortex finder length seem to be positive modifications to raise efficiency.

Not much research has been published on the enhancement of efficiency in wheat starch separation processes. The specific conclusions drawn from the tests performed on the geometry-based cyclone proposed and designed in this project are the following:

- The recommended prototype hydrocyclone should be tried without the spiral carved on its conical part because this element can increase the resistance to flow and, contrarily to what has been suggested by Svarovsky (1984), it might decrease the efficiency of the cyclone.

- Improvements are to be expected if the cyclone incorporates a different vortex. The current one introduced a significant change compared to those showing better efficiency values. In particular, it should be tried with a shorter vortex finder and with a smaller overflow diameter.

- The introduction of a central part in the hydrocyclone’s body to avoid the turbulences created by rough rotational flows produced when the feed enters tangentially will probably enhance efficiency although it involves a more sophisticated design. In fact, Chu et al. (2000) found that the insertion of a central part on a cyclone was the most significant parameter on the energy loss coefficient.
The influence of the average particle size on the hydrocyclone design still remains an unknown factor, which should be carefully studied in the future.

This interesting research opened several paths for further investigations. In particular, next steps could be taken in the following directions:

- Enhancement of the efficiencies of those hydrocyclones that gave the best results in the trials by slightly changing the geometry of the cyclone, especially for version 1 cyclone of 8 mm, which has very promising features.

- Study if the way of manufacturing cyclones has a notable influence on efficiency values. If the correlation is negative, hydrocyclones could be manufactured using rapid-prototyping techniques, with the consequent savings of manufacturing costs.

- Sequential testing of all the geometric modifications proposed by Chu et al. (2000) in one hydrocyclone model.
Chapter 6

Acknowledgements

I would like to thank Larsson M. Verkstad AB, and especially Jonas Oskarsson and Thomas Johansson, for allowing me to carry out this research project and have a wonderful industry experience for my degree project. I feel in debt with Professor Samir Khoshaba from the Department of Technology and Design of Växjö University, who has taken care of all my needs, both personal and academic, from my very first day in Sweden. I am deeply grateful for all his assistance and advice. I would also like to express my gratitude to the Erasmus Program and the Offices of International Programs at Växjö University and the Polytechnic University of Valencia. Credit needs to be given to my advisor in Valencia, Francisco Rovira Más, who has been very helpful with technical and research guidance from the early steps. Finally, it would not be fair to exclude my family from this section, who have encouraged me to get on board this adventure, and whose daily support has been crucial for a successful ending.

My most sincere appreciation to all of you.
Chapter 7

References


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APPENDIX I: MATLAB CODE FOR HELIX DESIGN

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

HYDROCYCLONES: DESIGN OF FLAT SPIRAL

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% By Verónica Sáiz Rubio. Växjö University, Sweden. February, 2009

% spiral_flat.m

% 1- Definition of variables

% NOTE: This is the only section that needs to be changed (input parameters: Rmax, Rmin)

Rmax = 5.5; % Radius for External circle
Rmin = 5; % Radius for Internal circle
sr2= 1.414214;

% 2- Determine size of array and generate vectors

t = linspace (0, 2*3.141592, 300); % the array has 300 points between 0 and 2*pi
[i,nt]= size(t);

%phi = linspace (0, (5/4)*3.141592, 300); % the array has 300 points between 0 and 225 deg
phi = linspace (-3.141592*0.25, 3.141592, 300); % the array has 300 points between -pi/4 and pi
[i,np]= size(phi);

Cext = zeros(1,nt); % Polar coordinates; initialization
Cint = zeros(1,nt);
R = zeros(1,np);

% 3- Create the helix for input parameters and bounding circles

% Based on cardioid equation

%R = (Rmax+Rmin)/2 + (Rmax-Rmin)*(sr2-2)*0.5/(2+sr2) + (2*(Rmax-Rmin)/(2+sr2)).*cos(phi);
R = Rmax + (Rmin-Rmax)*2/(2+sr2) + (2*(Rmin-Rmax)/(2+sr2)).*cos(phi);
Cext = Rmax.*ones(1,nt);
Cint = Rmin.*ones(1,nt);

% 4- Plot results

polar(t,Cext,'b.'); % External circle
hold on; polar(t,Cint,'g.'); % Internal circle
hold on; polar(phi,R,'ro'); % SPIRAL 0 - 225 deg
APPENDIX II: MATLAB CODE FOR HELIX DESIGN

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
HYDROCYCLONES: DESIGN OF SPIRAL [conical helix]
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By Verónica Sáiz Rubio. Växjö University, Sweden. February, 2009

1- Definition of variables

NOTE: This is the only section that needs to be changed (input parameters: Rmax, Rmin, L, Le)

Rmax = 5 ; % Radius in mm of wide section of the cone
Rmin = 1.5 ; % Radius in mm of narrow (output) section of the cone
L = 57 ; % Length of cone, always in mm
Le = 5 ; % helix pitch in mm

2- Determine size of array and generate parametric vector t

n = floor(L/Le); %number of loops

\[ t = \text{linspace}(0, \text{floor}(n*2*3.141592), 300) \]
\[ [i,nt]= \text{size}(t) \]

3- Create the helix for input parameters

Parametric equations with Cartesian coordinates

\[ z = \left( \frac{Le}{6.283185} \right) t; \]
\[ x = \left( Rmin + \left( Rmax - Rmin \right) \frac{L-z}{L} \right) \cos(t); \]
\[ y = \left( Rmin + \left( Rmax - Rmin \right) \frac{L-z}{L} \right) \sin(t); \]

4- Plot results

\[ \text{plot3}(x,y,z, 'r-'); \]
\[ \text{xlabel ('X [mm]'); ylabel ('Y [mm]'); zlabel ('Z [mm]'); title ('Conical helix for experimental hydrocyclone');} \]

figure; \[ \text{plot3}(x,y,z, 'm-'); \]
\[ \text{xlabel ('X [mm]'); ylabel ('Y [mm]'); title ('Front view of Conical helix');}] \]

view (0,90); \[ \text{figure; plot3}(x,y,z, 'b-'); \]
\[ \text{xlabel ('X [mm]'); ylabel ('Y [mm]'); title ('Lateral view of Conical helix');}] \]

view (90,0);