Determination of Rotary Filter Behavior

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Determination of Rotary Filter Behavior:
Evaluation of Rotary Filtration for Microalgae Concentration

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Final Report
Monday Lab

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“We have neither given nor received aid on this project, nor have we concealed any violation of the Honor Code.”

____________________________________  ______________________________
Justin Donofrio                           Christopher McMullen
ABSTRACT

Brown Industries, Inc. is looking to study the use of microalgae to produce biodiesel. Rotary filtration has been introduced to deal with removal of excess water from the algae feedstock. Rotary filtration Rotation Team 1 investigated the operation limits and basic behaviors of the rotary filter utilizing both water and dilute algae feedstock.

Objectives included:

(a) Characterization of filter behavior and operating limits with water

(b) Definition of operating limits with algae

(c) Suggestion of a procedure for concentrate concentration estimation

(d) Characterization of filter behavior and fouling with algae feedstock

Investigation of the rotary filter was successful. With a water feed, filtrate flow increases with chamber pressure and decreases with rotational speed. With algae feed, low chamber pressure and high rotational speed is not recommended because of low filtrate flow rate. The algae concentrate concentration can be accurately predicted under certain operating conditions. Filter fouling decreases filtrate flow rate over time when filtering algae feedstock, but can be controlled by altering the chamber pressure and filter rotation speed. Rotary filter operation may be enhanced by investigating the effects of agitation through periodic reverse filtration.
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INTRODUCTION

Overview

Brown Industries is investigating the use of rotary filtration to concentrate the algae effluent from the photobioreactor. Rotary filtration is useful for applications in which a stationary filter would become plugged with the concentrated product. The motivation for this project is to characterize filtration in the Brown Industries custom-built 5-micron 316 stainless steel rotary filtration apparatus. The information gained through this assignment will be used by other teams to optimize and scale-up the filter for 10 million gallon/year biodiesel production.

Goals and Objectives

The goal of this rotation assignment is to study the operating envelope and the basic behaviors of the Brown Industries rotary filtration unit. Based on the results of this assignment, future rotation assignments can find its optimal operating conditions and scale it up for an industrial-scale algae dewatering process. Specifically, this assignment will focus on the following objectives:

1. Characterize the properties and limitations of the filter using only water. Describe how the controlled variables of pressure drop and filter rotational speed affect filtrate flux.
2. Characterize the limitations of the filter with algae slurry.
3. Define a procedure to calculate estimated concentrations of the algae concentrate from the available process data.
4. Characterize the dependence of mass flux to changes in pressure drop, rotation speed, and time of operation. Study the effects of filter fouling on filter performance and the effectiveness of agitation in mitigating fouling.

Summary of Key Results

When water was fed into the filter, it was found that filtrate flow will increase with chamber pressure and decrease with the filter rotation speed. When algae was fed into the filter, it was determined that high filter rotation speed coupled with low chamber pressure are outside of the chamber’s operating envelope. Furthermore, a procedure was developed, based on mass balances, to estimate the concentration of the effluent algae; this procedure was accurate under certain operating conditions. As more algae was fed into the filter, the flow of filtrate decreased with time. There is a trade-off with filter rotation speed—faster rotation results in less fouling with a worse initial filtrate flow rate, but low rotation speed leads to significant fouling with higher initial filtrate flow rates. There is a second trade-off with chamber pressure—higher pressure allowed for better filtrate flow, but lower pressure resulted in purer filtrate.

BACKGROUND AND THEORY

In order to use microalgae in the production of biodiesel, some method of harvesting must be used to remove excess water. Algae can only grow in dilute solutions, so the algae slurry produced by a photobioreactor must be concentrated before lipid extraction. The rotary filter
utilizes a combination of centrifugation and filtration harvesting techniques to remove the excess water from microalgae.

The initial feed of dilute microalgae from a photobioreactor is generally in the concentration range of 0.02% to 0.06% TSS (total suspended solids). A final microalgae cell solution between 15% and 25% TSS is desired before lipid extraction. To achieve the desired algae concentration, a two-stage process is used. The first stage, harvesting, brings the algae concentration up to 7%. Harvesting can be performed using a number of techniques, but this report will investigate rotary filtration. The second stage can be completed by centrifugation (Uduman, 2010).

Rotary filtration uses centripetal forces to separate solids and liquids based upon the particle size and density differences of the mixture’s components (Uduman, 2010). In essence, the centripetal force created by the spinning filter effectively shears the microalgae solids off the filter, extending the time before the filter is rendered ineffective due to clogging of the filter pores. The Brown Industries apparatus operates at a semi-batch state, where the diluted algae feed from the photobioreactor is continuously fed into the rotary filter at a rate approximately equal to the rate of water filtrate leaving the filter. This results in an accumulation of concentrated algae in the filter chamber, which is then drained as the concentrate product.

Rotary filtration is one among many harvesting techniques used to obtain high concentration microalgae mixtures. Two other popular harvesting methods include standard filtration and flotation. Standard filtration utilizes membranes of modified cellulose (the modified cellulose is dependent on the type of algae harvested) and a suction pump system. The pump is used to pull water across the membrane, removing excess water from the microalgae mixture. The major issues with standard filtration include the frequency of filter clogging by packed algae cells along the filter wall and an intrinsic limitation to small working volumes based on filter size. The second harvesting method, flotation, works by bubbling air through a tank or column filled with the feed microalgae slurry. The microalgae accumulate above liquid level and are then collected using suction. Problems associated with flotation harvesting include inconsistent final concentration of the harvested algae, and high cost compared to centrifugal and standard filtration (“Harvesting of microalgae”).

Many attempts have been made to enhance the effectiveness of the three listed harvesting techniques. A popular enhancement strategy involves the use of flocculating agents. Flocculating agents are chemicals added to the pre-harvested microalgae slurry that induce faster settling rates and increased clumping of algae cells. Faster settling rates increase the efficiency of flotation harvesting, whereas increased clumping makes filtration methods more efficient. However, separating flocculating agents from harvested microalgae is difficult, costly and sometimes counterproductive in terms of obtaining pure microalgae (“Harvesting of microalgae”). As a result, combining other separation techniques to create flocculation-flotation or flocculation-centrifugation operations could be effective, but are cost ineffective at present (Uduman, 2010).
MATERIAL AND METHODS

Equipment

The following equipment is required for successful rotary filter operation.

*Essential components of the rotary filter*

- Porous metal cylindrical filter 9-in. long and 2.3-in. diameter. Filter is rated at a 5-micron pore size made of type 316 stainless steel.
- Polycarbonate plastic cylindrical pressure vessel with a 3.75 in. inside diameter equipped with stainless steel end pieces.
- Variable speed motor that can be adjusted between zero and 2000 RPM to rotate the filter inside the pressure vessel.
- Peristaltic pump to feed algae solution into the pressure vessel. Pump speed is adjustable to match desired filtrate flow rate.
- Back-pressure regulator used to regulate pressure outside the filter. Adjustable to any desired pressure between zero and 25 PSIG.
- Three plastic collection buckets with volume capacities greater than 12-L.
- Magnetic stir bar and stir plate.
- LabView data collection software for measuring filtrate flow rate.

*Essential components for visual absorbance*

- Kimax 13 x 100 mm optical test tubes with screw on caps
- Some method of marking test tubes (marker, tape)
- Micro stir bar
- Syringe (10 mL)
- Thermo Scientific Genesys 20 Spectrophotometer
- KimWipes lint-free paper towel

Figure 1, below, depicts the rotary filter apparatus.
Materials

Materials required for rotary filter operation include:

- 25–40 liters of dilute (~1 g/L) algae (C. vulgaris) solution
- Tap water
- At least two liters of 3% hydrogen peroxide solution
- Pressurized air (available at least 25 psi)

Experimental Procedure

Objective 1: Characterization of filter properties using water

When the feed is water, the filtrate flux is a function of the two process parameters: chamber pressure and filter rotation speed. With no algae in the system, there was no fouling of the filter, so filtrate flux was independent of the duration of filtration. In order to achieve Objective 1, chamber pressure and filter rotational speed were varied to study the effects on filtrate flux. LabView software recorded the mass flow rate of the filtrate stream.

In order for filtration to be effective, there must be sufficient water flux through the filter such that the algae slurry can be sufficiently dewatered. Operating situations where sufficient flux could not be produced with water would not be considered in the operating envelope for water.
feed.

Table 1, below, shows the experimental trials that were run to find the aforementioned correlations between flux and the process parameters, as well as to define the operating envelope. For each trial, the procedure outlined by “SOP for algae filtration using a rotary filter” (Reodacha, 2012) was used (with water in place of algae slurry). The trials were run until the flux of water through the filter reached steady state (i.e. - the mass flow rate of filtrate stabilized).

<table>
<thead>
<tr>
<th>Chamber pressure (psig)</th>
<th>Filter rotation speeds (rpm)</th>
<th>Repeats per trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0, 1010, 2100</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>0, 1010, 2100</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>1010</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>0, 1010, 2100</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1: Trial runs for achieving Objective 1

**Objective 2: Characterization of filter**

The second objective is similar to the first in that a characterization of the filter in different operating conditions was sought; however, the presence of algae in the slurry caused fouling of the filter. As such, duration of filtration becomes an additional parameter. To achieve Objective 2, a similar experimental setup was used as in Objective 1. The trials were run until the feed slurry bucket was emptied. Additionally, the filter was cleaned with water before each trial. The cleaning procedure was derived from “SOP for cleaning the rotary filter” (Reodacha, 2012); however, the hydrogen peroxide cleaning step was only carried out at the end of each lab session.

The trials run for Objective 2 are described in Table 2, below. The data from these trials was also used to achieve Objectives 3 and 4. It was desired to run more trials at higher chamber pressures, but the peristaltic pump failed during the final lab sessions before these trials could be run.

<table>
<thead>
<tr>
<th>Chamber pressure (psig)</th>
<th>Filter rotation speeds (rpm)</th>
<th>Repeats per trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0, 1010, 2100</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>1010, 2100</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 2: Trial runs for achieving Objective 1

**Objective 3: Procedure for estimation of the algae concentrate concentration**

The third objective, estimation of the concentration of the concentrate product, can be achieved through mass balances. A simplified illustration of the rotary filtration process is shown in Figure 2, below.
The system can be described using an overall mass balance:

\[ m_{\text{feed}} = m_{\text{filtrate}} + m_{\text{concentrate}} \]  \hspace{1cm} (1)

where

- \( m_{\text{feed}} \) = total mass of the algae slurry fed to filter (g)
- \( m_{\text{filtrate}} \) = total mass of effluent filtrate (g)
- \( m_{\text{concentrate}} \) = total mass of algae concentrate (g)

and the algae component mass balance (assumes that the filtrate contains no algae):

\[ m_{\text{feed}} x_{\text{feed}} = m_{\text{concentrate}} x_{\text{concentrate}} \]  \hspace{1cm} (2)

where

- \( x_{\text{feed}} \) = mass fraction of algae in feed (g algae / g feed)
- \( x_{\text{concentrate}} \) = mass fraction of algae in the concentrate (g algae / g concentrate)

The mass fraction of algae in the feed can be accessed through the density and algae concentration:

\[ x_{\text{feed}} = \frac{c_{\text{feed}}}{\rho_{\text{feed}}} \]  \hspace{1cm} (3)

where

- \( c_{\text{feed}} \) = concentration of algae in the feed (g algae / L feed)
- \( \rho_{\text{feed}} \) = feed density (g feed / L feed)

The density of the algae feed was measured by measuring the mass of a sample of known volume. The feed concentration was measured by visual absorbance using the Thermo Scientific Genesys 20 Spectrophotometer, using “SOP for Visual Absorbance” (Gonik, 2010). Equations (1), (2), and (3) can be combined and solved for the mass fraction of algae in the concentrate:
\[ x_{\text{concentrate}} = \frac{(m_{\text{filtrate}} + m_{\text{concentrate}})c_{\text{feed}}}{\rho_{\text{feed}} m_{\text{concentrate}}} \] (4)

Small discrepancy between the estimated concentration and the experimental concentration of the concentrate occurs for a number of reasons. To better understand the extent of the filter error, the concentrate concentration was measured for all experimental trials.

**Objective 4: Characterization of filtration, fouling, and fouling mitigation**

As was mentioned in Objective 2, the same trials and data may be reused in the characterization of filtration across different operating conditions.

**Safety**

The rotary filter is a fast spinning pressure gradient dependent device that should be utilized carefully. Operators should wear the proper personal protection equipment (PPE), which includes goggles, lab coats, long pants, and closed-toe shoes at all times. Operators should be aware that there are fast moving parts associated with the spinning filter, and that friction may cause these parts to get extremely hot. Operators should not try to adjust anything associated with the rotary filter while the device is in operation, taking care to turn the apparatus off before putting extremities within close proximity to moving parts. Operators should also refrain from exceeding design parameters. For instance, do not allow the backpressure regulator to exceed 25 psig. Operators should also take care to ensure that all pressure has been vented before opening exit valves, to avoid any accidental forceful discharge due to pressure buildup.

**RESULTS AND DISCUSSION**

**Objective 1: Characterization of filter properties using water**

Since no fouling should occur in the absence of algae, the mass flow rate of filtrate should be constant with respect to time in each of the trials run with water feed. This expectation was confirmed with the experimental data by plotting the filtrate flow rate against time. (See example trials in Figure 3.) If there was significant variance in the filtrate flow rate throughout the trial or if there was a trend in the flow rate, the trial was rejected. Few trials were rejected.
Figure 3: Various water runs at 5 psi show that filtrate flow remains mostly constant.

The filtrate flow was plotted as a function of filter rotational velocity and of the pressure drop across the filter. (It was assumed that the pressure inside the filter was approximately 0 psig so that Δp = pchamber.)

As is shown in Figure 4, below, the filtrate flow increased with chamber pressure (increased pressure drop), as was expected. The larger pressure drop provided a greater driving force for water through the filter.

Figure 4: Filtrate flow increases with chamber pressure
As is shown in Figure 5, below, the filtrate flow decreased with the filter rotational speed. This can be explained by the fact that a low-pressure boundary layer forms around the chamber-side of the filter. (The pressure in the boundary layer is lower because of the high fluid velocity relative to the bulk of the fluid.) The lower local pressure creates a lower effective pressure drop to drive water through the filter. Flow is also hindered in the direction normal to the tangential boundary layer flow.

![Figure 5: Filtrate flow decreases with filter rotational speed.](image)

There are practical operating limits to the Brown Laboratories rotary filtration apparatus. In particular, with water feed, too low of chamber pressure (in the range of 2.5 psi) coupled with high filter rotational speed (in the range of 2000 rpm) can actually cause water to flow in reverse through the filter because the lower local pressure in the boundary layer actually falls below the atmospheric pressure inside the filter.

**Objective 2: Characterization of filter limitations using algae**

In this objective, the limitations of a practical operating envelope for the rotary filter were explored. In order to determine operating limitations, criteria were set for a minimum filtrate flow so that the filtration would take too long. Also, purity requirements were considered for the concentration of algae in the filtrate. Based on these criteria, certain pressure and rotational speed combinations were deemed unacceptable for effective rotary filter operation.

When the filter is stationary, the initial filtrate flow is very high; however, the filter would almost immediately foul. The trial runs operating at 5 psi and zero rotational speed, shown in Figure 6, below, exhibit a very rapid drop in filtrate flow rate. The filtrate flow fell below 3 g/s after only 30 seconds of operation. As the operation time extended, fouling continued to worsen, rendering operation at zero rotational speed impractical for effective use of the filter.
Objectives:

Objective 3: Estimation of the algae concentrate concentration

Estimated and experimental concentrations of the algae concentrate obtained using the aforementioned procedure for four of our trails are shown below in Table 1.

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Rotation (rpm)</th>
<th>$x_{\text{conc}}$ (g/L) calculated</th>
<th>$x_{\text{conc}}$ (g/L) measured</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0</td>
<td>0.121</td>
<td>0.116</td>
<td>3.551</td>
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<tr>
<td>5</td>
<td>2100</td>
<td>0.136</td>
<td>0.124</td>
<td>9.526</td>
</tr>
<tr>
<td>10</td>
<td>1010</td>
<td>0.283</td>
<td>0.346</td>
<td>-18.089</td>
</tr>
<tr>
<td>10</td>
<td>2100</td>
<td>0.295</td>
<td>0.209</td>
<td>40.967</td>
</tr>
</tbody>
</table>

Table 3: Calculated versus actual concentrate concentrations

For the trials operating at 5 psi, the procedure provided a fairly accurate estimate of the algae concentrate concentration. The estimate was accurate because most of the assumptions made in...
formulating the procedure hold true, namely that the filtrate was fairly pure water. This was not
the case for the trails operating at 10 psi. As mentioned in the Objective 2 analysis section,
above, operation at 10 psi pushes algae through the filter pores resulting in an impure filtrate. If
the filtrate is impure, then accurate estimation of algae concentration in the concentrate can only
be found if the concentration of algae in the filtrate is measured. The algae mass balance outlined
in Equation 2 must be adjusted to include the algae contained in the filtrate.

In addition to the assumption of a pure filtrate, standard operational errors occur to account for
discrepancies between the estimated and actual algae concentrate concentration. It would seem
the most obvious source of error is a result of ignoring the mass of the algae that remain stuck to
the filter after the concentrate is collected. The mass of algae left on the filter wall is substantial
enough to account for the small difference between estimated and actual concentration values.
Investigation of how much algae is lost on the filter wall can easily be done during the backwash
cleaning step of the rotary filter operation using the same general procedure (mass balances)
outlined in Objective 3. However, algae loss due to clumping on the filter wall is beyond the
scope of this report.

Also, consideration must be given to the effects of the recycle stream resulting from the back-
pressure regulator valve. During operation, concentrated algae solution from within the
pressurized chamber is recycled back into the feed stock in order to keep the pressure in the filter
constant. A small amount of algae concentrate is returned back to the dilute algae feedstock
throughout filter operation, effectively making the concentration of the feedstock a function of
time of operation. This would suggest that to obtain a truly accurate estimation of the
concentration, variables accounting for time and reflux flow rate must be added to the estimation
procedure.

The reflux was neglected in this procedure because the flow rate of the reflux stream was
controlled to be as small as reasonably possible. The reflux was likely insignificant compared to
the much larger volume of the dilute algae feedstock, and would therefore not significantly affect
the initial concentration of the feed. However, this reflux issue will become more prominent the
longer the rotary filter is run and may be an even greater issue for scale-up.

Objective 4: Characterization of filtration and fouling

A modified version of the approach used in data analysis for Objective 1 can be used here. The
main difference, however, is that with the introduction of algae, fouling of the filter occurred.
With time, algae would clog the filter pores, so filtrate flow was expected to decrease with time.
In order to make a standard comparison between different process conditions, the flux was
compared for different trials at specific time intervals.

The rotation of the filter was used to combat fouling and extend how long the filter could operate
before it needed cleaning. The different operational settings tested suggest that rotation does help
prevent fouling, but at the cost of filtrate flow rate. Figure 7 below, shows the filtrate flow rate
as a function of rotational speed at 50 seconds elapsed. Similar plots are shown for 0, 180, and
360 seconds elapsed in Appendix A.
The above plots suggest that higher rotation speeds result in low filtrate flow rate, and that filter operation at moderate rotational speeds yields the highest filtrate flow rate. However, operation time must also be evaluated when looking for optimal running conditions. Figure 8, below, displays filtrate flow rate as a function of time at different rotation speeds.

**Figure 7**: Filtrate flow under various process conditions at 50 seconds elapsed

**Figure 8**: Filtrate flow as a function of time at different rotational speeds
Operation without rotation resulted in almost immediate filter fouling at 5 psi. After an additional repeat to confirm the initial results, the zero rpm operating condition was dropped from testing because of the infinitesimal filtrate flow that occurs so quickly after start-up.

For the remaining trials, the relationship between rotational speed and operation time was examined. As shown in the plots above, operation at max rotational speed (approximately 2100 rpm) results in the least amount of fouling. This allows the filtrate flow rate to remain fairly constant for long filter operation. Operation at moderate rotation speed (approximately 1010 rpm) results in a steady drop in filtrate flow rate that results in smaller operation time compared to max rotation speed. However, these results are a bit limited due to the small volume of dilute algae feedstock available for testing. As you can see on the above plots, there is a downward trend at moderate rotation speed. It is unknown whether this trend would continue for longer operation or if this downward slope would eventually level off at some equilibrium point were filter rotation is preventing algae from sticking to the filter and reducing the filtrate flow rate further.

In effect, there is a give-take relationship between high flow rate operation and extended operation time. Another factor to consider when examining rotary filter operation is how operation time, operating pressure, and rotational speed affect the final concentration of the algae concentrate. Analysis of final concentration proved difficult because of the constant change of the algae slurry feedstock concentration between runs and from week to week. To adjust for this, a concentration factor was introduced to the analysis to better judge filter run effectiveness in terms of concentration. The scaling factor used here is merely the ratio of the concentrate concentration to the feedstock concentration. The higher the resultant dimensionless number, the more concentrated the algae concentrate compared to the feedstock composition. A list of the concentration factor results for algae runs is located in Appendix B.

Even with the final concentrations adjusted for easy comparison between different runs, an investigation of what operating conditions yield the most concentrated algae concentrate is inconclusive. The data is inconclusive for a few reasons. Firstly, there are not enough repeat trials using algae to really foster a strong evidence base supporting any type of conclusion on how operating conditions affect concentration of the concentrate. Second, the algae trials were not designed with constant operation time in mind. The rotary filter’s operation time for this report was entirely dependent on how much feedstock was available in lab to work with. Since the feedstock was limited, data was collected until either steady state operation was judged to have been reached or until the feedstock for that particular trial ran out. Variable operating time could have a large impact on algae concentrate concentration, which cannot be deduced from this report’s data. To accurately compare the effects of operating conditions on the algae concentrate, experimental design must compare rotation speed, chamber pressure, and operation time.

**UNCERTAINTY AND ERROR**

**Sources of Error**

There were some blatant sources of error that plagued this investigation and may disrupt the repeatability of the experimental results. Firstly, variation in the algae feedstock was common throughout the investigation period of this report. On different lab days the algae feedstock
varied in total volume available for testing and in initial concentration. The low volume of the algae feedstock resulted in varying operation times, making it difficult to accurately compare operating conditions. Also, the changing initial concentration between trials makes it difficult to reproduce results. Between days two and three the algae feedstock was also left out of the refrigerator, altering the composition of algae on the third lab day. Second, the quality of the filter was different on different lab days, resulting in dramatically different filtrate flow rate between lab day two and three. Finally, the reflux of concentrated algae solution back to the feedstock solution and the impurity of the filtrate were not accounted for in the estimation procedure for algae concentrate. Inclusion of these factors may alter the validity of the concentration predictions.

**Error Analysis**

Most experimental trials were run in duplicate. (See tables of trials: Tables 1 and 2.) For these trials with water fed to the separator, the filtrate flow measurements were averaged and a standard deviation was taken to show error bars. Although there were duplicate trials for the algae trials, they were run across different days when the filter was behaving very differently. While these data points were not repeatable, the trends in filtrate flow remained the same on both days.

**CONCLUSION AND RECOMMENDATIONS**

**Conclusion**

When water was fed into the filter, it was found that filtrate flow will increase with chamber pressure and decrease with the filter rotation speed. When algae was fed into the filter, it was determined that high filter rotation speed coupled with low chamber pressure are outside of the chamber’s operating envelope. Furthermore, a procedure was developed, based on mass balances, to estimate the concentration of the effluent algae; this procedure was accurate under certain operating conditions. As more algae was fed into the filter, the flow of filtrate decreased with time. There is a trade-off with filter rotation speed—faster rotation results in less fouling with a worse initial filtrate flow rate, but low rotation speed leads to significant fouling with higher initial filtrate flow rates. There is a second trade-off with chamber pressure—higher pressure allowed for better filtrate flow, but lower pressure resulted in purer filtrate.

**Recommendations**

A few topics not investigated during this rotation due to time constraints could be worth pursuing in future rotations. Obtaining data to characterize how operating conditions affect algae concentrate concentration is one such topic, and is discussed at length in Objective 4 of the Results and Discussion section above. Time should also be spent collecting data on the effectiveness and efficiency of a second stage filtration approach, in which the algae concentrate is run through the filter again to remove more water from the concentrate. It would be interesting to see if multiple passes through the filter generate a noticeable increase in algae concentrate concentration compared to a single pass system. Future testing should also be conducted to determine how long the filter can sustain significant filtrate flow rate at different pressures and rotation speeds.
In terms of operating recommendations, operation at no rotational speed is strongly discouraged due to quick filter fouling. Utilizing the filter at pressures at and below 2.5 psi is also discouraged because of the extremely low filtrate flow rate. Operation at 10 psi (and presumably pressures higher than 10 psi) is also discouraged if a pure water filtrate is desired. Pressures at and above 10 psi force algae through the filter pores, resulting in algae loss to the filtrate. A filter with smaller pores could correct this high pressure operation issue, but another analysis would need to be conducted to characterize the new filter. However, high pressure operation yields higher filtrate flow rate, so if impure filtrate is not an operating constraint high pressure operation may be useful.

After analysis of the rotary filter in this first rotation it seems obvious that a determination of one set of optimal running conditions is not possible. A more suitable approach for characterizing this equipment is to instead determine optimal operating conditions with different goals in mind. For instance, a determination of what rotation speed at different operating pressure yields the best filtrate flow rate over a specified operation time may be a good way to characterize optimal running conditions. Determination of what set of operating conditions results in the most concentrated algae concentrate after some desired operating time may also be a good way to characterize the filter. In short, investigators should first establish what the target specifications are for the rotary filter before trying to characterize the most desirable running conditions.
REFERENCES


### NOMENCLATURE TABLE

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{\text{feed}}$</td>
<td>concentration of fed algae</td>
<td>g algae / L solution</td>
</tr>
<tr>
<td>$m_{\text{concentrate}}$</td>
<td>total mass of algae concentrate</td>
<td>g</td>
</tr>
<tr>
<td>$m_{\text{feed}}$</td>
<td>total mass of algae feed</td>
<td>g</td>
</tr>
<tr>
<td>$m_{\text{filtrate}}$</td>
<td>total mass of filtrate</td>
<td>g</td>
</tr>
<tr>
<td>$x_{\text{concentrate}}$</td>
<td>mass fraction of algae in concentrate</td>
<td>g algae / g concentrate</td>
</tr>
<tr>
<td>$x_{\text{feed}}$</td>
<td>mass fraction of algae in feed</td>
<td>g algae / g feed</td>
</tr>
<tr>
<td>$\rho_{\text{feed}}$</td>
<td>density of effluent filtrate</td>
<td>g / L</td>
</tr>
</tbody>
</table>
LIST OF APPENDICES

Appendix A: Filtrate Flow Profiles at Various Elapsed Filtration Times

Appendix B: Concentration Facts
Appendix A: Filtrate Flow Profiles at Various Elapsed Filtration Times

**At Start Time**

![Graph showing Filtrate Flow Profiles at Start Time](image)

*Figure A-1*: Filtrate flow profile at the beginning of filtration shows best filtration at medium rotation speeds

**After 180s Run Time**

![Graph showing Filtrate Flow Profiles after 180s Run Time](image)

*Figure A-2*: Filtrate flow profile 180 seconds into the filtration process shows best filtration at medium rotation speeds
Figure A-3: Filtrate flow profile at 360 seconds into the filtration process shows best filtration at medium rotation speeds.

Note: The trials shown in this Appendix were run on a different day than the one depicted in Figure 7. There was a significant difference in filter behavior between the two days, but the same trends were still apparent.
**Appendix B: Concentration Factors**

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Rotation (rpm)</th>
<th>Feed conc. (g/L)</th>
<th>Conc. Conc. (g/L)</th>
<th>Concentration factor</th>
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</thead>
<tbody>
<tr>
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<td>0.6601</td>
<td>0.99</td>
</tr>
<tr>
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<td>0.6647</td>
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<td>1.31</td>
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<td>0.6647</td>
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<td>2100</td>
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<tr>
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<td>0.9443</td>
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</table>

*Table B-1: Concentration factor calculations for algae trials on Day 2 (better filter performance)*

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Rotation (rpm)</th>
<th>Feed conc. (g/L)</th>
<th>Conc. Conc. (g/L)</th>
<th>Concentration factor</th>
</tr>
</thead>
<tbody>
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<tr>
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</table>

*Table B-2: Concentration factor calculations for algae trials on Day 2 (poorer filter performance)*