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Out of Scope Analysis of Fermentation and Recovery Processing

Introduction

This paper investigates the out of scope steps of the fermentation process in the xanthan gum senior design project as outlined in figure 1, as well as further exploring the recovery of xanthan gum following the precipitation step. The ideal conditions for the fermentation unit operation will be discussed and the cost analysis for these steps will be used to reevaluate the existing financial analysis of the process. For recovery, the methods of dewatering and drying will be investigated as well as the cost of drying the requested amount of xanthan gum production. Examining these unit operations which were originally out of scope for the design project allows further insight into xanthan gum production and a fuller understanding of the demands of process design for chemical engineering.

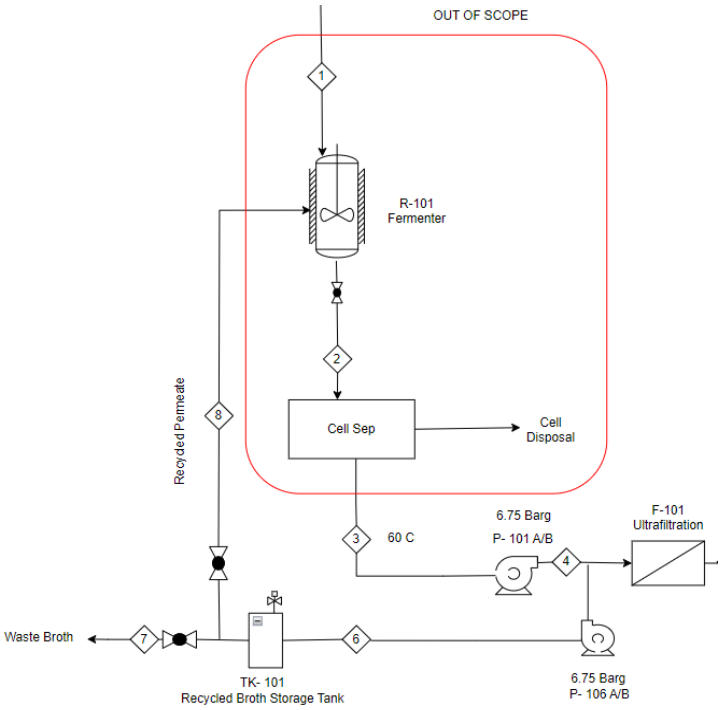

Figure 1. PFD of the out of scope step of fermentation which will be investigated.

Assumptions

The project guidelines only specify that the xanthan gum exits the fermentation process at 2.5 w/v% or 2.5 grams per 100 mL. All small scale researched values will be used for the

scale-up. The mass flows exiting precipitation were assumed from the submitted design final report, as well as the flow ratios of the wash line exit stream respective to the input.

Fermentation Process Conditions: Lab Scale

Xanthan gum is produced as a product from bacteria Xanthomonas campestris. Much research has been conducted to determine the best sources and concentrations of carbon, nitrogen, etc for the fermentation broth for the bacteria to produce the highest quantity of xanthan gum. The optimum broth composition is as follows: 20 g/L Sucrose, 2. I g/L citric acid, 1.144 g/L ammonium nitrate (NH_4NO_3), 2.866 g/L monopotassium phosphate (KH_2PO_4), 0.507 g/L magnesium chloride ($MgCl_2$), 0.089 g/L sodium sulfate (Na_2SO_4), 0.006 g/L boric acid (H_3BO_3), 0.006 g/L zinc oxide (ZnO), 0.0024 g/L iron (III) chloride hexahydrate ($FeCl*6H_2O$), and 0.020 g/L calcium carbonate ($CaCO_3$), and produced 10 g/L xanthan gum in 24 hours.[3]

The pH of the fermentation broth is critical to control. Since the pH will decrease due to organic acids forming during fermentation, a base should be added.[2] The best found operational pH and temperature range for growth as found in an experiment is a pH of 6-7.5 and a temperature range of 25-27°C.[1] The pH of the broth should not be permitted to decrease below 5.5, and potassium hydroxide is the best base to utilize to prevent this condition.[4] The figure below shows the relationship of how pH changes with fermentation time in a system where there were no efforts to correct pH.[8]

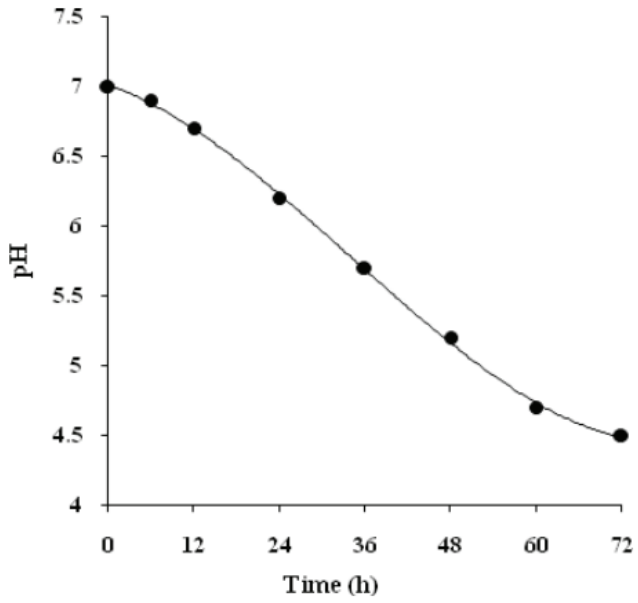

Figure 2. pH Changes of Broth During Fermentation at the Optimum Condition[8]

Another important material for consumption of the Xanthomonas campestris is dissolved oxygen. A study discussed by one source monitored the oxygen uptake rate (the empty circle),

specific oxygen transfer rate (the dark triangle) and the concentration of biomass (dark square) over time.[5]

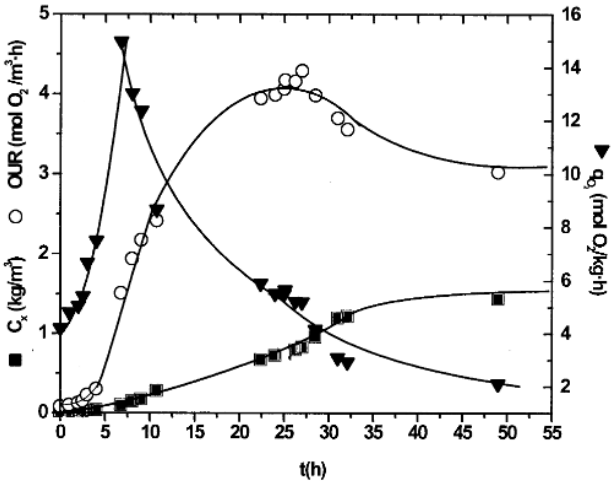

Fig. 3. Experimental data for oxygen uptake rate (○), specific oxygen uptake rate (▼) and biomass concentration ( ) in time course of xanthan production.

Figure 3. Oxygen Uptake, Specific Oxygen Uptake, and Biomass concentration over time[5]

As shown in figure 3 above, when the biomass is in lag and exponential phase, the specific oxygen uptake rate and oxygen uptake rate both increase quite abruptly and decrease during the stationary phase. In addition, the maximum oxygen uptake rate during the exponential phase is between 4.14 to 6.42 mol O_2 per cubic meter.[5] The dissolved oxygen concentrations should not drop below 10% or the bacteria will be damaged. Between 210-1000 rpm and an air gas flow rate of 1 L/L/min is needed.[5]

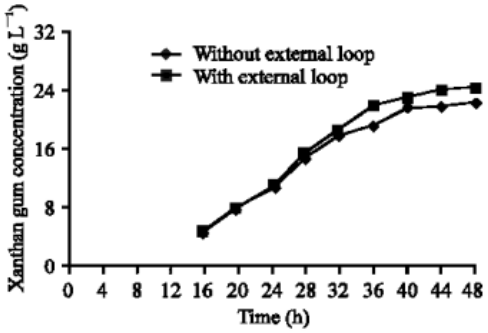

Figure 4. The time courses of total sugar concentration for xanthan fermentation with and without external loop[6]

The time allowed for fermentation has an exponential fit for the production of xanthan gum as shown in figure 4. The desired concentration for this project is 25 g/L, so a fermentation batch time of 36 hours is obtained.[6] The inoculum is added to the fermenter along with the broth medium. The best volume of xanthan gum inoculum to broth ratio is between 1:1000 and 1:5000.[7]

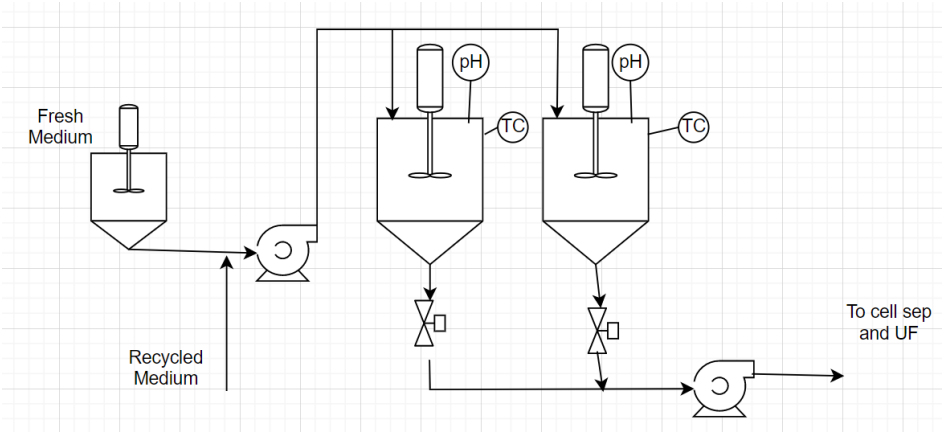

Figure 5. A proposed schematic of the fermentation process

Fermentation Conditions: Scale-Up

There are many difficulties when it comes to scaling up this process. First, the volume needed is an issue. The system requires 24,800 L/hour. With a batch time of 36 hours, this equates to 892,800 L/batch, at a minimum. In a 0.5 L xanthan gum experiment, a power consumption was found to be approximately 2.5 kW.[5] Using a similar method of upscale with the power per volume ratio as used in the precipitation reaction, a new power input can be found. This 2.5 kW to 1 L scales up to 2,340,000 kW or 3,137,991 hp. With our discussion during office hours stating an impeller should not exceed 100-150 hp, this would mean we would need 20,919 chemostats, which is a highly irrational model for scaling.

Using a constant tip speed between the experimental and scale up gave a more reasonable scale up chemostat number. The impeller rpm of 550 and impeller diameter to tank diameter ratio of 0.42 was used.[5] Following the calculations in excel and the appendix, 14 chemostats were needed. Therefore, each chemostat will be responsible for 63,771 L of the whole batch. This assumes an impeller power number of 1.5 and potential downtimes of having to sterilize chemostats. Assuming the extra downtimes will result in needing 19 chemostats. These numbers were later adjusted and explained in the cost analysis to 12 chemostats minimum and 16 total, giving each chemostat a volume of 74,400 L. In addition, a tank will need to be added after the cell separation and the ultrafiltration unit to have better control over the flow rate into the ultrafiltration unit and allow for an easy transition for running the chemostats on a timed schedule. The tank will be equipped with low and high level alarms to prevent an overflow or having no liquid to enter the downstream steps. Frequent occurrence of these alarms can be mitigated by adjusting the timing schedule of the chemostats.

Assuming the ideal reaction conditions remain the same for the scale-up, compressors will be sized for 1L/L/min of O_2. Each chemostat will need this to ensure sufficient mass transfer of oxygen to the bacteria cells and provide 74,400 L of O_2 per minute for the 74,400 L chemostats. In addition, pumps must be used to drain the tank and add new medium at a constant

rate. Using a dilution rate of 0.12 per hour,[7] 8,880 L of medium will be removed/added per hour. Furthermore, the reaction temperature range should be kept between 25-27°C and will be monitored with a probe. The literature sources consulted were unable to provide any specifics on the extent of the exothermic reaction, but cooling water supply will likely be needed. Lastly, since the pH drops over time, a pH probe will be in the chemostats to administer KOH and maintain a pH range of 7.5 to 6.

Recovery of Xanthan Gum

In the original design project, centrifugation was implemented to separate water, isopropyl alcohol, and residuals from the precipitated xanthan gum. Continuing in gum recovery, the produced slurry would be washed and spray dried - both of which were assumed to be approximately equivalent to the respective unit operations in a process without ultrafiltration.

Research regularly states xanthan gum is washed and dried after precipitation,[3] but frequently, sources also mention dewatering without detailing the process to do so.[2] [11] Some data implies dewatering may not be necessary when planning to wash and spray dry the precipitated xanthan gum. For example, the *Journal of Food Engineering* describes centrifugation for the removal of cells, but if cell-free xanthan gum is not required, it conveys precipitated xanthan gum is typically sprayed dry or may be washed and then re-precipitated.[2] The *Encyclopedia of Food Microbiology* even states, “Spray-drying can be used to process the broth directly, for applications that do not require a cell-free product.”[4]

Specifically considering the recommended inclusion of ultrafiltration, xanthan broth could be directly dried to product form following ultrafiltration or, more likely, drying may occur after a precipitation step.[10] The journal estimates, if following precipitation, drying will consume approximately 9 MJ per kg of xanthan gum produced.[10] Further estimates for the drying process and cost can be found in the tables below.[12]

Rough Costing Analysis

Both pumps for the removed material and the added material are sized for 142,080 L/hr, which includes all 16 chemostats. Cast steel and centrifugal pumps are used and the cost includes a backup. Chemostats are made of carbon steel and assumed to operate at 80% full to provide space for any foam. A mechanical seal is chosen for the agitator to prevent contaminants from entering. Since the chemostats are the most expensive item, the amount each is responsible for was increased slightly because the actual impeller requirement ended up at 81.5 hp, which is under the 100-150 hp maximum range. It is far cheaper to increase the height at which the pumps need additional kW to operate than to increase the number of chemostats.

Table 1. Equipment sizing information and the supplemental Excel spreadsheet included contains applicable calculations.

Pumps		**Q m^3/h**	**row kg/m^3**	**g m/s^2**	**deltah m**	**Power (kW)**
P-101A/B	Chemostat Feed	142	1000	9.81	30	11.6085
P-102A/B	Chemostat Exit	142	1008	9.81	30	11.701368
Reactors		**L**	**80% full L**	**m^3**	**Height**	**Diameter**
V-101-116	Chemostats	74,400	93000	93	30	2
Dryer		**m (kg/h)**	**Gum (kg/h)**	**Vol (L/h)**	**80% full L**	**Power (kW)**
DR-101	Spray dry after wash	4996	654	5208	6510	163.5
Mixer		**kW**				
M-101-116	Chemostat mixer	60.8				
Tank		**1 batch L**	**m^3**			
TK-101	Holding before UF	892,000	892			

Table 2. Equipment costing values found in provided textbook Capital Cost Estimation Data.[12]

Pumps		**C_p**	**F_m**	**F_p**	**F_{bma}**	**C_{bm}**	**Inflation**	**Total**
P-101A/B	Chemostat Feed	$10,000	1.4	1	4	$40,000	2.0775	$ 83,100
P-102A/B	Chemostat Exit	$10,000	1.4	1	4	$40,000	2.0775	$ 83,100
							Subtotal (2):	$ 332,400
Reactors		**C_p**	**F_m**	**F_p**	**F_{bma}**	**C_{bm}**	**Inflation**	**Total**
V-101-116	Chemostats	$60,000	1	1.2	4.5	$ 270,000	2.0775	$ 560,925
							Subtotal (16):	$ 8,974,800

Mixers		**C_p**			**F_{bma}**	**C_{bm}**	**Inflation**	**Total**
M101-116	Chemostat mixers	$60,000			2	$120,000	2.0775	$ 249,300
							Subtotal (16):	$ 3,988,800
Dryer		**C_p**			**F_{bma}**	**C_{bm}**	**Inflation**	**Total**
DR-101	Spray dry after wash	$240,000			2.7	$648,000	2.0775	$ 1,346,220.00
Tank		**C_p**			**F_{bma}**	**C_{bm}**	**Inflation**	**Total**
TK-101	Holding before UF	$50,000			2.1	$105,000	2.0775	$ 218,137.50
							Total	**$ 14,860,357.50**

Table 3. The utility cost accumulates to a total of approximately $6,487,266.

Electricity	**kW**	**kWh**	**$/year**
P-101	11.6	92707.2	$ 64,895.04
P-102	11.7	93506.4	$ 65,454.48
DR-101	163.5	1306692	$ 914,684.40
M101-116	60.8	485913.6	$ 340,139.52
		16 mixers per chemostat	$ 5,442,232.32
		Total	$ 6,487,266.24

Conclusion and Recommendations

For fermentation, the estimated total of FCI and utilities is $19,086,720. This number is very similar to the financial analysis without an ultrafiltration unit. This will not affect the discussion of whether to add the ultrafiltration unit, but the company is unlikely to become profitable in 3 years as previously estimated. The assumption that fermentation reaction conditions will remain the same and all flow rates of materials will remain consistent is highly unlikely for the scale up. It is suggested that the company make a pilot chemostat based on the lab scale set-up and adjust reaction conditions as needed before making 14 larger chemostats.

Furthermore, it is expected that an additional cycle of both washing and drying the gum may be needed due to the greater flow without the centrifugation step. It is recommended that a pilot scale of the entire process be produced to optimize production before moving forward and building the full-scale process. Running a centrifuge in addition to the wash line and spray dryer is unnecessary, unless the centrifuge is intended mostly for cell-removal. The pilot scale production would help to better understand the comparison of power consumption physically measured to determine the annual cost comparison of running the centrifuge with the other unit ops versus operating a larger dryer at higher power.

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