5-2018

Ceramic Microfiltration of High-Strength Industrial Wastewater Using an Automated System

Weiming Qi
Clemson University, weiminq@g.clemson.edu

CERAMIC MICROFILTRATION OF HIGH-STRENGTH INDUSTRIAL WASTEWATER USING AN AUTOMATED SYSTEM

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Environmental Engineering and Earth Sciences

---

by
Weiming Qi
May 2018

Accepted by:
Dr. David Ladner, Committee
Chair Dr. Sudeep Popat
Dr. Yi Zheng

ABSTRACT

Fats, oils, and grease (FOG) wastewater is a kind of high-strength industrial wastewater that contains a high amount of total suspended solids (TSS), chemical oxygen demand (COD), and proteins. One industry that has high-FOG wastewater is the rendering industry, which converts animal byproducts to protein meal and fat, which have value as a commodity. FOG wastewater in the rendering industry is usually treated by dissolved air flotation (DAF) and the recovered proteins and fats are sent back to the rendering process stream. An important drawback to DAF is that chemical flocculants are usually needed, but these chemicals become contaminants in the final protein and fat streams sold to customers. Another drawback is that oxygen in the DAF process can oxidize proteins and degrade their quality.

An alternative to DAF is membrane technology. Because membranes have not been heavily used in FOG wastewater applications (especially in the rendering industry) this project sought to create a test system to evaluate membranes in this context, with real-world operating conditions.

There were three main objectives in this project. The first objective was to build a field-deployable semi-autonomous filtration unit. This was achieved by improving an existing system from previous research. Other pumps, valves, and electronic components were added to the system to realize semi-autonomous filtration. A control program was created in LabVIEW for system operation.

The second objective was to operate the system continuously to test its capabilities. The algorithms in the control program were updated according to the results from test filtrations of tap water, lake water, and effluent from a wastewater treatment plant.

The third objective was to employ chemical cleaning to recover flux decline, similarly as would be done in a full-scale system. Rendering plant wastewater was used for testing the system and three chemicals were employed for cleaning the foulant formed during filtration.

A software interface was built for system operation and data recording. Three main programs aimed to control the filtration loop, actuator valve, and record data, respectively. Other programs were also created for the stabilization of the system and protecting the hardware. For example, an averaging program was used for decreasing the influence of extreme values. A pump reverse program aimed to protect the flowmeter after the backwash. The hardware cooperated with the software interface for signal processing and fluid handling. A data analysis program was coded in MATLAB for plotting and calculating experimental results.

The ability and stability of the system were tested. Results showed that the system could handle filtration, backwash, and chemical cleaning in a time-based operational scheme. Twenty-two data were recorded and emails with data and alarms were sent to students and professors during the experiments. Chemical cleaning efficiencies were calculated based on balance flowrate during filtration. A 2% sodium hydroxide solution had the highest flux recovery (70%) compared to 39% for a 2% solution of hydrogen chloride and 56% for a 0.02% solution of ethylenediaminetetraacetic acid (EDTA).

TABLE OF CONTENTS

Table of Contents (Continued)

Table of Contents (Continued)

TABLE OF FIGURES

Table of Figures (Continued)

Page

Table of Figures (Continued)

Table of Figures (Continued)

Table of Figures (Continued)

Page

Table of Figures (Continued)

Table of Figures (Continued)

Page

Table of Figures (Continued)

Page

TABLE OF TABLES

Page

Table of Tables (Continued)

Page

1 Background

The advantages of membrane technology lead to extensive focus and application of microfiltration (MF) in removing macromolecular pollutants.[1,2] Nowadays, at least 50 individual membrane bioreactor (MBR) manufacturers are supplying membrane modules to hundreds of large-scale MBR plants worldwide and the application of MBR systems are increasing continuously due to the requirement of high effluent water quality.[3] During the past decades, ceramic membranes have received a great deal of attention in research and development due to their high chemical resistance, thermal stability and endurance in high flux backwash.[4,5] These advantages make ceramic membranes appropriate for the treatment of high strength industrial wastewater which usually presents high chemical oxygen demand (COD) and turbidity.

High strength industrial wastewater is defined as that wastewater with high concentrations of COD, ammonia, suspended solids, and heavy metals.[6] It contains fats, oil and other organic or inorganic pollutants. The exact nature of the wastewater varies with the type of industry.[7] Rendering industry aims to convert livestock by-products to fats, oils, and protein rich meals.[8] Wastewater from the this industry is a kind of high strength industrial wastewater which contains significant amounts of suspended solids, fats, oils, greases (FOG) and proteins.[9] Fats, oils, and grease in wastewater often contribute to significant problems to bioreactors.[10] Dissolved air flotation (DAF) is the most popular method for primary treatment for the treatment of FOG wastewater,[11] but it has limitations. During DAF, chemicals must be added to maintain pH and enhance flocculation efficiency. Chemical addition is not desirable since the fats and proteins

recovered during DAF are valuable products that are sent to the head of the facility for recovery. Polymer coagulants such as polyacrylate are contaminants in the final protein and fat products, which means their use must be carefully monitored and controlled. Also, fats and proteins have the potential to be oxidized when aeration is introduced in DAF.[9] These limitations lead to this thesis, using ceramic membrane as a primary treatment method to replace DAF. Because ceramic membrane filtration is a physical separation which means chemical agents will not be added directly to wastewater. Also, the system can be sealed that air will not connect to the wastewater.

Fouling is a key difficulty during filtration, especially in high strength industrial wastewater.[12] Sumihar studied different strategies for cleaning ceramic membranes fouled by produced water. Temperature, cleaning pressure, chemical agents, and chemical concentration were compared.[13] However, the author only focused on produced water which is different from rendering wastewater. Various factors like cleaning time and crossflow velocity were studied by Hongjoo for recovering the flux of ultrafiltration (UF) membranes fouled by natural organic matter (NOM).[14] These factors should be considered during real operations for minimizing the fouling in our system. Enzymes were employed by Chen for cleaning membranes fouled by protein mixtures.[15] Protease A as the enzyme he used shown a better flux recovery than 0.1M sodium hydroxide (NaOH) solution and 0.05 M hydrogen chloride (HCl) solution. A fouling-resistant membrane was created by Wandera for the treatment of high-strength wastewaters and produced water.[9,16] Ceramic membrane was employed in Abadi's experiment for oily wastewater which indicated that the best operating parameters were 1.25 bar of transmembrane pressure (TMP) and 2.25 m/s of crossflow velocity (CFV).[4] Zhang studied the cleaning procedure in ultrafiltration membranes for the treatment of

dairy wastewater.[2] The researches above show different strategies for mitigation of membrane fouling during the filtration of wastewater with proteins and oil.

Although current literature gives insights into membrane fouling from different areas. There remains little- published data for the treatment of high strength wastewater especially from the rendering industrial with ceramic membranes. Automatic operation was always employed in membrane wastewater treatment because many actions needed to be implemented with higher frequency, and membrane processes are inherently modular.[17,18] Because of this need for automation, this research focues on building an automated membrane system to optimize membrane cleaning strategies for the flux recovery of ceramic membranes fouled during the treatment of rendering wastewater.

Automatic control system is another key topic for filtration optimization. Plenty of researches have been done in academic and industrial area. Programmable logic controller (PLC) is primary used in industrial area as the control system. LabVIEW is mainly employed in the lab for a further research. Based on these programs automatic control systems were studied from different researches. Ferrero built a membrane bioreactors with automatic control system for energy saving.[19] But, the system did not include the chemical cleaning procedure. Robles created an advanced control system for submerged anaerobic MBRs,[18] in which fuzzy-logical controller[20] were used for filtration optimization. The optimized system decreased the energy cost and downtime for different actions like backwash and ventilation. TMP triggered physical cleaning was studied by Villarroel.[21] Other concept for automatic control were also described. Critical flux was proposed by Field[22] ,and many researchers determined it with different aspect.

Howell compared the TMP at different flux situation to determine the critical flux.[23] Kwon employed particles lift velocity to theoretically estimate critical flux.[24] Bouhabila described the critical flux as the transition between pressure-dependent and pressure-independent flux.[12] Kwon also monitored the change of particle concentration in the fluid phase for critical flux determination.[25] These different concepts of critical flux provide us different method for measuring the critical flux during filtration. And the system should be operated lower than critical flux to avoid quickly fouling.

On the other hand, online method ware tested to realize control. Monclús proposed that using fouling rate to predicted fouling behavior, which has the advantage that fouling rate would more sensitive to the fouling which could predict the irreversible fouling during the filtration.[26] Diez presented another way to calculate of fouling rate and determine the resistance in situ.[27] The online method for fouling rate calculation bring us a possibility that using fouling rate to control our system for deep optimization.

Although other researchers have done many studies on ceramic membrane filtration with oily water and automated system. However, none of them used an automated system with ceramic membrane for the filtration of FOG wastewater. Our research aims to build, test, and optimize that system until it can be employed in rendering wastewate to replace DAF.

2 Objective and Hypothesis

The objectives of the study are

1. Create a prototype field-deployable membrane separation unit.
2. Automate the system and test it with different wastewaters.

3. Employ chemical cleaning to recover the flux decline due to fouling with the treatment of wastewater containing high concentrations of fats, oils, and grease from a rendering plant.

1st Objective

Create a prototype field-deployable membrane separation unit. The membrane unit was improved from a current system from other research (Figure 1). Additional sensors, pumps and valves will be employed to realize filtration, backwash and chemical cleaning. A program written in LabVIEW was created to control the components. The membrane unit could be operated semi-automatically, which meant the system could record the data, cycle the filtration, and maintain the TMP or flux. But other actions like backwash should controlled manually.

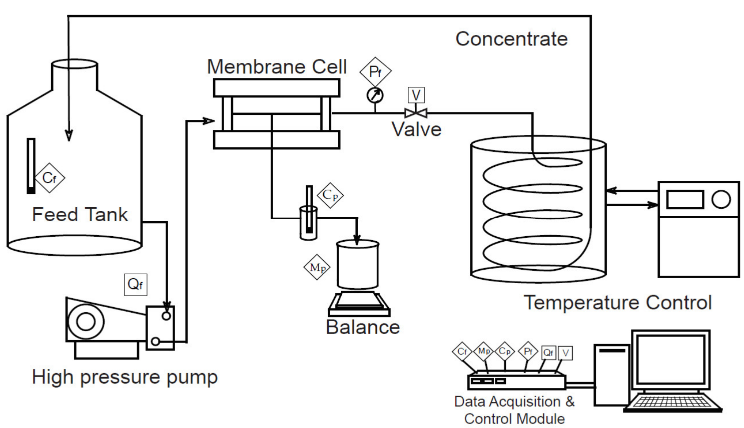


Figure 1. Schematic of a membrane testing unit currently employed in our labs. Square symbols denote controls (V for needle valve actuator voltage and Qf for feed flow rate control). Diamond symbols denote data acquisition (Cf for feed concentration, Mp for permeate mass, Cp for permeate concentration, and Pf for feed pressure).

2nd Objective

Operate the system continuously in our lab for twenty days with no maintenance for the last eight days. In this objective, the program and algorithms were updated to operate the physical system according to the results from the tests. Tap water was used to test the LabVIEW program. Several overnight tests were employed to identify and correct bugs and make the software run stably.

Once the system was stabilized with tap water, lake water and rendering wastewater was employed. Parameters in the algorithm were adjusted according to the performance of the system, which made long-term operation possible that aimed to simulate the situation the unit working in the wastewater plant. At the end of this objective, the membrane system worked automatically, which indicated that students or professors should only set the system at beginning. The students and professors received the data sent by email from the control program.

3rd Objective

Employ chemical cleaning to recover the flux decline due to fouling with the treatment of wastewater containing high concentrations of fats, oils, and grease from a rendering plant. Real FOG wastewater was collected from a rendering plant and tested in the membrane system. This created a high-fouling situation, so the operational parameters and control schemes had been updated to give stable operation. The FOG wastewater was then used to test the cleaning efficiency of different chemical agents.

3 Methodology

3.1 Membrane filtration hardware and software interface

The system design can be divided into two parts: software interface and hardware. Figure 2 presents a schematic of the membrane system. Filtration, backwash, and chemical cleaning could be realized by using different operation methods.

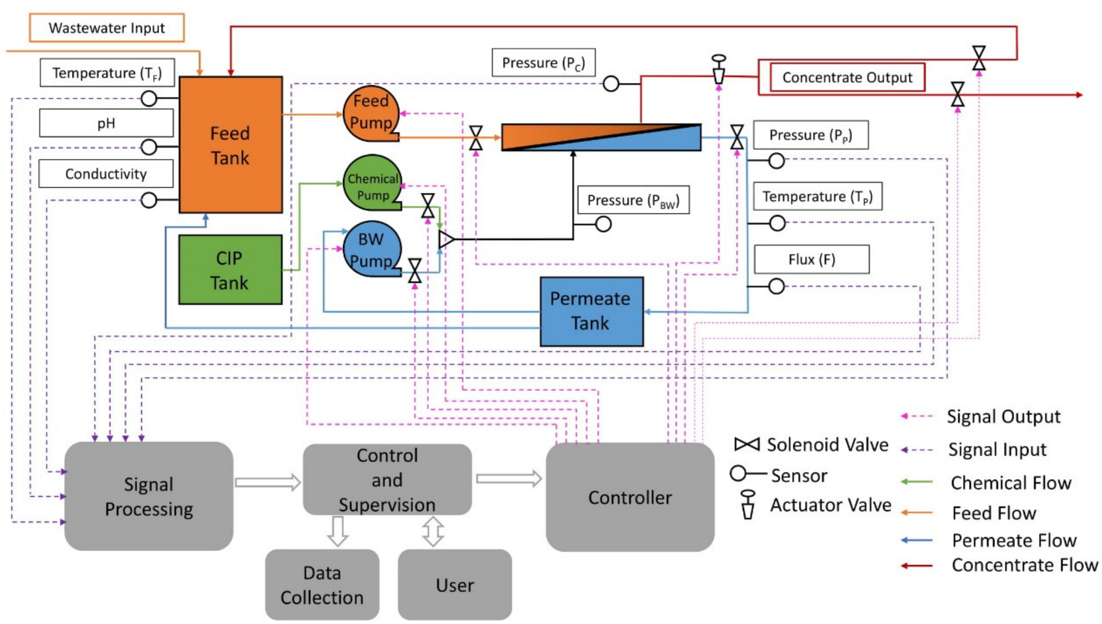


Figure 2. Schematic of the filtration system with hardware and software interface.

3.1.1 Software interface

A program was created in LabVIEW for data acquisition and system control. The operation program involved three main components: filtration loop control, actuator auto adjustment,

and data acquisition and presentation. The fundamental structure of the program was the while loop which iterated continuously until a stop signal was sent by the user. One iteration usually lasted 0.7 seconds, on average, which depended on how many programs were running during each iteration. For example, when the iterations had relative time ending in five or zero, the data would be written to data file which lasted for a little more time than other iterations.

3.1.1.1 Filtration Loop Control program

The Filtration Loop Control program was the fundamental part during filtration, which adjusted pumps, solenoid valves, and the actuator valve to achieve automatic backwash and chemical cleaning after filtration. Filtration, backwash and chemical cleaning periods could be set manually at the beginning of the run.

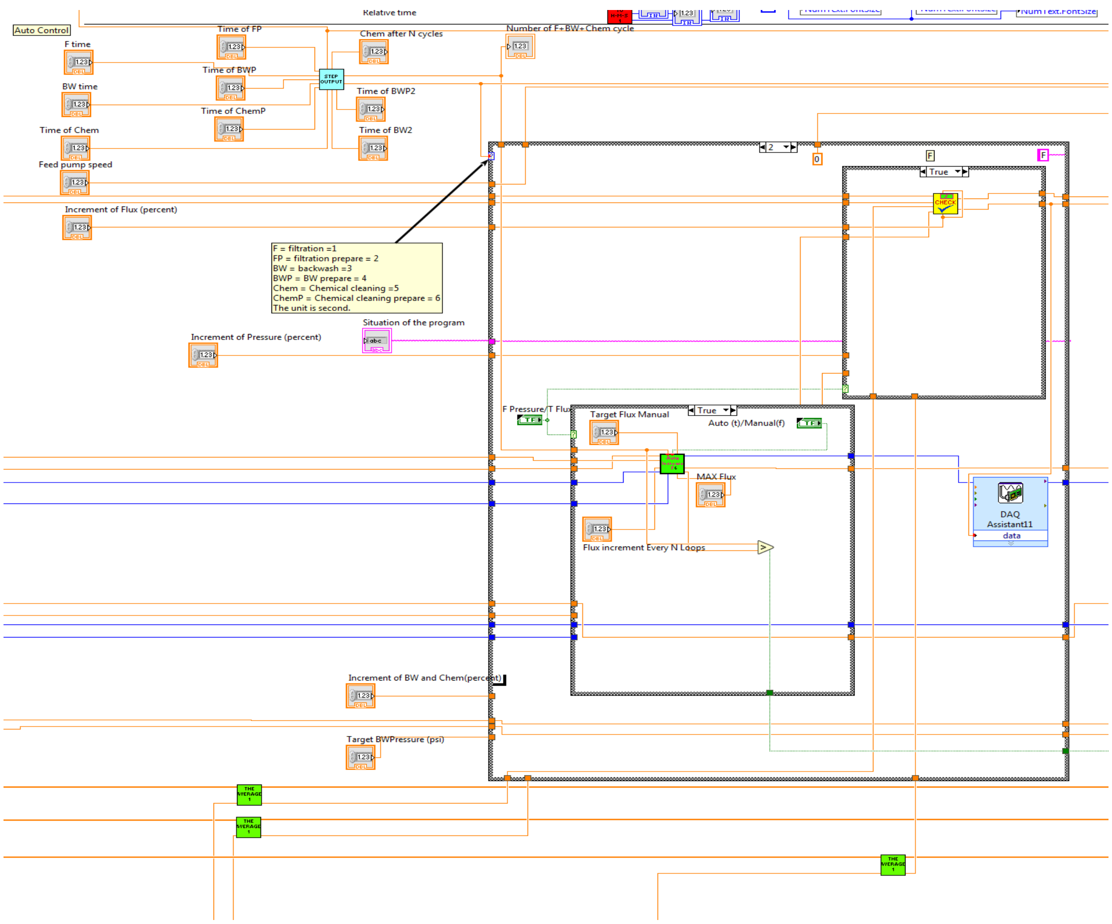


Figure 3. Filtration Loop Control program block diagram. Two sub-programs are included. They are Time-Based Step Choose program and Case Structures.

Figure 3 shows the Filtration Loop Control program which contains a case structure and a Time-based Step Choose program. The case structure had eight different cases which correspond to eight steps during filtration. They were

i. Step One - Filtration Prepare (FP)

In this step, a Sequence Structure (Figure 4) was built, which contained five settings in sequence. The first one was to reverse the pump and provide the suction to release the pressure outside the membrane for 3.5 second. The second one restored all components to initial state and waited for 1 second to make sure all signals are sent to hardware. The third one set actuator input voltage as 1.5 V and waited for 27 seconds which provided enough time for the actuator valve to respond. The forth one set 1-6 solenoid valves as closed and waited for 1 second. The last one set backwash pump and chemical pump speed as 0 rmp and feed pump speed as 100 rmp and waited for 27.5 seconds. This step lasted 60 second for all of the processes for Filtration Prepare.

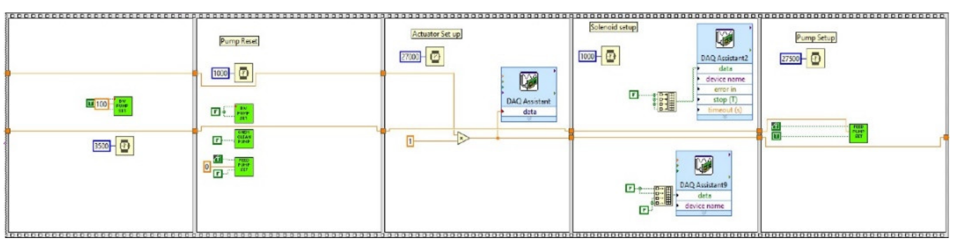


Figure 4. Step one Filtration Prepare block diagram. There are five cases in sequence which correspond to five actions during filtration prepare. They are BW pump reverse, pump reset, actuator adjustment, solenoid valve set, and pump set.

ii. Step Two – Filtration (F)

Now that the pump was running (from Step 1) Step 2 adjusted actuator voltage automatically for maintaining TMP or flux. This lasted forty minutes.

iii. Step Three – Backwash Prepare (BWP)

This step was similar to Step One which had four settings in sequence (Figure 5). The first one restored all components to their initial state and lasted for 1 second to make sure all signals be sent to hardware. The second set actuator input voltage as 5 and waited for 10 seconds which provided enough time for actuator valve to response. The third one set the third and sixth solenoid valves as closed and the rests as open, and then waited for 1 second. The last one set chemical pump speed as 0 rmp, feed pump speed as 100 rmp, and backwash pump speed as 90 rmp; and then waited for 48 seconds. This step lasted 60 second for all of the processes for backwash prepare.

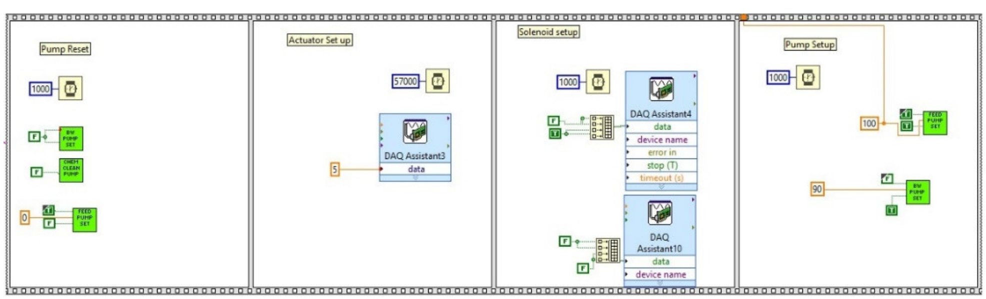


Figure 5. Step three Backwash Prepare block diagram. There are four cases in sequence which correspond to four actions during backwash prepare. They pump reset, actuator adjustment, solenoid valve set, and pump set.

iv. Step Four – Backwash (BW)

Now that the pump was running (from Step 3) Step 4 adjusted backwash pump speed automatically for maintaining backwash pressure. This lasted two minutes.

v. Step Five – Chemical Cleaning Prepare (ChemP)

This step was similar to Step Three which also had four settings in sequence (Figure 6). The first and second settings were the same as Step Three. The third one set the third and the fifth solenoid valves as closed and the rests as open, and then waited for one second. The last one set chemical pump speed as 20 rmp and feed pump and backwash pump speed as 0 rmp; and then waited for 48 seconds. This step lasted 60 seconds for all of the processes for Chemical Cleaning Prepare.

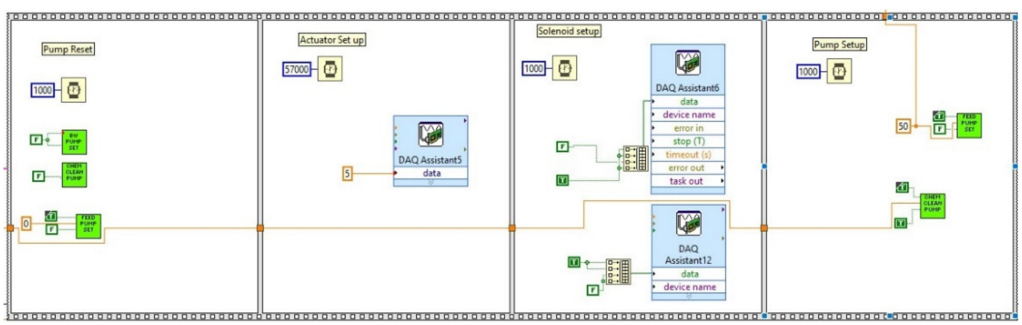


Figure 6. Step five Chemical Cleaning Prepare block diagram. There are four cases in sequence which correspond to four actions during chemical cleaning prepare. They pump reset, actuator adjustment, solenoid valve set, and pump set.

vi. Step Six - Chemical Cleaning (Chem)

Now that the pump was running (from Step 5) Step 6 adjusted Chem pump speed automatically for maintaining Chem pressure. This lasted fifteen minutes.

vii. Step Seven - Backwash after Chemical Cleaning Prepare (BWCP)

This step was similar to Step Three which also had four setting in sequence (Figure 7). The first and second settings were the same as Step Three. The third one set the third and fifth solenoid valves as closed and the rests as open, and then waited for one second. The last one set chemical pump speed as 0 rmp, feed pump speed as 20 rmp, and backwash pump speed as 90 rmp. These changes lasted about 12 seconds, then the system sits idle until the 60 second time setting has elapsed.

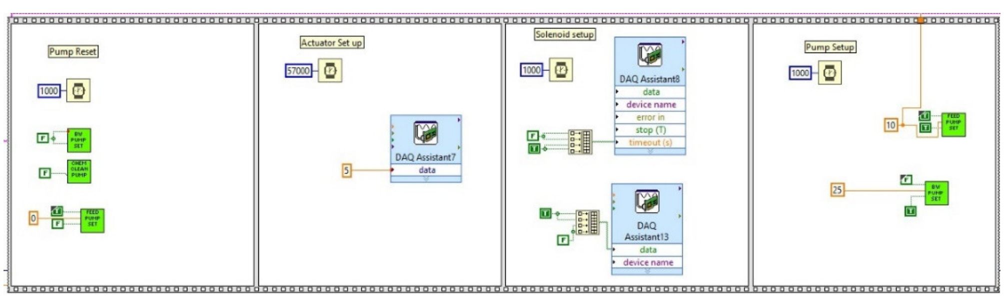


Figure 7. Step sever Backwash after Chem Prepare block diagram. There are four cases in sequence which correspond to four actions during backwash after chemical cleaning prepare. They pump reset, actuator adjustment, solenoid valve set, and pump set.

viii. Step Eight – Backwash after Chemical Cleaning (BWC)

Now that the pump was running (from Step 7) Step 8 adjusted backwash pump speed automatically for maintaining backwash pressure. This lasted two minutes.

Table 1 shows an example of running schedule when N equals to 2, which means 2 filtration and backwash cycles before chemical cleaning.

Table 1. Actions of components during a typical run. "Relative time" is the elapsed time since initiation of the run.

Step Number	Status	Relative Time			Pump Speed			Solenoid Valve						AC Valve
		Start	End	Last	F	BW	Ch	1	2	3	4	5	6	
		Second	Second	Second	rpm	rpm	rpm	× = off, ○ = on						V
1	FP	0	3.5	3.5	0	-100	0	×	×	×	×	×	×	0
		3.5	4.5	1	0	0	0	×	×	×	×	×	×	0
		4.5	31.5	27	0	0	0	×	×	×	×	×	×	1.5
		31.5	32.5	1	0	0	0	×	×	×	×	×	×	0
		32.5	60	27.5	100	0	0	×	×	×	×	×	×	0
2	F	60	2460	2400	100	0	0	×	×	×	×	×	×	A
3	BWP	2460	2461	1	0	0	0	×	×	×	×	×	×	0
		2461	2518	57	0	0	0	×	×	×	×	×	×	5
		2518	2519	1	0	0	0	×	○	○	×	×	×	0
		2519	2520	1	100	90	0	×	○	○	×	×	×	0
4	BW	2520	2640	120	100	A	0	×	○	○	×	×	×	0
1	FP	2640	2643.5	3.5	0	-100	0	×	×	×	×	×	×	0
		2643.5	2644.5	1	0	0	0	×	×	×	×	×	×	0
		2644.5	2671.5	27	0	0	0	×	×	×	×	×	×	1.5
		2671.5	2672.5	1	0	0	0	×	×	×	×	×	×	0
		2672.5	2700	27.5	100	0	0	×	×	×	×	×	×	0
2	F	2700	5100	2400	100	0	0	×	×	×	×	×	×	A
3	BWP	5100	5101	1	0	0	0	×	×	×	×	×	×	0
		5101	5158	57	0	0	0	×	×	×	×	×	×	5
		5158	5159	1	0	0	0	×	○	○	×	×	×	0
		5159	5160	1	100	90	0	×	○	○	×	×	×	0

4	BW	5160	5280	120	100	A	0	×	○	○	×	×	×	0
5	Chem P	5280	5281	1	0	0	0	×	×	×	×	×	×	0
		5281	5338	57	0	0	0	×	×	×	×	×	×	5
		5338	5339	1	0	0	0	×	×	○	○	○	○	0
		5339	5340	1	20	0	20	×	×	○	○	○	○	0
6	Chem	5340	5460	120	20	0	A	×	×	○	○	○	○	0
7	BWCP	5460	5461	1	0	0	0	×	×	×	×	×	×	0
		5461	5518	57	0	0	0	×	×	×	×	×	×	5
		5518	5519	1	0	0	0	×	○	○	×	○	○	0
		5519	5520	1	10	25	0	×	○	○	×	○	○	0
8	BWC	5520	5640	120	10	A	0	×	○	○	×	○	○	1

Red means that characteristic(s) is changed during that step. A means these values will be adjusted by system according to operation condition. × means "switch off", and ○ means "switch on". Solenoid valve 1, 3, and 5 is normally opened which indicates the valves will be opened when it switched off. Solenoid valve 2, 4, and 6 is closed in nature which means the valves will be closed when it switched off. The positive pump speed for BW pump means the pump is working to provide pressure for backwashing, and the negative one is for providing suction to release pressure outside the membrane.

The case structure with eight steps was controlled by a Time-based Step Choose program which is shown in Figure 8. This program aimed to decide which case should run during filtration based on relative time. The prepare steps (FP, BWP, ChemP and BWCP) only required 60 seconds, so all prepare steps were set as 60 seconds in the front panel (Figure 9 shows the time settings part of the front panel). The F, BW, Chem and BWC step could be set as different time as required. The relative time was originated from another program which uses the absolute time of a certain iteration minus the absolute time of the first iterations.

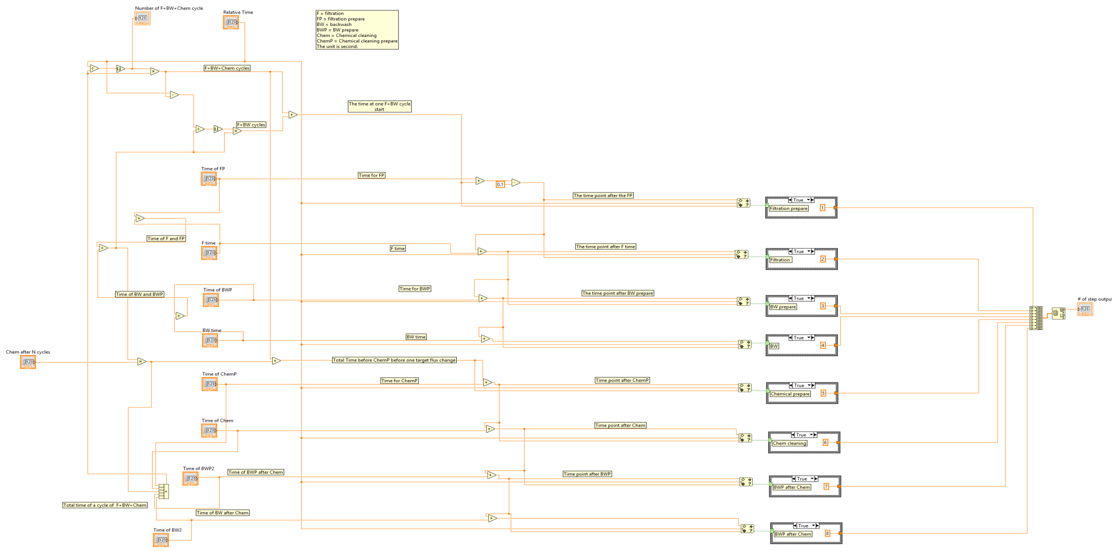


Figure 8. Step Choose program block diagram. The step number will be output according to relative time input.

In Filtration Loop Control program, user could set the frequency of the chemical cleaning by setting “Chem after N cycles”. This setting meant after N cycles of filtration and backwash there would be a chemical cleaning. For example, if we set “Chem after N cycles” as two, the process will be: [FP → F → BWP → BW] → [FP → F → BWP → BW] → ChemP → Chem → BWCP → BWC, which means chemical cleaning will be carried out after two groups of filtration and backwash.

The flexibility of the program is a key factor of the system. Sometimes, there was not chemical cleaning required, which meant only FP, F, BWP, and BW steps were employed. For this reason, we designed the Time-based Step Choose program that allowed no chemical cleaning by simply setting ChemP, Chem, BWCP, and BWC as zero. On the other hand, we could also set filtration and backwash time as zero for only employing chemical cleaning and backwash after chemical cleaning. Another method for cancelling

chemical cleaning was setting “Chem after N cycles” to a very large value, such that the number of cycles was never reached, and cleaning never occurred.

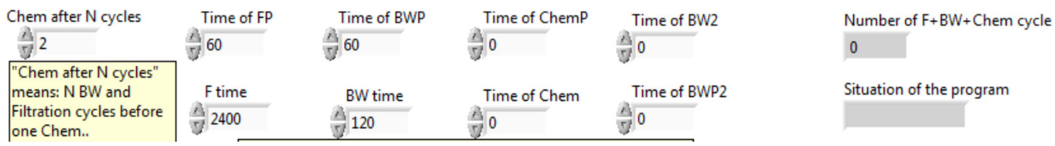


Figure 9. Filtration setting in front panel. “Chem after N cycles” means N backwash and filtration cycles before one chemical cleaning. The input time is in seconds. The four prepare steps must be sixty-second or zero-second. When ChemP and BWCP equal to zero the Chem and BWC time should also be zero.

3.1.2 Actuator Auto Adjustment program

The Actuator Auto Adjustment program (Figure 10) worked for maintaining the TMP or flux. During filtration, the membrane was fouled by wastewater, which increased the resistance to water flux. An Actuator Auto Adjustment program was coded to increase the TMP, which created a change in the driving force and kept the flux stable. For example, in constant-flux mode, the program automatically closes the valve a little to provide a higher trans-membrane pressure and maintain the same flux when the fouling increases.

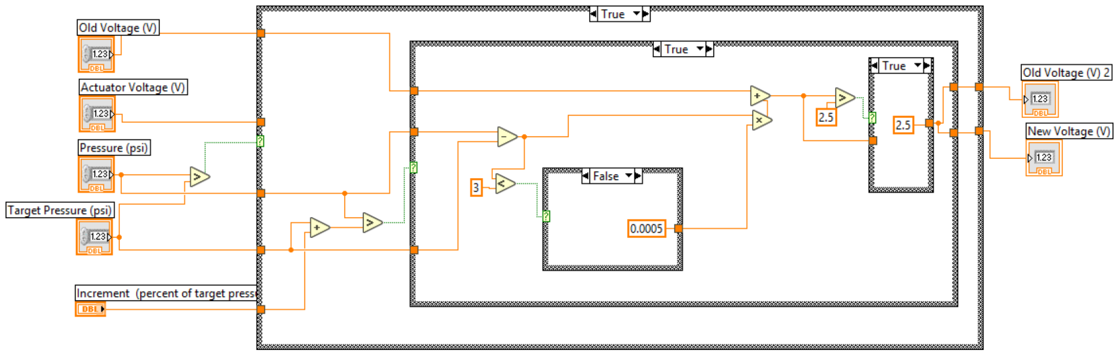


Figure 10. Actuator Auto Adjustment program block diagram. The program receives the real TMP and output the actuator voltage.

In the constant-pressure mode, the TMP would not increase in theory. Because the resistance directly influenced the flux only, no adjustment was required during constant-TMP mode. However, the TMP during filtration did increase especially when treating FOG wastewater. The reason appeared to be that the particles and organic matter fouled on the needle valve, which increased the resistance inside the valve and enhanced the TMP during filtration. The program processed and maintained the TMP by adjusting the needle valve actuator.

The Actuator Auto Adjustment program originated from a similar program called P Check, which was created by Dr. Ladner for an RO system.[28] Figure 10 shows the block diagram of Actuator Auto Adjustment program. The program used case structures to compare the real TMP and the target TMP. If the real TMP is in the range of target TMP plus or minus an increment, no adjustment is required and the output signal to the actuator valve will be zero Volts. If the real TMP is lower or higher than the range, the output voltage will decrease or increase according to the calibration.

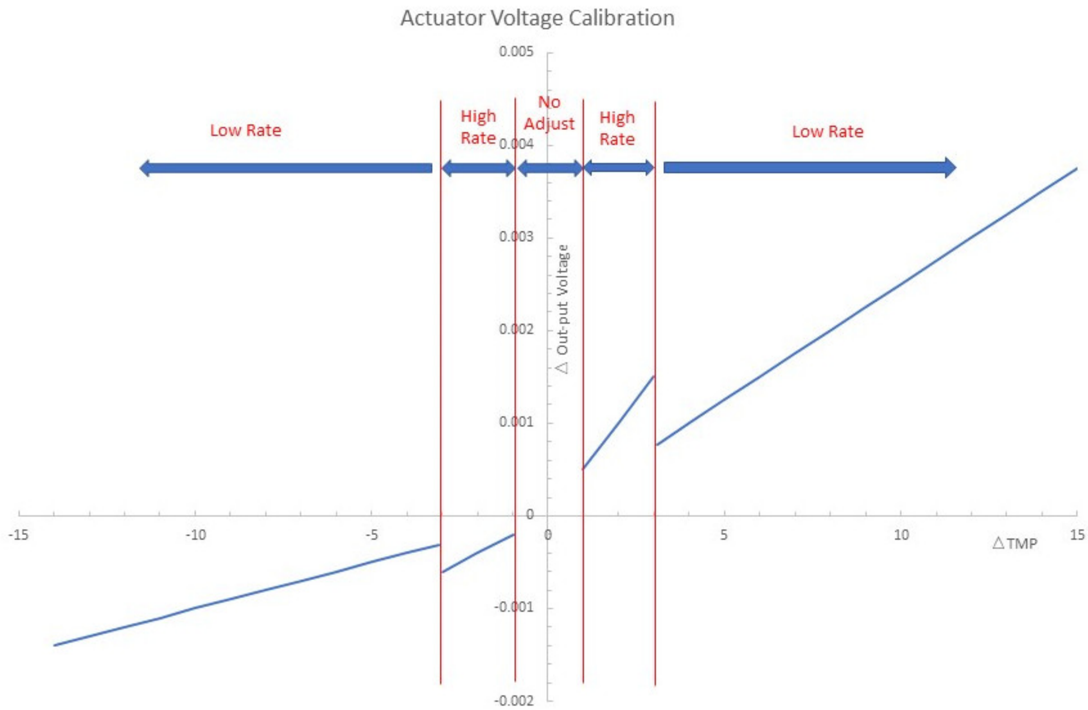


Figure 11. Actuator Voltage Calibration, which is simplified from Actuator Auto Adjustment program. The curve has five different ranges: two high-adjustment-rate ranges and low-adjustment-rate ranges, and one no adjustment range.

The calibration curve (Figure 11) releases the difference between real TMP and target TMP (△TMP) to the required change in voltage (△V). This voltage change is added to the old actuator voltage. There are four linear relationships in the curve. When the absolute value of△TMP is lower than three psi the slopes much higher than the slopes at the absolute value of △TMP higher than three psi. Because we found that the TMP always over adjusted after the first time reaching the target TMP, we used two slopes to describe the relationship between TMP and voltage in each quadrant. The two lines in the third quadrant have lower slopes than the first quadrant's, respectively. The reason for this setting was to avoid sine oscillation. A situation happened before this setting that the △ TMP was always higher than the increment, which meant the Actuator Auto Adjustment

program adjusted the actuator valve all the time, and the actuator voltage showed as a sine curve. We broke the sine oscillation by using lower slopes in the third quadrant, which meant the △V had a higher increase speed and a lower decrease speed.

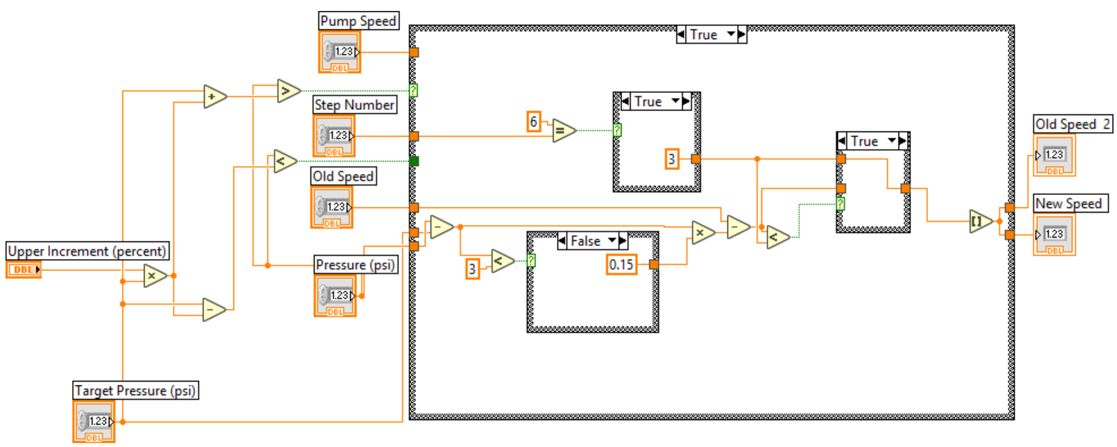


Figure 12. Pump Auto Adjustment program block diagram. The difference of this program is that the true case does not have another case structure inside.

Another similar program named Pump Auto Adjustment program (Figure 12) was also used for keeping backwash and chemical cleaning pressure stable. The program was similar to Actuator Auto Adjustment program but with the different parameters since the pump-speed range was 0 – 100 rpm and the BW pressure was maintained at 30 psi. In Pump Auto Adjustment program, two types of parameter were used for the reason that tubing in Chem pump had a different diameter than BW pump. In this case, the step number was used to control the threshold of the pump speed during BW and Chem. BW pump employed a small tubing which requires higher speed. The limit was from 30 to 100 rpm when the step number was 4 or 8. When step number input was 6 which meant chemical cleaning the limit was adjusted to 3 to 50 rmp. During BW or Chem, the pressure should always be higher than the target. Thus, the Pump Speed Calibration curve were plotted as Figure 13.

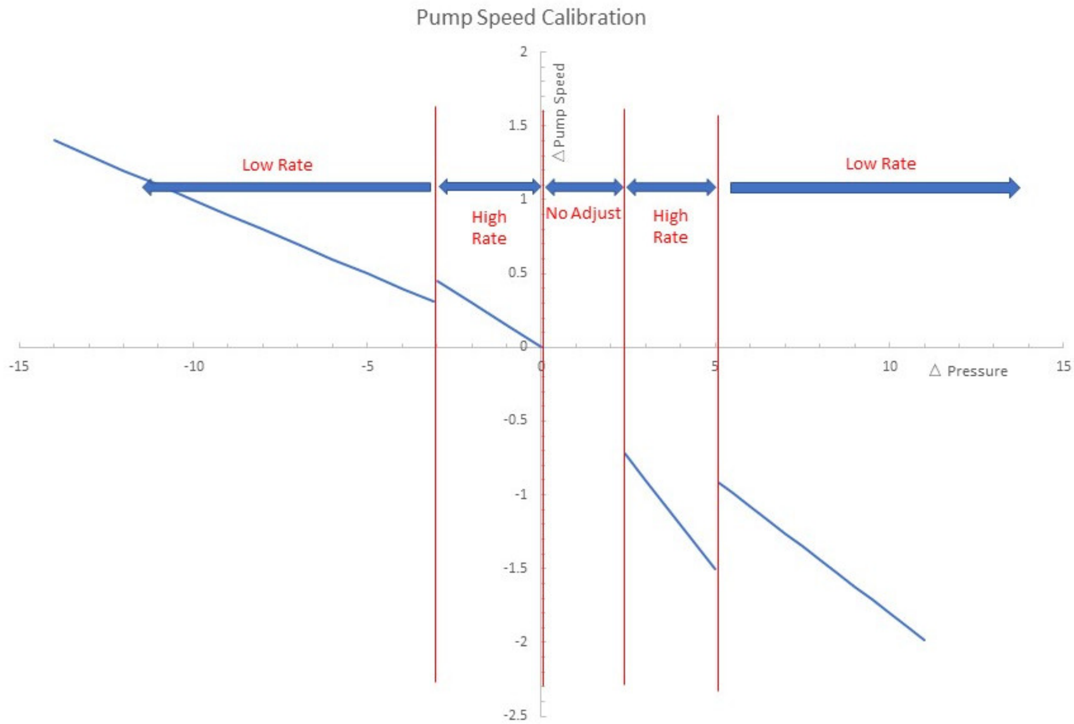


Figure 13. Chem pump speed calibration, which is simplified from Pump Auto Adjustment program. The curve has five different ranges: two high-adjustment-rate ranges and low-adjustment-rate ranges, and one no adjustment range.

In future research, this system may be used as a test system for treatment of different wastewater with various membrane, which means the target flux or pressure should be auto-adjustable. For this reason, Auto Pressure/Flux program (Figure 14) were built. The program adjusted the target pressure or flux according to filtration-backwash cycle. Thus, with the Actuator Auto Adjustment program, the treatment efficiency could be tested automatically.

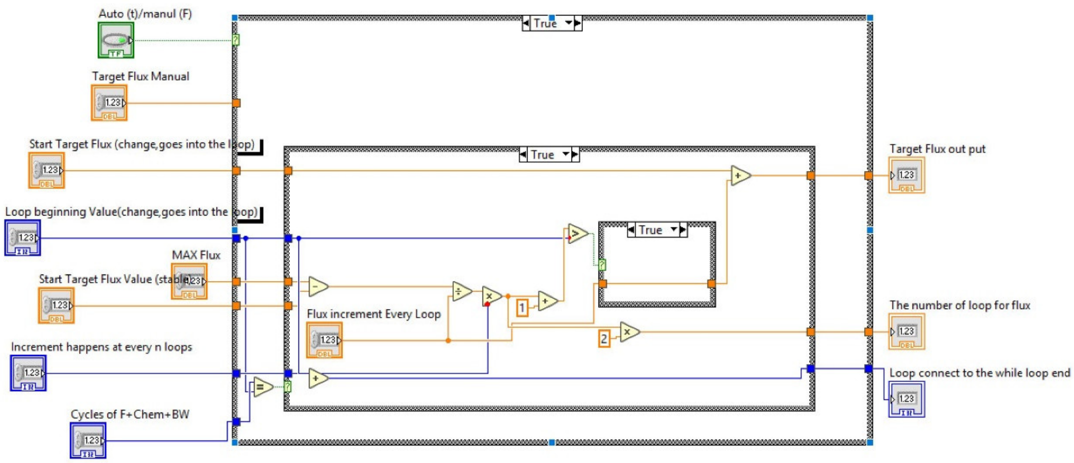


Figure 14. Auto Pressure/Flux program block diagram. The program will increase the flux of TMP based on cycles of chemical cleaning.

3.1.2.1 Data Acquisition and Presentation program

Data Acquisition and Presentation program is shown as Figure 15; twenty-two data were written to a text file every five seconds and the file was sent to our email account (ACRECproject@gmail.com) every 3 hours which was accessed to students and professors. A figure was also saved every 3 hours before the email, which included the flux plots for the last 3-hour period. This plot could inform user of the fundamental information of the system and whether the system run well.

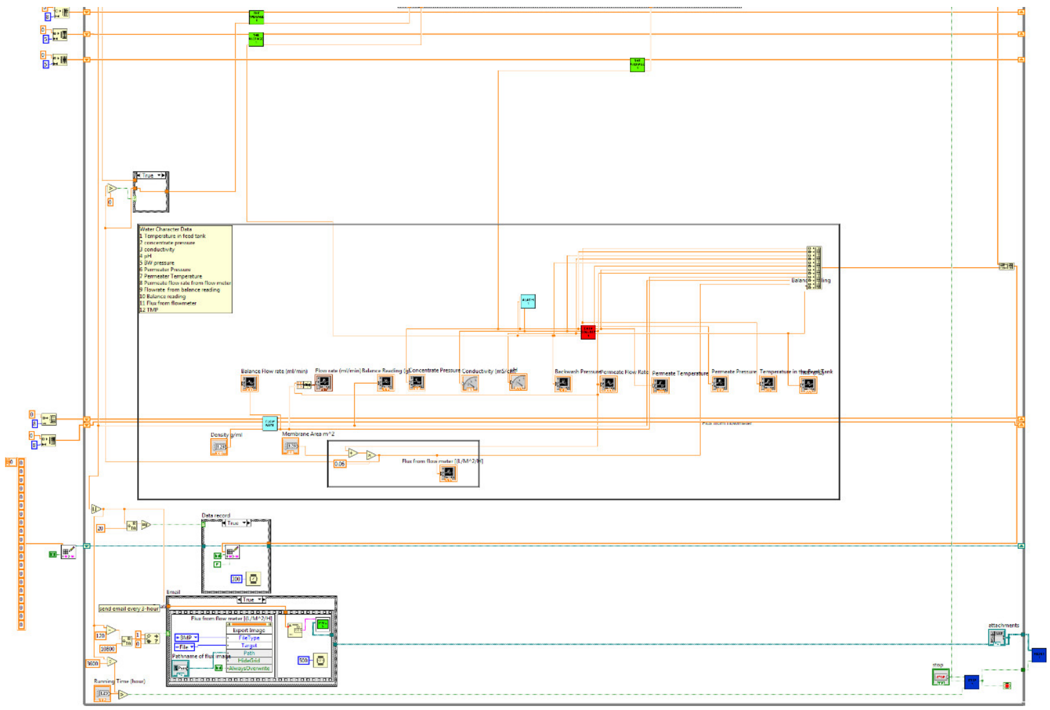


Figure 15. Data Acquisition and Presentation program block diagram. The program receives the voltage signals from interfaces. Then, calibrations are made to interpret the voltage back to experimental parameters which are used for plotting and recording.

The signals received from transmitter and transducer were voltage signals, which meant we have to translate them to real physical parameters. In this case, the signals from pressure transducers and pH, conductivity and temperature transmitters were calibrated according to the calibration curves shown in Figure 16. According to the calibration line we created, a data translation program was built (Figure 17), by which the program transferred the voltage signals to physical parameters.

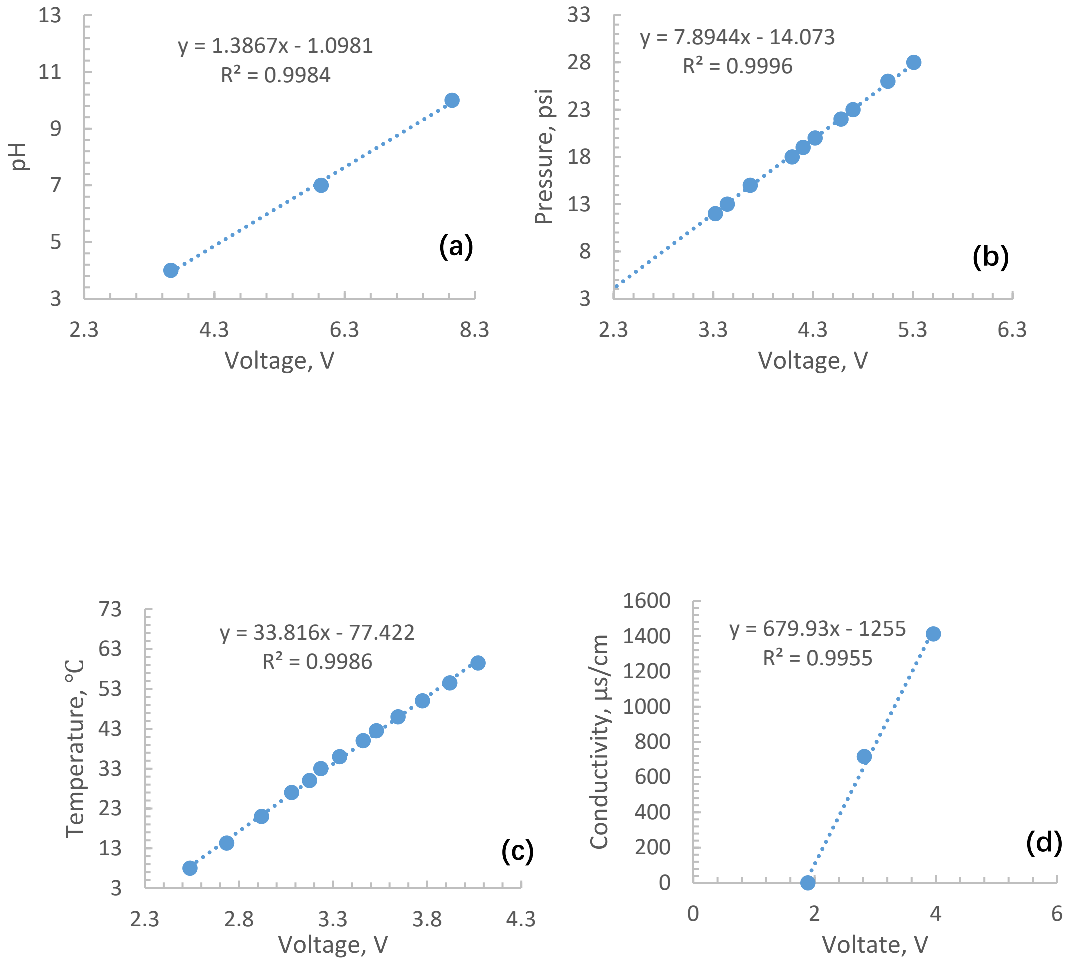


Figure 16. Calibration curve used for interpreting the voltage signal back to experimental parameters; a) pH, b) BW pressure, c) Temperature, d) Conductivity

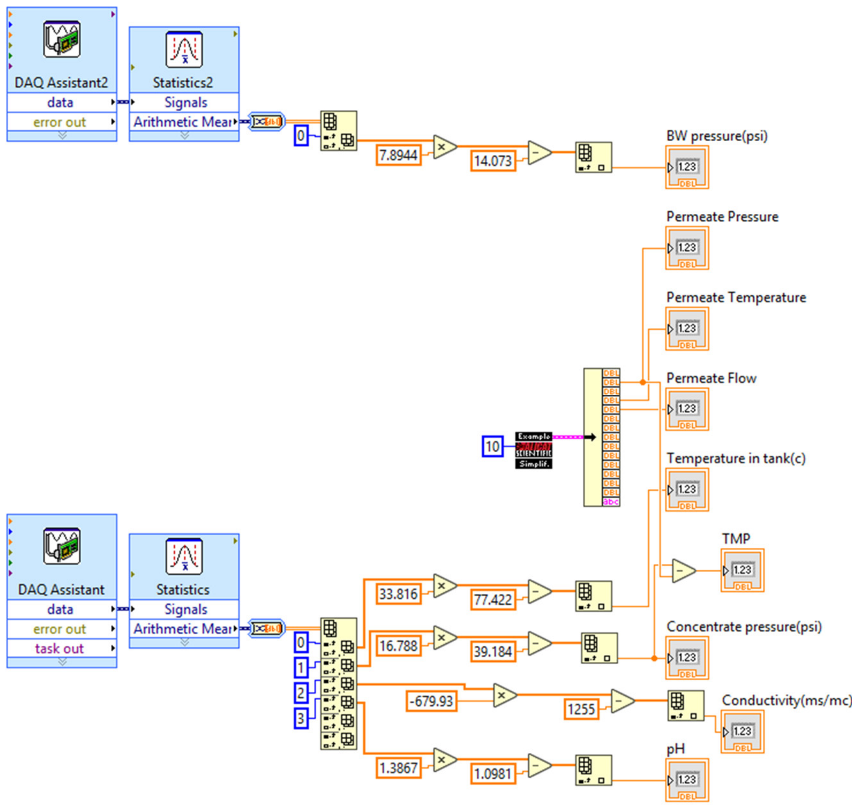


Figure 17. Calibration block diagram.

An alarm program (Figure 18) was also employed for monitoring the concentrate pressure, backwash pressure, and water level in feed tank. If the pressures are higher than the limitation or water level is lower than the conductivity probe (when the system is leaking) the system will send alarm emails to our email account (ACRECproject@gmail.com) every iteration, which means we can receive an email every second via Gmail APP on our cell phone. If we receive that emails we can use Chrome Remote Desktop (an APP on cell phone and PC) to stop the system remotely.

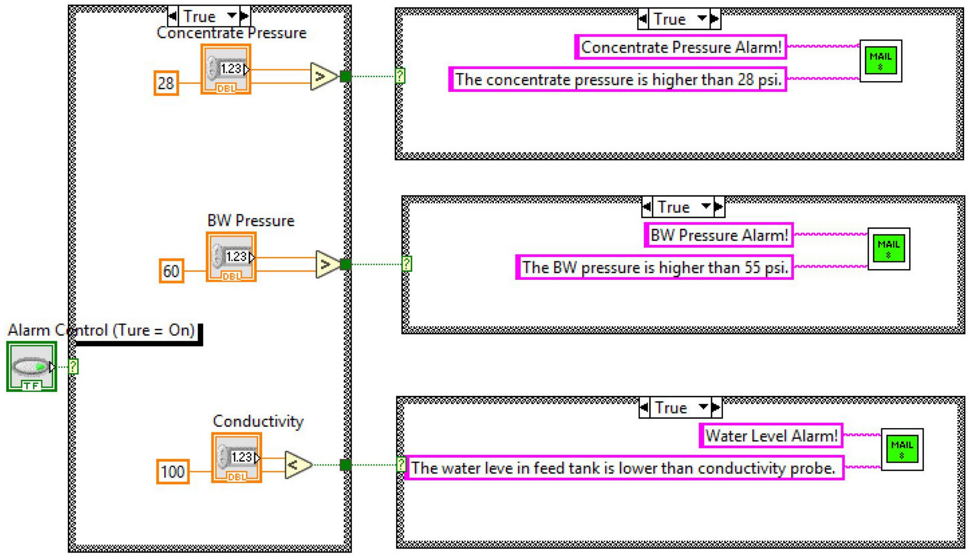


Figure 18. Alarm system block diagram. Concentration pressure, backwash pressure and water level are monitored by alarm system. The system can be turned off manually.

The email program was also designed (Figure 19). The decision of sending email was made according to the relative time. When relative time was in the range from (n*3 hours +120 seconds) to (n*3 hours+122 seconds), where n is positive integer, the email case structure would turn to “true” which indicated an email would be sent. The reason we chose two-second interval was that, in some cases, one iteration last longer than one second especially in the iteration with data recording. Under these circumstances, the relative time would pass a one-second interval which meant the email would not be sent.

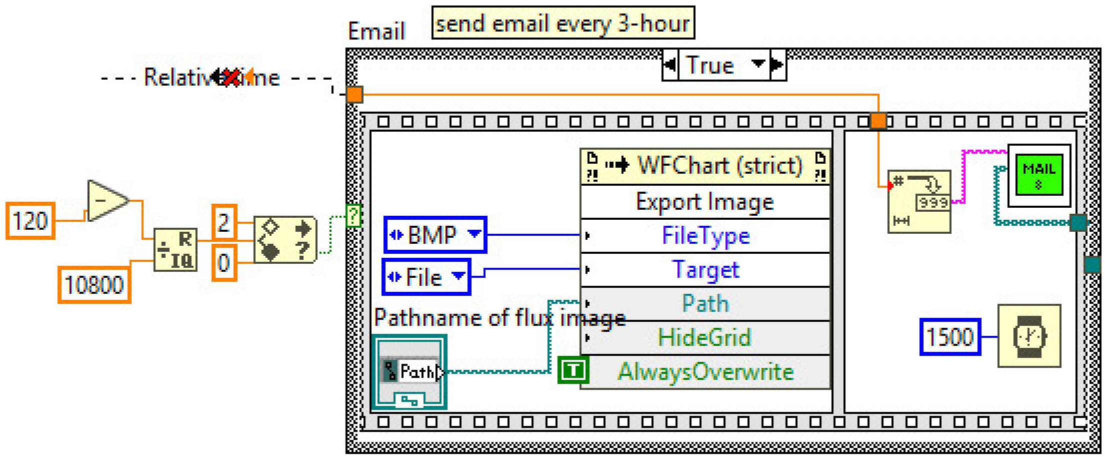


Figure 19. Email program block diagram.

The true case contained a Flat Sequence structure (Figure 20). Firstly, a flux plot was saved to a BMP file which would be attached in the email notification. Secondly, email-sending program was on process. In the second step, 1.5 second would wait to avoid sending twice in next iteration. We had received three emails in two seconds since three iterations were finished in the two-second interval until waiting 1.5 second was added to program. The email included two attachments: the flux plot, and data file. The flux plot served as a key indicator for our system; when flux looked stable, it was reasonable to assume everything else is stable. The data file could be used for plotting in MATLAB if more evaluation were needed.

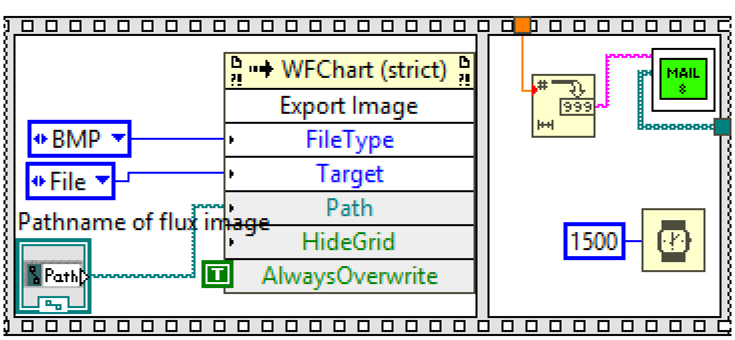


Figure 20. Plot saving and email program block diagram

3.1.2.2 Other Programs

Other programs were also built to make sure the system can run continuously and safely.

Some data processing programs were used for the enhancement of the stability to the system. For example, during the filtration, the TMP curve was unstable due to particles blocking the actuator valve. When pressure control was used to maintain the TMP close to the target TMP this turbulence would make the Actuator Auto Adjustment program adjust the needle valve all the time (no 0 V output), which not only would influence the experiment results by providing extreme values but also would overuse the actuator valve since at most of filtration time the actuator valve should not be adjusted. To avoid this situation, the average of a set including eight TMP values (Figure 21) was calculated which contained the newest value at a certain iteration and another seven values from the nearest iterations, according to Equation 1.

$$TMP_{average} = \sum_{i=n}^{i=n+7} TMP \qquad (1)$$

The average had much lower extreme values which could be used for the Actuator Auto Adjustment program input. During the backwash, the above problem also happened since the pressure provided from peristaltic pumps shows as the sine curve especially during dead-end backwash. Because of that, an average value was also calculated for the Pump Auto Adjustment program input.

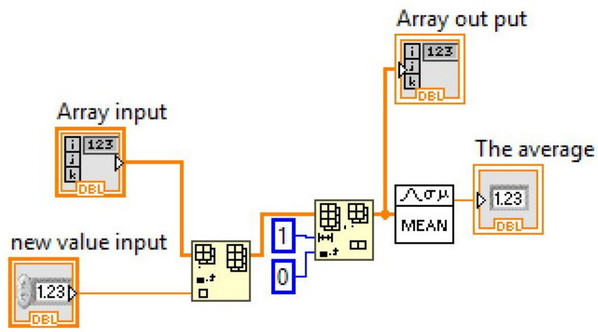


Figure 21. Average TMP calculation block diagram.

Another program was about the Flowrate Calculation program (Figure 22). As mentioned above, the flowmeter and the balance were used to measure the permeate flowrate. The flowmeter could directly output the flowrate as ml/s, however, the balance could only output the current weight as gram. A program was built to calculate the flowrate based on the weight at every iteration. The program was based on a self-empty device by which the permeate could accumulate in the temporary tank and leave away when the water level reaches to a certain level with siphon. The equation as below was employed to calculate the flowrate.

$$Flowrate = \frac{Mass_n - Mass_{n-1}}{Time_n - Time_{n-1}} \tag{2}$$

$Mass_n$ and $Mass_{n-1}$ means the weight values from balance at iteration n and n-1, respectively. The difference between two weight values means the mass accumulated between two iterations. The difference of mass is divided by the time interval to get the mass flowrate (g/s). An assumption was made that the density of the permeate is 1 g/ml, which means the flowrate has the same values with the unit of ml/s.

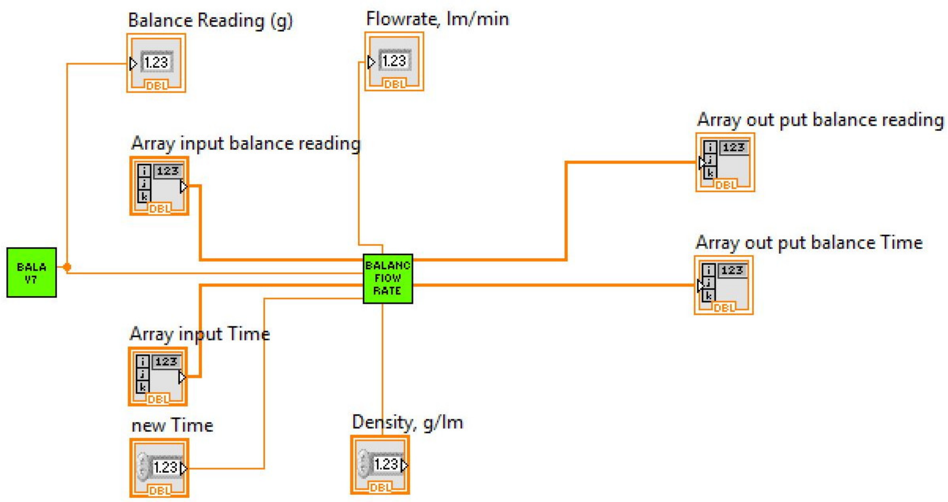


Figure 22. Balance Flowrate program block diagram.

The backwash input port and the permeate output port were outside the ceramic membrane and interlinked. After the backwash, the backwash pressure was still higher than 10 psi until several minutes which meant the pressure outside the membrane was much higher than usual (lower than 2 psi). If there was only 60 second interval between backwash and filtration the high-pressure water outside the ceramic membrane would go through the permeate output port with high flowrate. Even though this high flowrate could not last long it was still much higher than the flowmeter limitation (30 ml/min), which might damage the flowmeter. In this case, an improvement was made in Step One (Figure 23) that the backwash pump would suck the water out from the backwash input port for 3.5 second, which made the pressure outside the membrane lower than 5 psi before the filtration start.

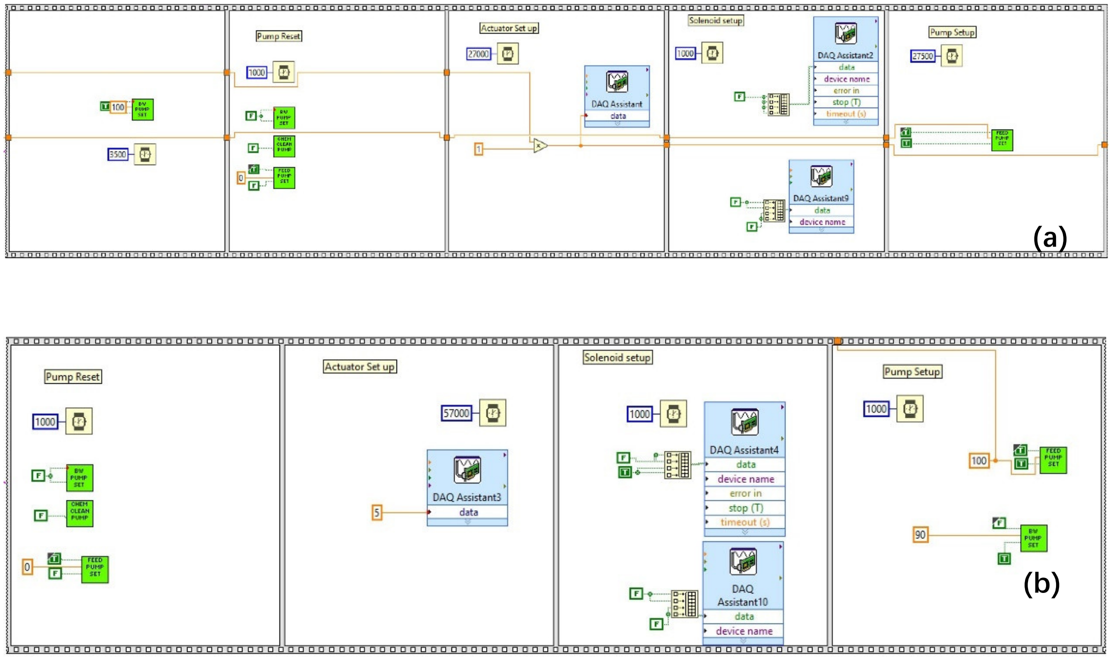


Figure 23. BW pump reverse program block diagram; a) with reverse, b) without reverse

An auto-stop program and the resetting program were also built (Figure 24-a). The auto-stop program (Figure 24-b) aimed to make the auto stop possible after the experiment. There were three methods to stop the program. The first was stop by clicking the Stop button on the front panel. The second method was according to the time setting on the front panel. And the third way was triggered by Auto Pressure/Flux program when the TMP or flux reached again to the beginning value. From Figure 24-c, we could notice that the whole program was in a while loop except a resetting program. When the while loop was stopped, the resetting program would work to reset all of the hardware. The program would set all solenoid valves to default status, set actuator valve to fully open, set pump to stop and send us an email with the data and flux figure.

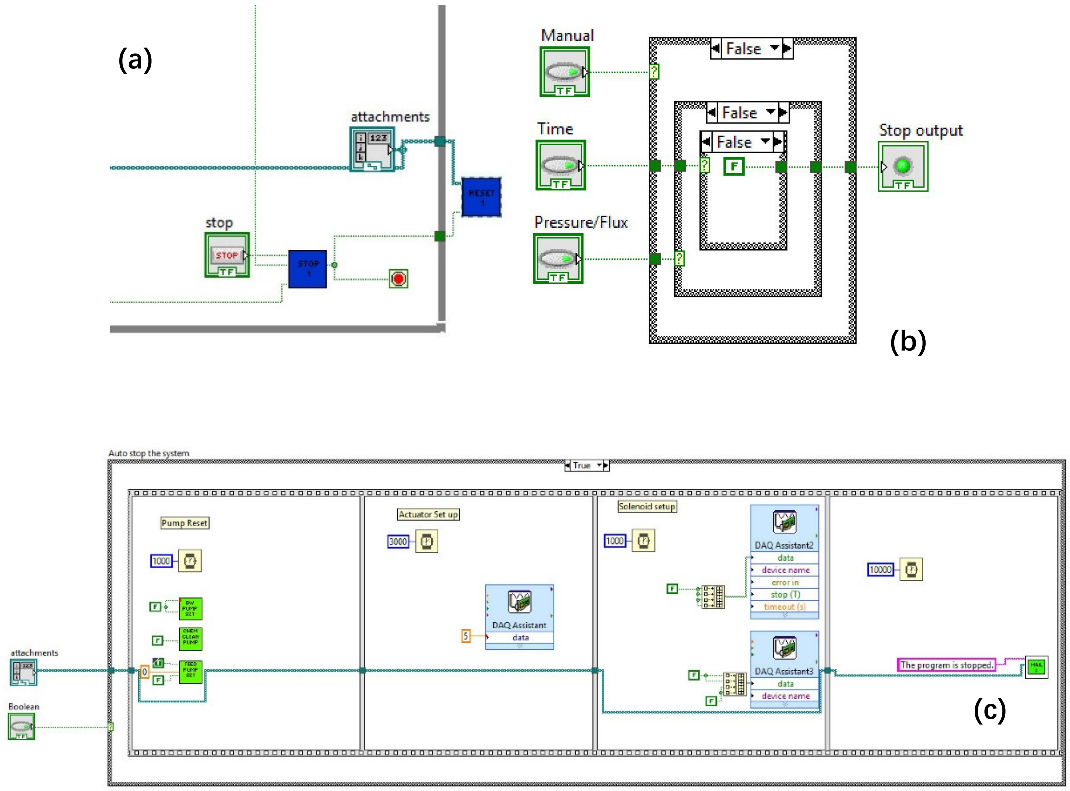


Figure 24. Reset program; a) reset program and decision program in main program block diagram, b) stop decision program block diagram, c) Auto-stop program block diagram

The Relative Time Calculation program also played an important role in the system since it provided a time line for all other sub-programs. Figure 25 shows the Relative Time Calculation program. At every iteration, an absolute time was read from the computer and used to subtract the absolute from last iteration. The result would be how long the system had run which was the relative time.

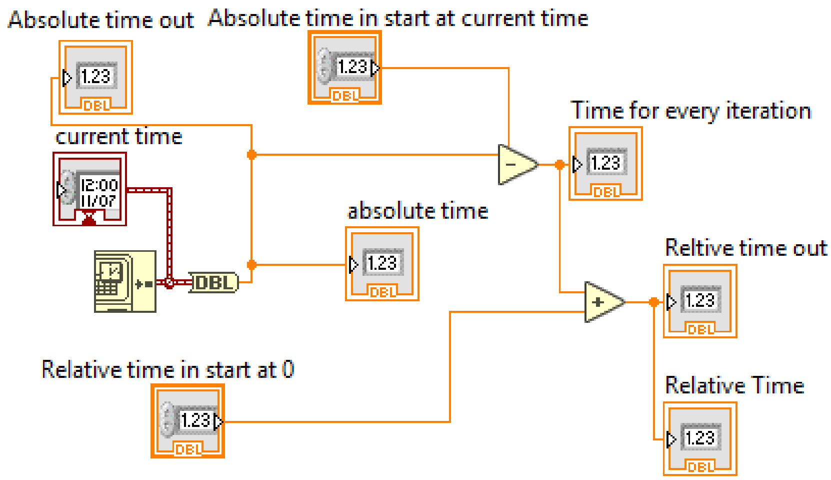


Figure 25. Relative Time Calculation program block diagram

3.1.3 Hardware

The hardware is another important part of the membrane unit. All of the hardware can be divided into three parts: basic components, fluid-handling hardware, and electronic interface. The component list is found in Appendix D.

3.1.3.1 Basic Components

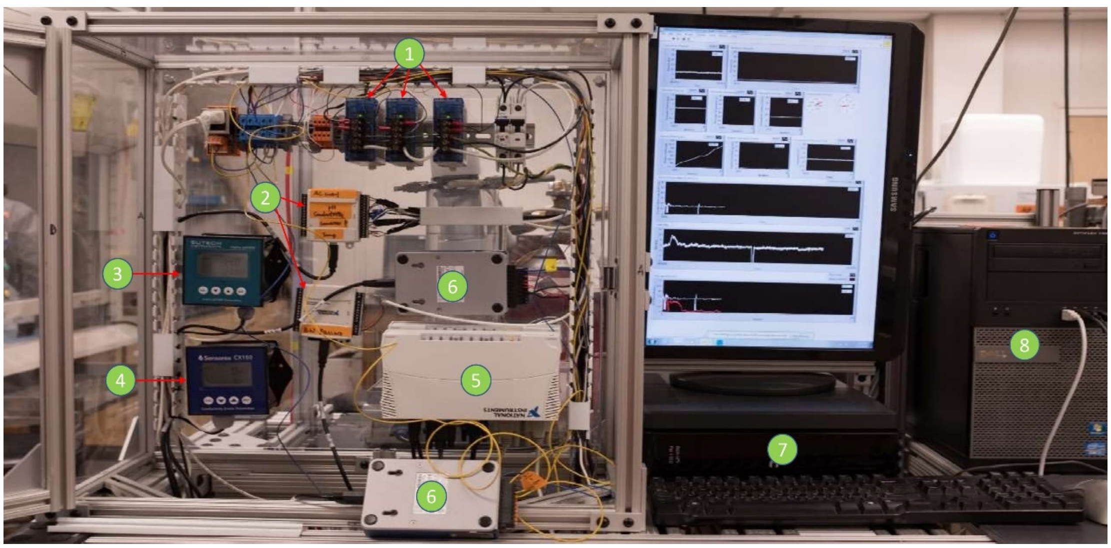


Figure 26. Control panel and desktop. 1) A/C to DC power transformers; 2) USB6009; 3) pH transmitter; 4) conductivity transmitter; 5) USB-323; 6) NI cDAQ-9171 and NI 9482; 7) Uninterrupted Power Supplies; 8) Desk top

The frame of our membrane unit was built with T-slotted structural framing material (so called “80/20” extruded aluminum) and associated parts like brackets, hinges, connectors, plexiglass, and casters. The size of the pallet unit was small enough to transport with a small truck and fit through typical doorways. The frame had two floors. The lower floor was for liquid-processing components, and the upper floor housed different electrical components. A desk-top computer (8 in Figure 26) mounted on the upper floor was for controlling all electrical components. An Uninterrupted Power

Supplies (UPS) (7 in Figure 26) was also employed on the upper floor to make sure the system ran stably. Because we found the computer might shut down at the moment that several solenoid valves were adjusted together. A light and a video webcam were mounted on the roof of the lower floor which enabled us to monitor the fluid-handling hardware day and night.

3.1.3.2 Electrical Interface and Sensors

Most electrical components were centralized in a panel (Figure 26) at the front of the unit on the upper floor since we could easily access and operate it and protect it from water spills. Three A/C to DC power transformers (1 in Figure 26) at the top of the front panel provided power to transmitter and transducers. Other visible components were wiring conduits and terminal blocks.

Different transducers and transmitters were employed to transfer physical characteristics to electrical outputs. Two multifunction I/O devices (National Instruments USB-6009, 2 in Figure 26) were used to read electrical outputs (4-20 mA) from pH transmitter, conductivity transmitter, temperature transmitter, and two pressure transducers, and to output valve actuator control signals (0-5V). Two serial interface devices (National Instruments USB-323/4 and USB-323/2, 5 in Figure 26) aimed to transform USB port into a single asynchronous serial port for communication with RS232 devices, which controlled three pumps and receive electrical outputs from flowmeter and balance. NI cDAQ-9171 and NI 9482 (6 in Figure 26) worked together to receive the signal from the USB and provide access to an electromechanical relay for switching signals. A pH transmitter (α pH 500, 3 in Figure 26) transfered the pH values to electrical output (4-20

mA), and a conductivity transmitter (4 in Figure 26) and temperature transmitter transfered conductivity and temperature values to electrical output.

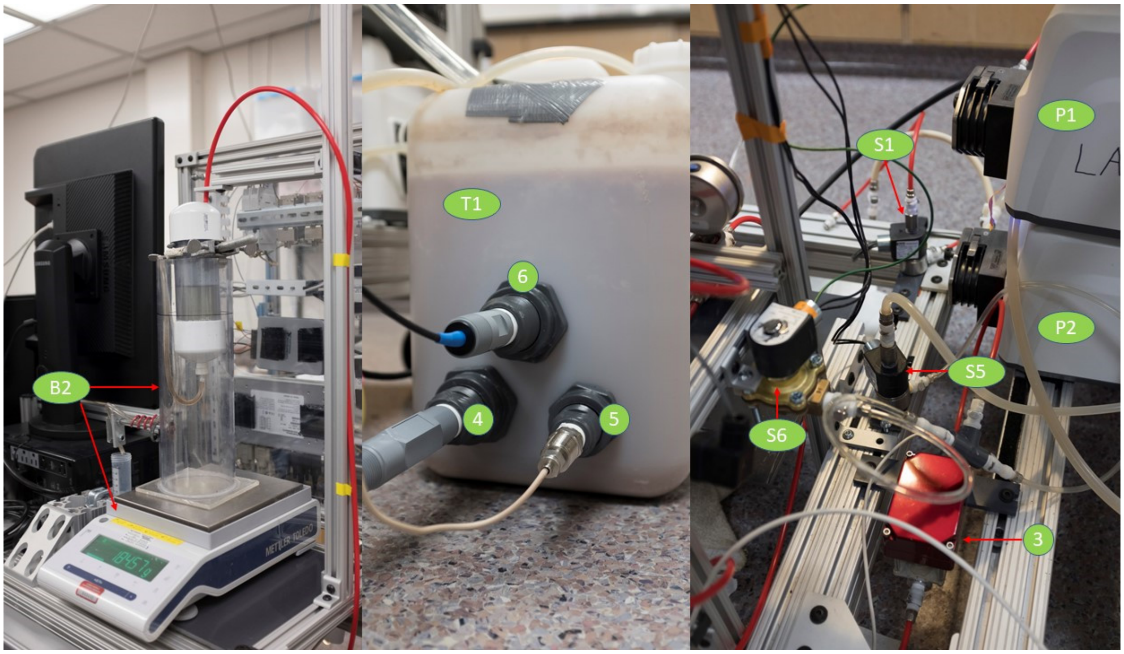


Figure 27. Balance, probes and some fluid handling hardware. B2) self-empty device; T1) feed tank; 4) pH probe; 5) temperature probe; 6) conductivity probe; S1) solenoid valve 1; S5) solenoid valve 5; S6) solenoid valve 6; P1) backwash pump; P2) feed pump; 3) actuator valve;

Three probes were inserted into feed tank to measure the pH (Figure 27-4), conductivity (Figure 27-6), and temperature (Figure 27-5). Two pressure transducers were mounted at the end of concentrate port and the entrance of backwash port to record the pressure. A flowmeter was placed at the permeate port for permeate pressure, temperature and flowrate.

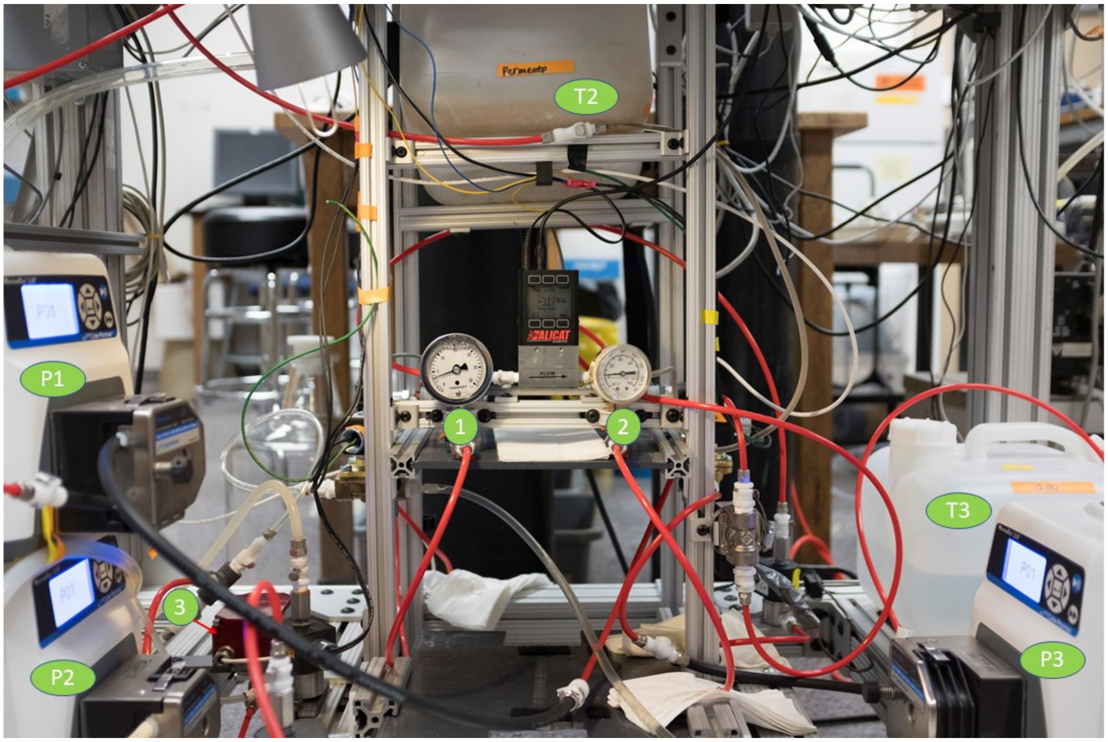


Figure 28. Fluid handling hardware. 1) concentrate pressure gauge; 2) backwash pressure gauge; 3) actuator valve; P1) backwash pump; P2) feed pump; P3) chemical cleaning pump; T2) permeate tank; T3) chemical tank

3.1.3.3 Fluid-Handling Hardware

The fluid-handling hardware carries out the different filtration steps. The components are as follows:

- Ceramic membranes (Al_2O_3) were fabricated by Inopor with mean pore sizes of 100 nm. The effective membrane area is 0.025 m^2.
- The membrane holder (Figure 29) was a 316-stainless steel cell with feed wastewater in and out ports, backwash port and permeate port. Four manual ball

valves were mounted on four ports for easily unload the membrane module after the experiment.

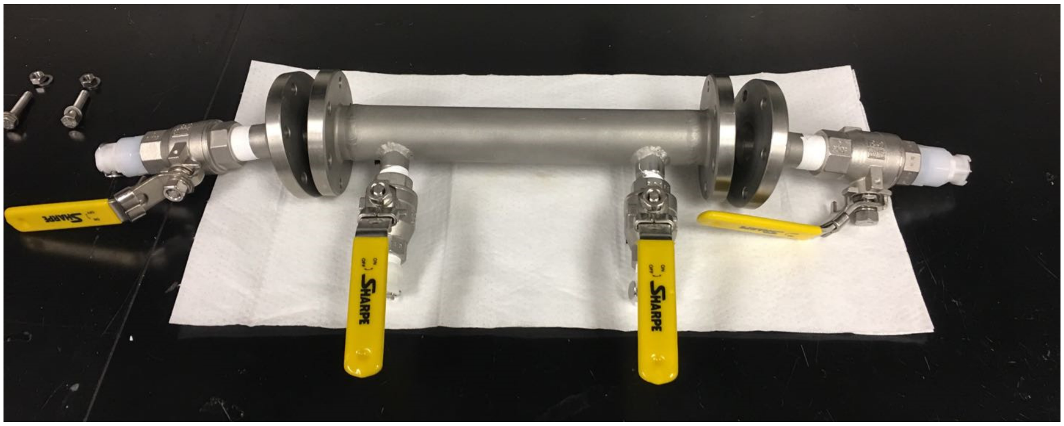


Figure 29. Membrane holder with four valves.

- Three peristaltic pumps were used for creating feed flow, backwash flow, and chemical cleaning flow, respectively.
- Four solenoid valves (Figure 27-S1 and Figure 31-S2, S3, S4), were employed to control the flow entering or leaving the module during filtration, backwash, and chemical cleaning. The first solenoid valve was on the feed enter port which avoided reflux. The third solenoid valve was on the permeate port. During BW or Chem, this port would close for blocking BW or Chem flow to provide high pressure. The second and fourth solenoid valves were for control BW and Chem, respectively. Two other solenoid valves (Figure 27-S5, S6) were used for waste control. During chemical cleaning, chemical contamination was produced, which would react with the FOG wastewater. In this case, the cleaning agents would not go back to the feed tank but to the waste tank, which was control by the fifth and sixth solenoid valve (Figure 27-S5, S6).

- An actuator valve (Figure 27-3), was used at the concentrate port to control TMP and flux by provide concentrate pressure. The concentrate flowrate was stable when feed pump speed was constant at 100 rpm. The valve would open or close a little to create various velocities which could provide different frictions in the valve. These frictions contributed to different concentrate pressures.
- Two pressure gauges (Figure 28-1 and 2) were used to measure the pressure at the concentrate port and BW/Chem port.
- A balance (Figure 27-B2) was mounted on the flow way before the permeate tank. A self-empty measurement device (Figure 27-B2) was employed to calculate flowrate according the mass increase. The device on the balance could accumulate the permeate to 300 ml, and then, the permeate in the device would empty automatically with the mechanism of siphon. Permeate entering and leaving ports on the device only was driven by gravity, and the self-empty device

did not touch with any tubing which made the results more precise (Figure 30).

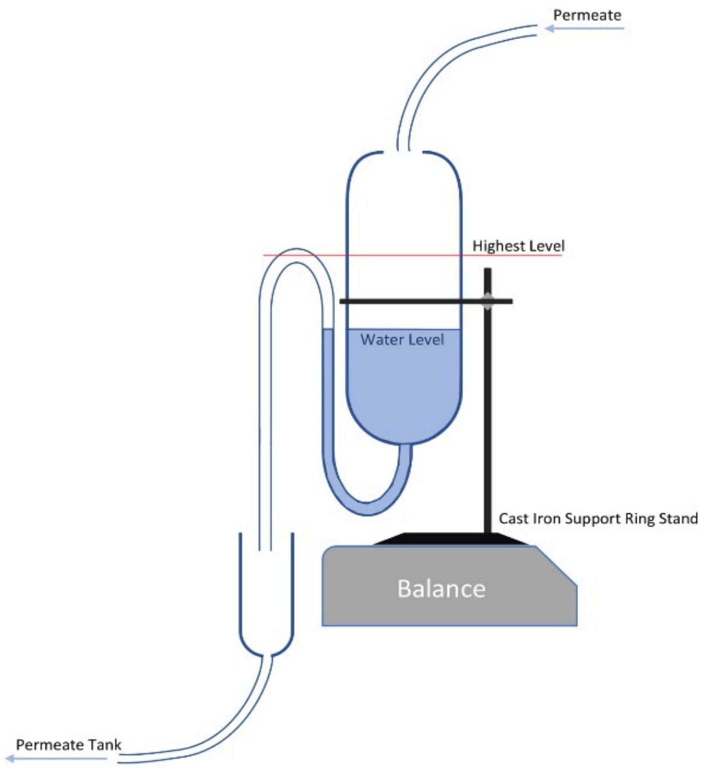


Figure 30. Self-empty device and balance.

- Three carboys worked as feed tank (Figure 27-T1), permeate tank (Figure 28-T2), and chemical tank (Figure 31-T3), respectively. The permeate tank had a limit level of permeate water. When the water level was higher than the level permeate would flow back to the feed tank for avoid overflow. And one glass bottle was for collecting chemical waste.
- High pressure tubing and normal tubing were used to connect each component.

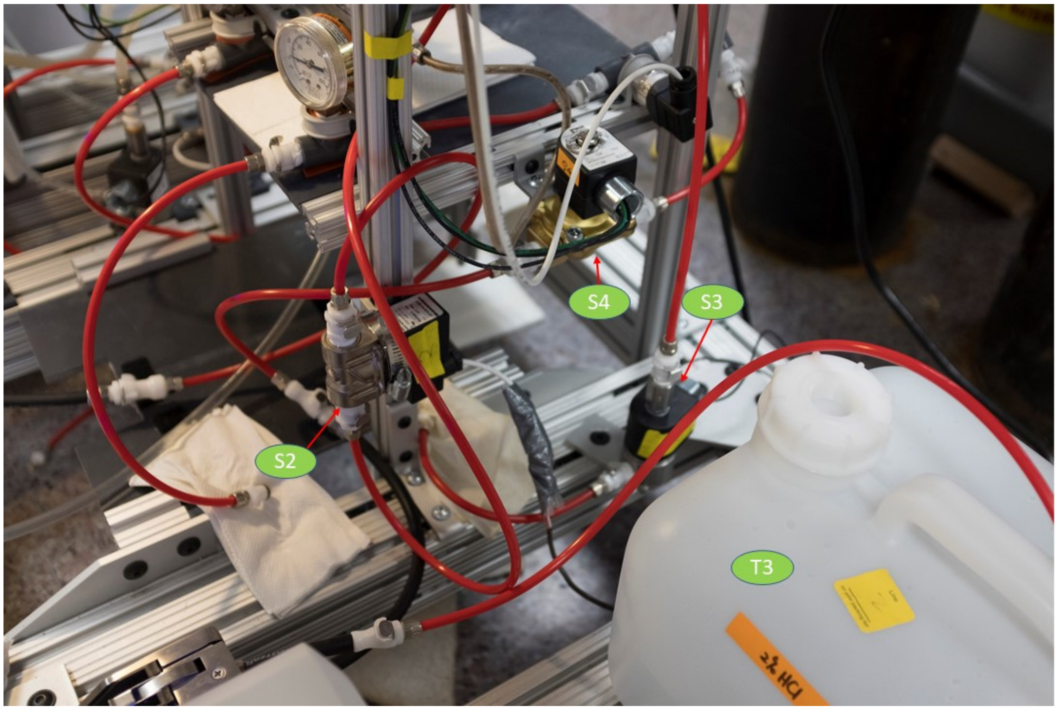


Figure 31. Fluid handling hardware. T3) chemical tank; S4) solenoid valve 4; S3) solenoid valve 3; S2) solenoid valve 2.

3.2 Experiment Procedure

A cleaning experiment using the membrane unit described above was carried out. Three chemical agents were employed for cleaning the membrane fouled by FOG wastewater. Before and after each experiment a cleaning was made for removing the contaminations on the membrane. The whole experiment cost for six days, where the 1st, 3rd, and 5th days were running the system and testing the cleaning efficiency; 2nd, 4th, and 6th days were for cleaning out of place between the runs.

3.2.1 Ex-situ Cleaning

We removed the ceramic membrane from it cell and cleaned it with 2% NaOH, 2%HCl, and DI water in sequence before each experiment. One liter of 2% NaOH, 2%HCl, and DI water were prepared in a tank before cleaning. After each experiment, the membrane was taken out of the module and placed in the tank with chemical agents. Each cleaning with chemical agents lasted for 2 hours in sequence. After that, the membrane stayed in DI water overnight until the next experiment.

3.2.2 Experiment

Wastewater was collected from a rendering plant within driving distance of Clemson University and reserved in the refrigerator under 4℃. In the experiment, there were 3.8-hour filtration before chemical cleaning which meant 6 cycles (N = 6) of filtration and backwash before the chemical cleaning. Each filtration lasted for 30 minutes with TMP of 15 psi; backwash lasted for 2 minutes with pressure of 30 psi; chemical cleaning lasted for 15 minutes; and all prepare steps lasted for 1 minute. Table 2 shows the experiment schedule of one chemical experiment which lasted for 12.28 hours. Chemical cleaning would remove the fouling inside the membrane. Three chemical cleanings were processed with one chemical agent in an experiment. There were another two filtration cycles after the last cleaning procedure, which worked as comparisons. The experiment was running at room temperature (18-24℃). The cleaning condition and fouling condition are shown in Table 3. Three chemical agents were tested. They were 2% NaOH,

2%HCl, and 0.2% Na_2EDTA which represented base, acid and chelator, respectively. The reason we used 0.2% Na_2EDTA was the solubility of EDTA could not reach to 2% unless we adjust the pH to 12. This might influence the results that we could not figure out whether the fouling was removed by EDTA or alkalinity.

Table 2. Experiment schedule. Green cells are the beginning of the filtration, and the red cells are the chemical cleaning.

N	Action	Interval Second	Start Second	End Second	Action	Interval Second	Start Second	End Second	Action	Interval Second	Start Second	End Second	Action	Interval Second	Start Second	End Second
1	FP	60	0	60	FP	60	13380	13440	FP	60	26760	26820	FP	60	40140	40200
	F	1800	60	1860	F	1800	13440	15240	F	1800	26820	28620	F	1800	40200	42000
	BWP	60	1860	1920	BWP	60	15240	15300	BWP	60	28620	28680	BWP	60	42000	42060
	BW	120	1920	2040	BW	120	15300	15420	BW	120	28680	28800	BW	120	42060	42180
2	FP	60	2040	2100	FP	60	15420	15480	FP	60	28800	28860	FP	60	42180	42240
	F	1800	2100	3900	F	1800	15480	17280	F	1800	28860	30660	F	1800	42240	44040
	BWP	60	3900	3960	BWP	60	17280	17340	BWP	60	30660	30720	BWP	60	44040	44100
	BW	120	3960	4080	BW	120	17340	17460	BW	120	30720	30840	BW	120	44100	44220
3	FP	60	4080	4140	FP	60	17460	17520	FP	60	30840	30900				
	F	1800	4140	5940	F	1800	17520	19320	F	1800	30900	32700				
	BWP	60	5940	6000	BWP	60	19320	19380	BWP	60	32700	32760				
	BW	120	6000	6120	BW	120	19380	19500	BW	120	32760	32880				
4	FP	60	6120	6180	FP	60	19500	19560	FP	60	32880	32940				
	F	1800	6180	7980	F	1800	19560	21360	F	1800	32940	34740				
	BWP	60	7980	8040	BWP	60	21360	21420	BWP	60	34740	34800				
	BW	120	8040	8160	BW	120	21420	21540	BW	120	34800	34920				
5	FP	60	8160	8220	FP	60	21540	21600	FP	60	34920	34980				
	F	1800	8220	10020	F	1800	21600	23400	F	1800	34980	36780				
	BWP	60	10020	10080	BWP	60	23400	23460	BWP	60	36780	36840				
	BW	120	10080	10200	BW	120	23460	23580	BW	120	36840	36960				
6	FP	60	10200	10260	FP	60	23580	23640	FP	60	36960	37020				
	F	1800	10260	12060	F	1800	23640	25440	F	1800	37020	38820				
	BWP	60	12060	12120	BWP	60	25440	25500	BWP	60	38820	38880				
	BW	120	12120	12240	BW	120	25500	25620	BW	120	38880	39000				
	ChemP	60	12240	12300	ChemP	60	25620	25680	ChemP	60	39000	39060				
	Chem	900	12300	13200	Chem	900	25680	26580	Chem	900	39060	39960				
	BWCP	60	13200	13260	BWCP	60	26580	26640	BWCP	60	39960	40020				
	BWC	120	13260	13380	BWC	120	26640	26760	BWC	120	40020	40140				

The FOG wastewater was treated at room temperature for more than 6 days. The TSS of wastewater could be degraded by microbes in the feed tank. In all experimental days expect experiment time, the feed tank was in an ice bath to mitigate degradation. TSS was measured before and after the experiment on every experimental day. The pH of each cleaning agent was also measure before the experiments (Table 3).

Table 3. Experimental condition for NaOH, HCl, and EDTA cleaning experiment.

Date	Cleaning						Filtration		
	#	Agents	Time, min	Concentration, w/w%	pH	Pressure, Psi	TMP	F and BW Time, min	N
28-Feb	1	NaOH	15	2%	13.41	30			
2-Mar	2	HCl	15	2%	0.68	30	15	30/1	6
4-Mar	3	Na_2EDTA	15	0%	5.56	30			

Two 40-ml wastewater samples were collected to clean bottles before and after the experiments. Six samples in total were collected and stored in refrigerator. Six clean crucibles with filters were prepared, which were placed in the 103℃ oven and stayed overnight before being cooled in a desiccator. The clean crucibles were weighted and the weight was recorded before 16 ml of wastewater was filtered. After filtration, six crucibles were placed in the oven again for drying overnight. The weight of filtered crucibles and recorded. The difference of weight was the TSS in 16 ml wastewater. The TSS concentration can be calculated as below:

$$TSS = \frac{W_{after\ filteration} - W_{before\ filtraion}}{16ml \Big/ 1000\frac{ml}{l}} \tag{3}$$

Table 4. TSS concentration in the feed at beginning and the end of each experiment.

Collecting Date	Collecting Time	Measure Date	TSS, g/L
28-Feb	9:00	5-Mar	0.65
28-Feb	21:00	5-Mar	0.5
2-Mar	8:37	5-Mar	0.475
2-Mar	22:00	5-Mar	0.445
4-Mar	9:23	8-Mar	0.455
4-Mar	21:32	8-Mar	0.395
26-Feb	8:10	8-Mar	0.975

3.3 Data Analysis

Several characteristics of wastewater, such as temperature, conductivity, and pH were plotted to understand how these variables influenced the membrane performance. Basic parameters like, the length of filtration time and backwash time, pump speed, and actuator voltage input will be recorded to know the operation state. The pressure of concentrate and permeate, flowrate crossing membrane, and balance reading were analyzed to evaluate transmembrane pressure, flux, and resistances. These parameters could be used to not only describe the membrane system, but also give insight into the characteristics of the fouling.

3.3.1 MATLAB Program

A tailored program was created in MATLAB for analyzing and plotting raw data recorded from experiment. The MATLAB program was called seeACRECdata with version number in the end. TXT file from LabVIEW could directly be read to seeACRECdata19 (19th version). Twenty-two columns of data were named with different functions (Table 5).

Table 5. Functions in MATLAB for data analysis and plotting.

Column #	Parameter	Function Name
1	Absolute Time	Atime
2	Iteration	iteration
3	Relative Time	Relativetime
4	Step Number	StepN
5	Feed Pump Speed	pumpSpeed
6	Actuator Output Voltage	actuatorV
7	Target Flux	TargetF
8	Target Pressure	TargetP
9	BW Pump Speed	BWpumpSpeed
10	Chem Pump Speed	ChempumpSpeed
11	Temperature in Feed Tank	temp
12	Concentration Pressure	Apressure
13	Conductivity in Feed Tank	Acond
14	pH in Feed Tank	pH
15	BW Pressure	Bwpressure
16	Permeate Pressure	permPressure
17	Permeate Temperature	permTemp
18	Permeate Flowrate from Flowmeter	AperFlow
19	Permeate Flowrate from Balance	balanceFlow
20	Balance Reading	balancereading
21	Flux from Flowmeter	Fluxflowmeter
22	Transmembrane Pressure	TMP

Some other functions were defined by calculation like running time and fouling rate.

3.3.1.1 Running Time

The x-axis of thirty-one plots was always the running time (RT) which was calculated by equation:

$$RT = AT\ (i) - AT\ (0) \tag{4}$$

where AT (i) and (0) were the absolute time at i^{th} and zero iteration during the experiment, respectively. The reason for that relative time from LabVIEW was not

directly employed as x-axis was the relative time was a calculated value but not an original value from LabVIEW like absolute time.

3.3.1.2 Fouling Rate

Fouling rate (FR) was calculated by MATLAB based on online fouling monitoring method[26]. There were three main steps of online fouling monitoring method calculation when constant flux was employed:

i. Concentrate pressure (P_C) and permeate pressure (P_P) were collected during filtration and transmembrane pressure will be calculated automatically by the following equation:

$$TMP = P_C - P_P \quad (5)$$

ii. The FR were calculated every ten minutes according to the following equation:

$$FR_{TMP} = \frac{\Delta TMP}{\Delta t} \quad (6)$$

iii. FR values were plotted with time, and the slops of FR versus time will be used to describe wastewater characteristics in a certain target flux or pressure. [26]

When the TMP was constant the decline of flux could be used to express the fouling rate. The calculation process showed as Equation 7.

$$FR_{Flux} = \frac{\Delta J}{\Delta t} \quad (7)$$

where J is flux. Since there was no requirement for monitoring fouling rate at real time, linear fitting was employed in MATLAB for getting a more stable result. Function of Polyfit was used to fit the linear relationship between vector X and vector Y. Vector X contained eight continuous absolute times, and vector Y had eight corresponding flux or TMP values. If the experiment employed pressure control (constant TMP) the vector Y would be eight flux values. On the other hand, if the experiment worked as flux control (constant flux) the vector X would be eight TMP values. The slop of two vectors was the fouling rate of the experiments.

3.3.2 Flux Recovery Efficiency

The flux recovery efficiency can be defined as the flux recovery rate after the chemical cleaning when the TMP was fixed at 15 psi.

3.3.2.1 Reversible Fouling

Fouling can be removed by physical scouring of backwash water, which is classified as reversible fouling. Reversible fouling from the experiment is the difference between flux before and after the backwash. The reversible fouling can be calculated as Equation 8.

$$F_r = J_{ab} - FJ_{bb} \tag{8}$$

Where J_{ab} is the flux after the backwash, and J_{bb} is the flux before backwash.

3.3.2.2 Irreversible Fouling

Physical cleaning cannot remove irreversible fouling (F_{ir}), which can only be removed by chemical cleaning. In the experiment, irreversible fouling cannot be removed by

backwash, which means the irreversible fouling after five filtrations is the difference between the flux right after the first and fifth backwash. However, the last filtration cannot be used for calculation of irreversible flux since the chemical cleaning is right after the backwash. In this case, an assumption has been made that irreversible fouling formed in each filtration cycle is the same, which means the 7^{th} filtration has the same trend as the first six. The calculation was done using Equation 9.

$$F_{ir} = (J_{begin\ of\ 1st\ F} - J_{begin\ of\ 6th\ F}) * \frac{6}{5} \quad (9)$$

3.3.2.3 Flux Recovery Rate

After the chemical cleaning, irreversible fouling is removed by chemical agents. However, chemical cleaning happens right after backwash, which means flux recovery by chemical cleaning only cannot be measured directly. Another assumption was made in this situation that the reversible fouling removed by backwash after each filtration is the same. Based on this assumption, the fouling removal by chemical agents is the difference between total removal and backwash removal. The calculation of flux recovery rate was done using Equation 10.

$$R = \frac{(J_{ac} - J_{bc}) - F_r'}{F_{ir}} \quad (10)$$

where J_{bc} and J_{ac} are flux values at end of filtrations before and after a chemical cleaning, F_r' is the average of reversible removed in last five backwashes.

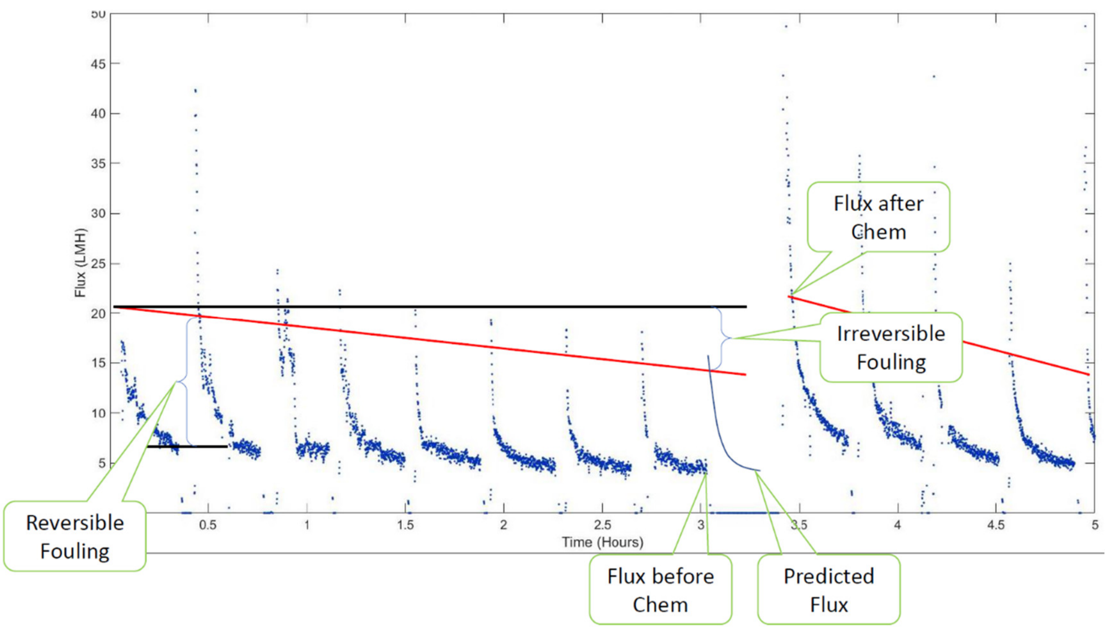


Figure 32. Flux calculation example. The reversible fouling and irreversible fouling are defined in the plot. The irreversible recovered by chemical cleaning can also be calculated based on the plot.

Figure 32 shows an example of a flux plot during filtration. There are eight filtration cycles before backwash. And reversible fouling from seven filtrations can be calculated as shown in figure. After the eighth filtration, a backwash happens before chemical cleaning. The reversible fouling removed during eighth backwash can be predicted as the average of last seven reversible fouling. If there was the ninth filtration (Predicted Flux in Figure 32), the irreversible fouling after the eighth filtration would be calculated and shown in the figure. However, there is no other filtration after the eighth one and before the chemical cleaning. In this case, another assumption is made that the irreversible fouling formed in the eighth filtration equals to the average of first seven filtrations. After the chemical cleaning, flux is recovered. The difference between flux after chemical cleaning and flux before chemical cleaning is the sum of chemical flux recovery and the eighth reversible fouling removal which was calculated above. Thus, the real chemical flux recovery can be calculated. Then, the recovery rate can also be

carried out by dividing chemical flux recovery with irreversible fouling. A calculation example is shown in Appendix A - Calculation Example.

4 Results

The performance of the system for operating the auto-cleaning membrane to treat wastewater from rendering plant was evaluated. Also, cleaning efficiency of different chemical agents were compared. The rejection coefficient was also analyzed.

4.1 Automation System Performance

We carried out more than five hundred of experiments for testing our system to make sure every program in LabVIEW worked well. Test experiments included three phases: tap water testing, lack water or effluent water testing, and FOG wastewater testing. We used the tap water for filtration test more than six month before FOG wastewater was employed. Because tap water had much less foulants than FOG wastewater, which made the membrane could be used for a long time without cleaning out of place. Then, lake water and effluent water from wastewater treatment plant were used to test the system. A little fouling was formed during these runs, but fouling was still easy to remove. Before the formal experiment, FOG wastewater had been used to comprehensively test the system.

4.1.1 Filtration Loop Control

Filtration operation is the fundamental and vital part of the experiment. At beginning of tap water testing period, chemical cleaning was not included in our program, since there was not urgent cleaning request. Only filtration and backwash cycles were tested. During the lake water and FOG wastewater testing phases, chemical cleaning was introduced

to maintain the membrane. Figure 33 shows a running example including filtration, backwash and chemical cleaning, which treated FOG wastewater and applied 2%NaOH as the cleaning agent.

Figure 33-A is the step number of filtration, where 2 = filtration (F), 4 = backwash (BW), 6 = chemical cleaning (Chem), and 8 = backwash after chemical cleaning (BWC). The step number was originated from Step Choose program. From figure 33-A, step 1, 3, 5, and 7 are not recorded in some cases since the data only were recorded every five second. And some prepare steps were started between two recording time. The data could be recorded every second; however, it will not only bring the burden to the computer but also increased the time for every iteration which made the system less sensitive. So, the data were recorded every 5 seconds, which was seen as robust data collection, yet not overly burdensome on the computer.

In Figure 33-B to E, TMP, Flux, BW pressure and BW pump speed were plotted, from which filtration details corresponded to filtration steps were clearly presented. During the step 2, TMP is maintained at 15 $\pm$ 1.8 psi. With the same time, flux decreased from 50 LMH (filtration beginning) to the 10 LMH (filtration end) in 30 minutes due to fouling accumulated on or in the ceramic membrane. Between two filtrations, there was the backwash and chemical cleaning. Figure 33-D, and E represents the BW pressure and BW pump speed. Backwash before chemical cleaning lasted for 2 minutes at pressure of 30 psi with pump speed decreasing from 80 to 50. Then, it was chemical cleaning for 15 minutes at the same pressure, during which the pump speed increased from 50 to 80 again. After the chemical cleaning, another backwash was run for removing chemical

agent inside the membrane module for eliminating the influence from chemicals at next filtration time.

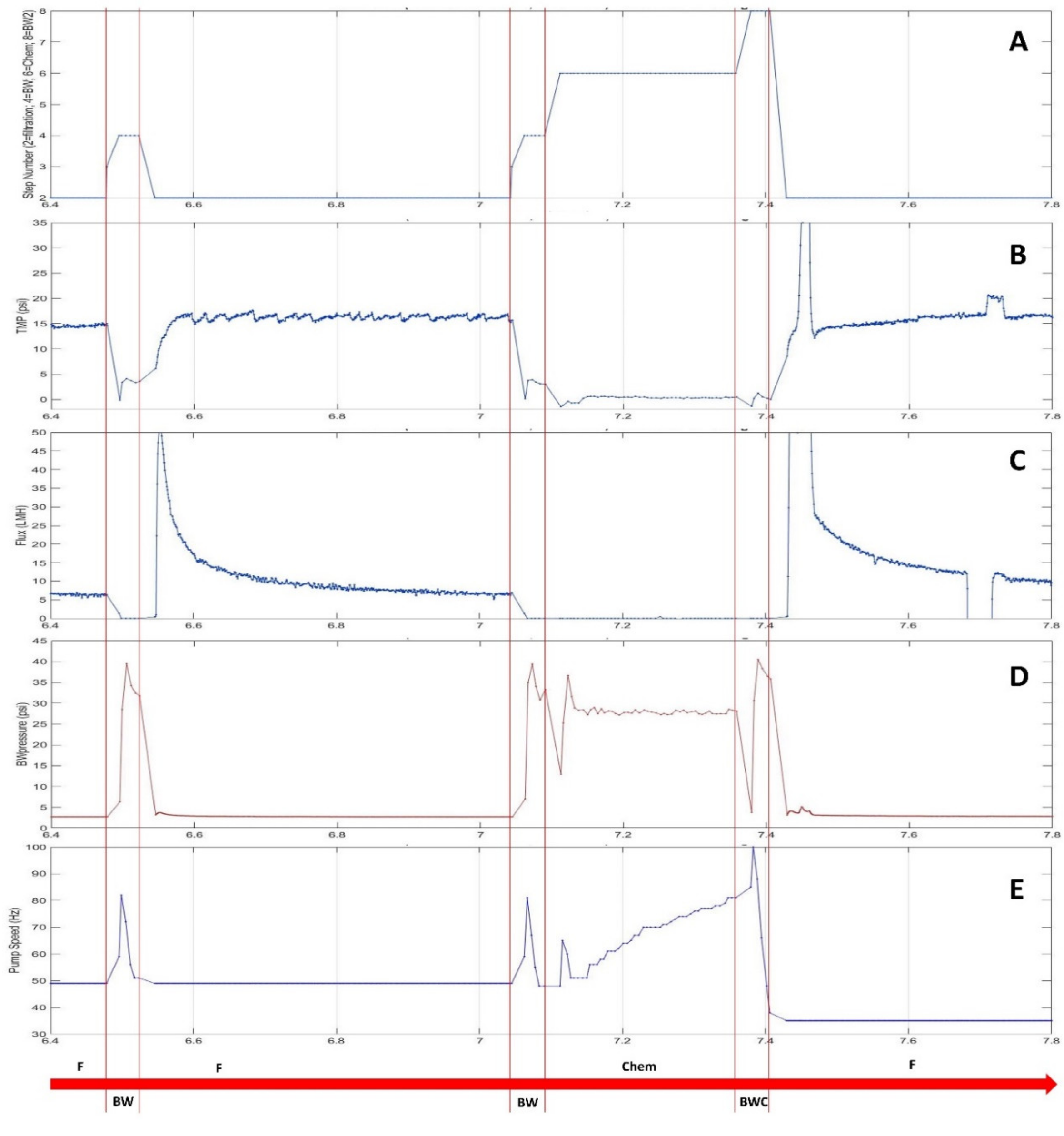


Figure 33. Filtration Cycle performance from a specific filtration, A) step number; B) TMP; C) Flux; D) backwash pressure; E) backwash and chemical pump speed.

4.1.2 Actuator Auto Adjustment

The Actuator Auto Adjustment program worked for maintaining the TMP or flux. In Figure 34, a comparison of TMP and actuator voltage is plotted, where the orange line is the real TMP; the dash line is the target TMP; and the blue circles are actuator voltages. When TMP was in the desired range (target TMP $\pm$ 12%), the output voltage was zero.

From Figure 34 that most output voltage from this program is zero, the feature apparently decreases adjustment times, which protects the actuator valve and extends its life.

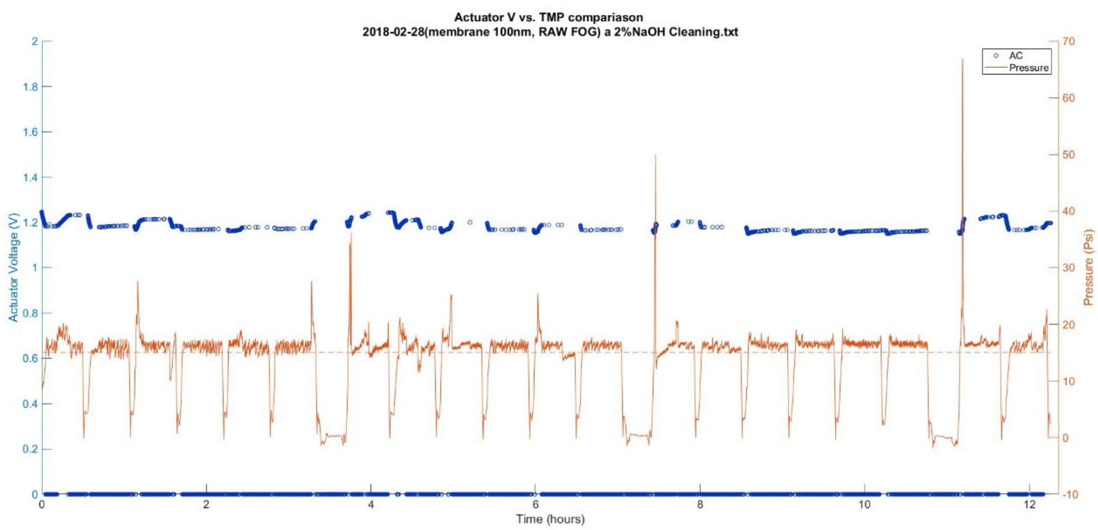


Figure 34. Actuator Auto Adjustment program performance. The blue cycles are the actuator voltage, the orange line is the real TMP and the dash line is the target TMP.

Figure 35 gives more details about how the actuator was adjusted according to TMP. At 8 hours, the TMP started increasing due to fouling or particle blocking in the valve. When the TMP researched to 17 psi the program adjusted the actuator valve once to decrease the TMP. There are eight TMP peaks in Figure 35, and five adjustments for stabilizing the TMP. Another three adjustments must have done, and the non-zero voltage might

not be recorded since the actuator voltage was change in five seconds without recording.

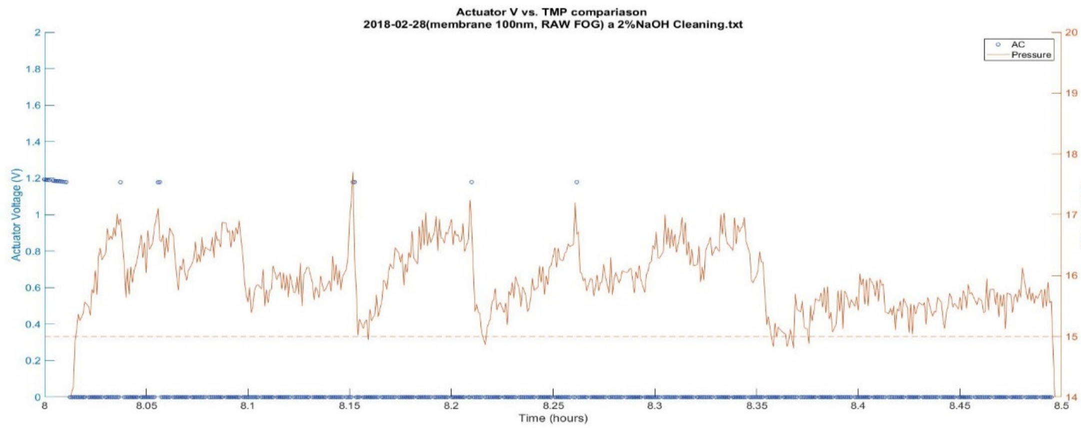


Figure 35. TMP and actuator voltage in a specific experiment for Actuator Auto Adjustment program performance.

Figure 36 contains an extreme value at filtration beginning right after chemical cleaning. The TMP raised to 60 psi between 11.1 and 11.2 hour. The output voltage went up from 1.15 to 1.22 V. At beginning, the voltage rise slowly since the TMP was a little higher than the target. Then, a quickly increase happened to output voltage due to extreme TMP. When TMP got near to target value, the increasing trend of voltage slowed down. There was not over adjustment during this process, which indicated that the actuator voltage calibration curve relieved the sine oscillation.

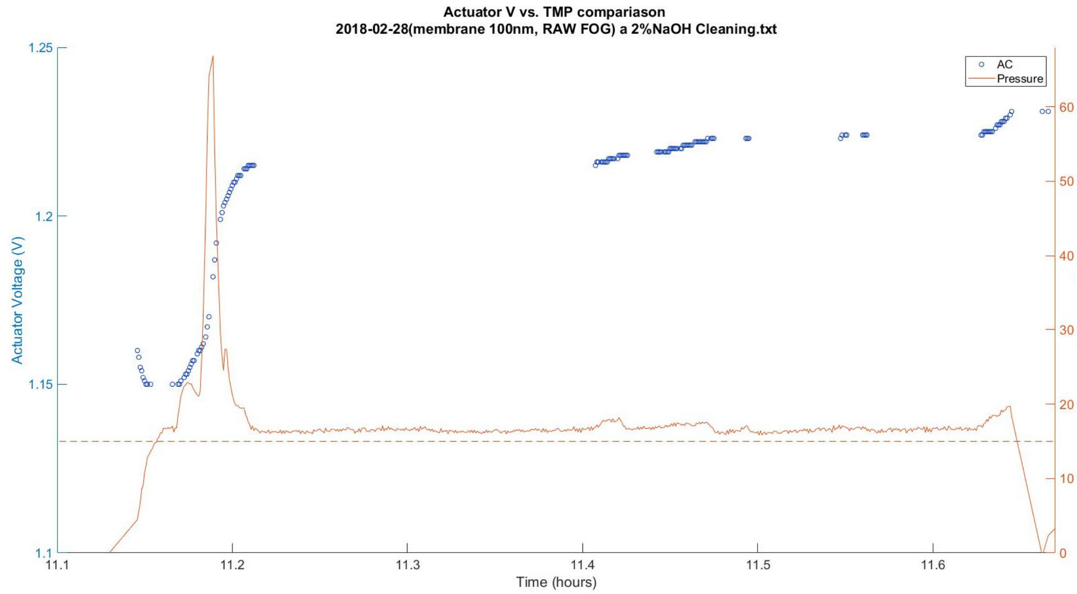


Figure 36. Actuator Auto Adjustment program performance during extreme value.

The Pump Auto Adjustment program also showed functionality. Figure 37 presents the Chem pump speed and Chem pressure. The pressure was stable at 28 psi where the target pressure was set as 30 psi. The pump speed increases to maintain the pressure. At the beginning, the pump speed sharply increased for accelerating the pressure increase. Then, the increase of pump speed slowed down until the end, which indicated that the fouling remove rate is decreasing.

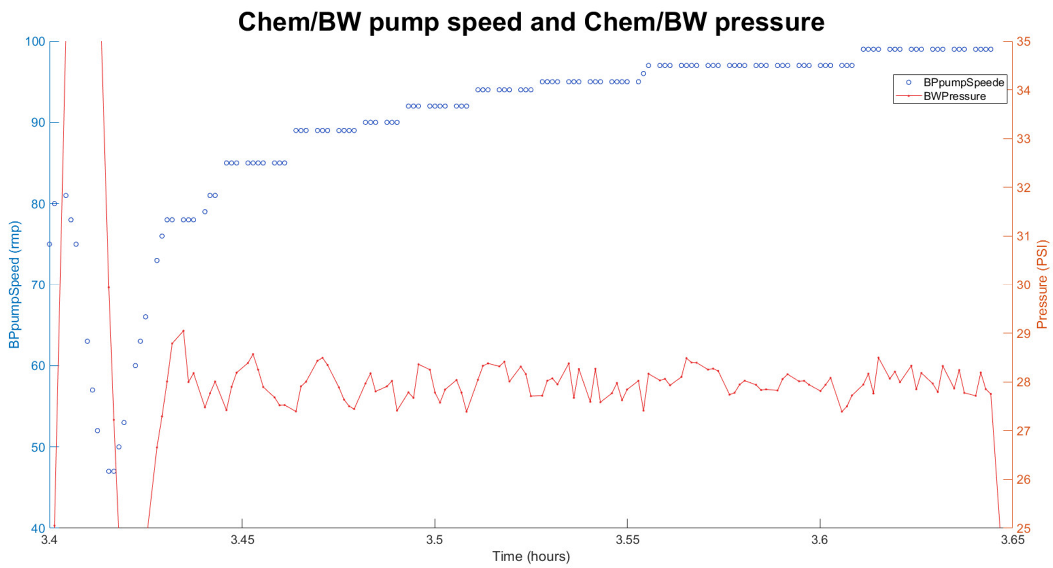


Figure 37. Pump Auto Adjustment program performance.

Auto Pressure/Flux program was also tested. Figure 38 provides a result of auto-pressure program. The blue line is the target pressure, and red line presents the real pressure. The target pressure increased 0.4 psi every two filtration cycles from 3 to seven psi in twenty-hour experiment. The concentrate pressure followed the target pressure and increased four psi in twenty-one hours. Since this is an early experiment, the Actuator Auto Adjustment program corrected the valve according to concentrate pressure.

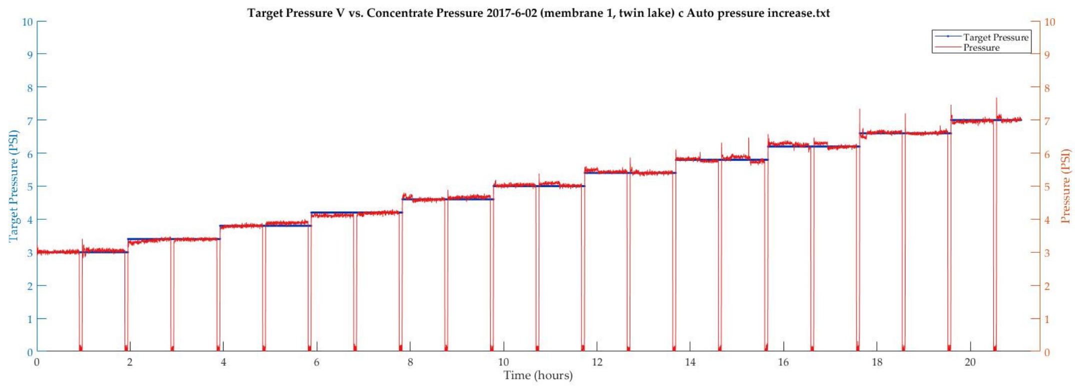


Figure 38. Auto Pressure/Flux program performance.

4.1.3 Data Acquisition and Presentation

Twenty-two groups of data are collected and recorded into a txt file (Figure 39). They were absolute time, iteration, relative time, step number, feed pump speed, AC voltage, target flux, target pressure, BW pump speed, Chem pump speed, temperature in feed tank, concentrate pressure, conductivity in feed tank, pH in feed tank, BW pressure permeate pressure, permeate temperature, permeate flow rate from flowmeter, permeate flowrate from balance reading, balance reading, flux from flowmeter, and TMP from the left to the right in the txt file. The first line of each file contained twenty-two zeros which indicated the beginning of the program and the zero iteration of the experiment.

2018-03-04(membrane 100nm, RAW FOG) a 0.2%EDTANa2 Cleaning.txt - Notepad

File Edit Format View Help

0.000 0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
3603018152.378	0.000	15.829	1.000	100.000	0.000	15.000	10.000	10.000	0.000	13.503	-0.452	3367.850	4.347	0.896	-0.070	23.880	1.020	-0.000	0.000	2.432	-0.382
3603018216.858	3.000	80.309	2.000	100.000	1.246	15.000	15.000	10.000	0.000	13.575	5.416	3356.612	4.346	1.364	0.170	23.780	1.240	-0.939	-1.210	2.957	5.246
3603018222.365	7.000	85.816	2.000	100.000	1.242	15.000	15.000	10.000	0.000	13.540	5.659	3354.201	4.346	1.544	0.040	23.820	2.060	-1.086	-1.210	4.912	5.619
3603018226.580	10.000	90.031	2.000	100.000	1.239	15.000	15.000	10.000	0.000	13.524	5.830	3357.445	4.343	1.415	-0.000	23.840	1.920	-0.000	-1.210	4.578	5.830
3603018232.088	14.000	95.539	2.000	100.000	1.235	15.000	15.000	10.000	0.000	13.584	5.978	3357.132	4.346	1.384	0.380	23.740	8.610	-0.000	-1.210	20.529	5.598
3603018246.694	25.000	110.145	2.000	100.000	1.225	15.000	15.000	10.000	0.000	13.672	7.092	3313.741	4.346	3.357	1.460	23.240	32.830	0.000	-1.210	78.278	5.632
3603018252.203	29.000	115.654	2.000	100.000	1.221	15.000	15.000	10.000	0.000	13.581	7.465	3311.503	4.346	3.502	1.540	23.170	32.980	0.000	-1.210	78.636	5.925
3603018266.670	38.000	130.121	2.000	100.000	1.213	15.000	15.000	10.000	0.000	13.543	8.263	3301.028	4.348	3.912	2.100	23.070	29.590	-0.000	-1.210	70.553	6.163
3603018272.162	42.000	135.613	2.000	100.000	1.209	15.000	15.000	10.000	0.000	13.521	8.685	3298.080	4.345	4.136	2.380	23.050	29.380	-0.000	-1.210	70.052	6.305
3603018281.556	49.000	145.007	2.000	100.000	1.203	15.000	15.000	10.000	0.000	13.490	10.087	3287.588	4.345	4.661	2.680	22.990	34.340	-0.000	-1.210	81.879	7.407
3603018287.065	53.000	150.516	2.000	100.000	1.200	15.000	15.000	10.000	0.000	13.512	10.857	3284.397	4.345	4.740	2.660	22.950	36.360	6.845	0.180	86.695	8.197
3603018301.704	64.000	165.155	2.000	100.000	1.194	15.000	15.000	10.000	0.000	13.657	13.306	3276.280	4.347	5.027	2.810	22.870	38.400	35.824	8.950	91.559	10.496
3603018307.266	68.000	170.717	2.000	100.000	1.192	15.000	15.000	10.000	0.000	13.556	14.050	3277.095	4.346	5.062	2.830	22.830	38.400	38.365	12.540	91.559	11.220
3603018316.783	75.000	180.234	2.000	100.000	1.189	15.000	15.000	10.000	0.000	13.491	15.777	3277.529	4.345	5.071	2.830	22.780	38.400	40.266	18.900	91.559	12.947
3603018322.366	79.000	185.817	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.613	17.531	3275.638	4.347	5.106	2.870	22.760	38.400	39.023	22.480	91.559	14.661
3603018326.611	82.000	190.062	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.636	18.934	3275.257	4.346	5.119	2.850	22.730	38.400	39.616	25.350	91.559	16.084
3603018332.182	86.000	195.633	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.708	21.010	3278.448	4.342	5.071	2.840	22.710	38.400	40.179	29.050	91.559	18.170
3603018341.608	93.000	205.059	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.620	12.252	3295.739	4.343	4.199	2.300	22.690	29.110	36.608	34.720	69.409	9.952
3603018347.084	97.000	210.535	2.000	100.000	1.186	15.000	15.000	10.000	0.000	13.714	11.322	3302.554	4.345	3.881	2.180	22.700	25.500	27.814	37.050	60.801	9.142
3603018361.628	108.000	225.079	2.000	100.000	1.180	15.000	15.000	10.000	0.000	13.694	12.147	3306.058	4.347	3.784	2.110	22.670	24.240	22.007	42.470	57.797	10.037
3603018367.121	112.000	230.572	2.000	100.000	1.178	15.000	15.000	10.000	0.000	13.696	11.802	3306.734	4.342	3.738	2.100	22.660	23.770	21.833	44.450	56.676	9.702
3603018381.665	123.000	245.116	2.000	100.000	1.173	15.000	15.000	10.000	0.000	13.765	12.640	3307.601	4.346	3.701	2.070	22.620	22.840	20.650	49.500	54.459	10.570
3603018387.158	127.000	250.609	2.000	100.000	1.171	15.000	15.000	10.000	0.000	13.837	12.695	3308.503	4.341	3.663	2.080	22.600	22.730	19.802	51.220	54.196	10.615
3603018396.569	134.000	260.020	2.000	100.000	1.168	15.000	15.000	10.000	0.000	13.880	13.351	3307.601	4.350	3.658	2.090	22.570	22.500	19.780	54.370	53.648	11.261
3603018402.062	138.000	265.513	2.000	100.000	1.166	15.000	15.000	10.000	0.000	13.869	13.934	3309.145	4.350	3.666	2.060	22.550	22.260	19.426	56.160	53.076	11.874
3603018407.540	142.000	270.991	2.000	100.000	1.165	15.000	15.000	10.000	0.000	13.883	13.837	3308.260	4.348	3.624	2.060	22.530	22.000	19.738	57.940	52.456	11.777
3603018411.731	145.000	275.182	2.000	100.000	1.164	15.000	15.000	10.000	0.000	13.871	13.871	3309.145	4.350	3.620	2.010	22.520	21.820	19.318	59.290	52.027	11.861
3603018417.239	149.000	280.690	2.000	100.000	1.162	15.000	15.000	10.000	0.000	13.870	14.756	3308.746	4.351	3.628	2.040	22.500	21.650	19.276	61.020	51.621	12.716
3603018426.657	156.000	290.108	2.000	100.000	1.159	15.000	15.000	10.000	0.000	13.854	15.290	3309.370	4.350	3.596	2.040	22.470	21.370	18.606	63.970	50.954	13.250
3603018432.180	160.000	295.631	2.000	100.000	1.157	15.000	15.000	10.000	0.000	13.904	14.999	3309.943	4.347	3.582	2.030	22.460	21.120	18.731	65.690	50.358	12.969
3603018441.580	167.000	305.031	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.912	15.205	3311.243	4.347	3.531	2.000	22.430	20.610	17.834	68.530	49.142	13.205
3603018447.089	171.000	310.540	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.873	15.986	3310.844	4.348	3.546	2.010	22.410	20.580	18.069	70.160	49.070	13.976
3603018461.644	182.000	325.095	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.811	16.500	3310.775	4.350	3.510	1.990	22.370	20.050	17.534	74.440	47.806	14.510
3603018467.121	186.000	330.572	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.886	17.225	3310.810	4.348	3.507	1.980	22.360	19.970	17.289	75.990	47.616	15.245
3603018481.711	197.000	345.162	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.972	17.640	3311.538	4.349	3.485	1.960	22.320	19.390	16.773	80.150	46.233	15.680
3603018487.205	201.000	350.656	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.913	17.183	3312.197	4.348	3.460	1.950	22.300	19.090	16.692	81.680	45.517	15.233
3603018496.613	208.000	360.064	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.963	17.323	3312.128	4.351	3.425	1.950	22.280	18.710	16.040	84.220	44.611	15.373
3603018502.088	212.000	365.539	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.950	17.848	3313.394	4.349	3.422	1.960	22.270	18.460	16.199	85.650	44.015	15.888
3603018516.662	223.000	380.113	2.000	100.000	0.000	15.000	15.000	10.000	0.000	13.883	17.900	3314.400	4.350	3.383	1.920	22.230	17.980	15.521	89.410	42.871	15.980
3603018522.154	227.000	385.605	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.034	17.768	3314.538	4.350	3.375	1.910	22.220	16.600	15.200	90.810	39.580	15.858
3603018536.731	238.000	400.182	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.023	18.192	3316.151	4.350	3.350	1.890	22.180	16.100	14.910	94.420	38.388	16.302
3603018542.203	242.000	405.654	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.035	17.787	3314.642	4.347	3.346	1.890	22.170	15.980	14.459	95.720	38.102	15.897
3603018551.594	249.000	415.045	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.065	17.661	3315.163	4.349	3.334	1.880	22.150	15.770	14.359	97.960	37.601	15.781
3603018557.061	253.000	420.512	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.043	18.271	3315.163	4.349	3.299	1.870	22.140	15.570	14.229	99.230	37.124	16.401
3603018562.532	257.000	425.983	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.076	18.378	3314.746	4.351	3.305	1.880	22.130	15.460	14.024	100.550	36.862	16.498
3603018566.713	260.000	430.164	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.057	18.617	3316.637	4.349	3.301	1.870	22.120	15.310	13.883	101.460	36.505	16.747
3603018572.223	264.000	435.674	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.072	17.828	3316.221	4.350	3.282	1.860	22.110	15.130	13.724	102.750	36.075	15.968
3603018581.628	271.000	445.079	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.078	17.665	3317.174	4.349	3.251	1.840	22.090	14.890	13.283	104.800	35.503	15.825
3603018587.105	275.000	450.556	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.124	18.828	3315.579	4.349	3.258	1.840	22.080	14.810	12.981	106.000	35.312	16.988
3603018601.696	286.000	465.147	2.000	100.000	1.155	15.000	15.000	10.000	0.000	14.122	19.072	3315.856	4.349	3.261	1.850	22.050	14.540	12.670	109.200	34.669	17.222
3603018607.170	290.000	470.621	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.129	16.655	3315.197	4.352	3.232	1.840	22.050	14.060	13.004	110.350	33.524	14.815
3603018621.728	301.000	485.179	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.118	17.295	3318.926	4.350	3.189	1.790	22.030	13.580	11.763	113.300	32.380	15.505
3603018627.219	305.000	490.670	2.000	100.000	0.000	15.000	15.000	10.000	0.000	14.123	16.879	3317.209	4.348	3.182	1.820	22.020	13.590	12.115	114.410	32.403	15.059

Figure 39. An example of data recording file from Data Acquisition and Presentation program.

4.1.3.1 Alarm System and Email System

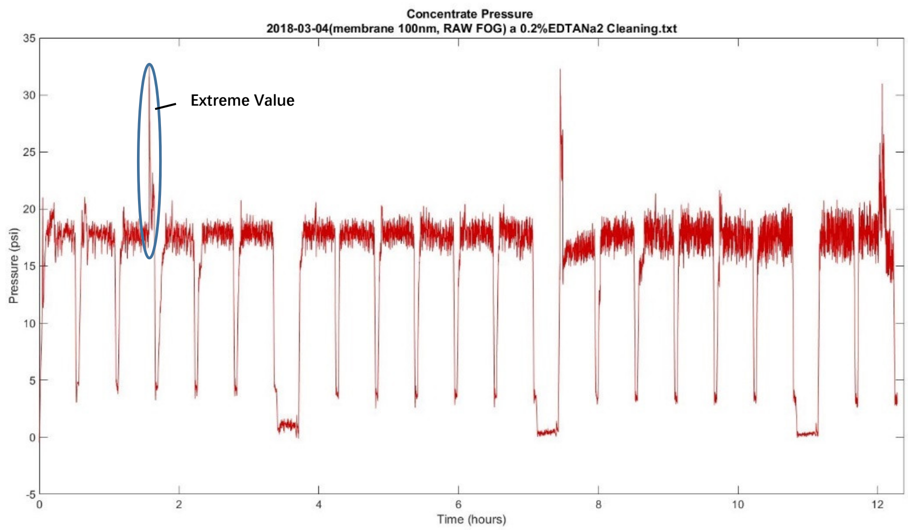


Figure 40. Alarm system performance - Concentrate pressure alarm

In Figure 40, an extreme value exists at 1.4 hours that the concentrate pressure is higher than 28 psi, which can damage the pressure gauge since the range of it is 0-30 psi. The extreme pressure was caused by particle blocking the actuator valve. Although the Actuator Auto Adjustment program handled it in minutes, several emails were still sent to ACRECproject@gmail.com.

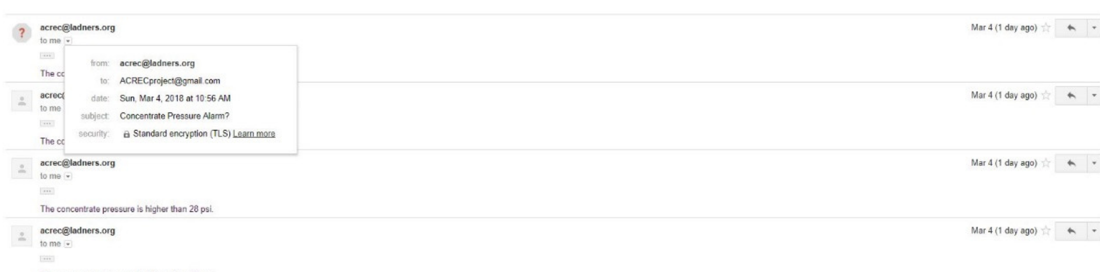


Figure 41. Alarm emails for concentrate pressure

Figure 41 shows these emails. In some cases, manual control was required when the Actuator Auto Adjustment program could not solve the extreme pressure or other reasons contributed to the pressure alarm.

With the same principle the BW pressure alarms were also sent to the email account when BW pressure was higher than 55 psi, which would destroy the pressure transducer with the measurement range from 0 to 60 psi. Figure 42– a and b shows the BW pressure during the experiment and the alarm emails.

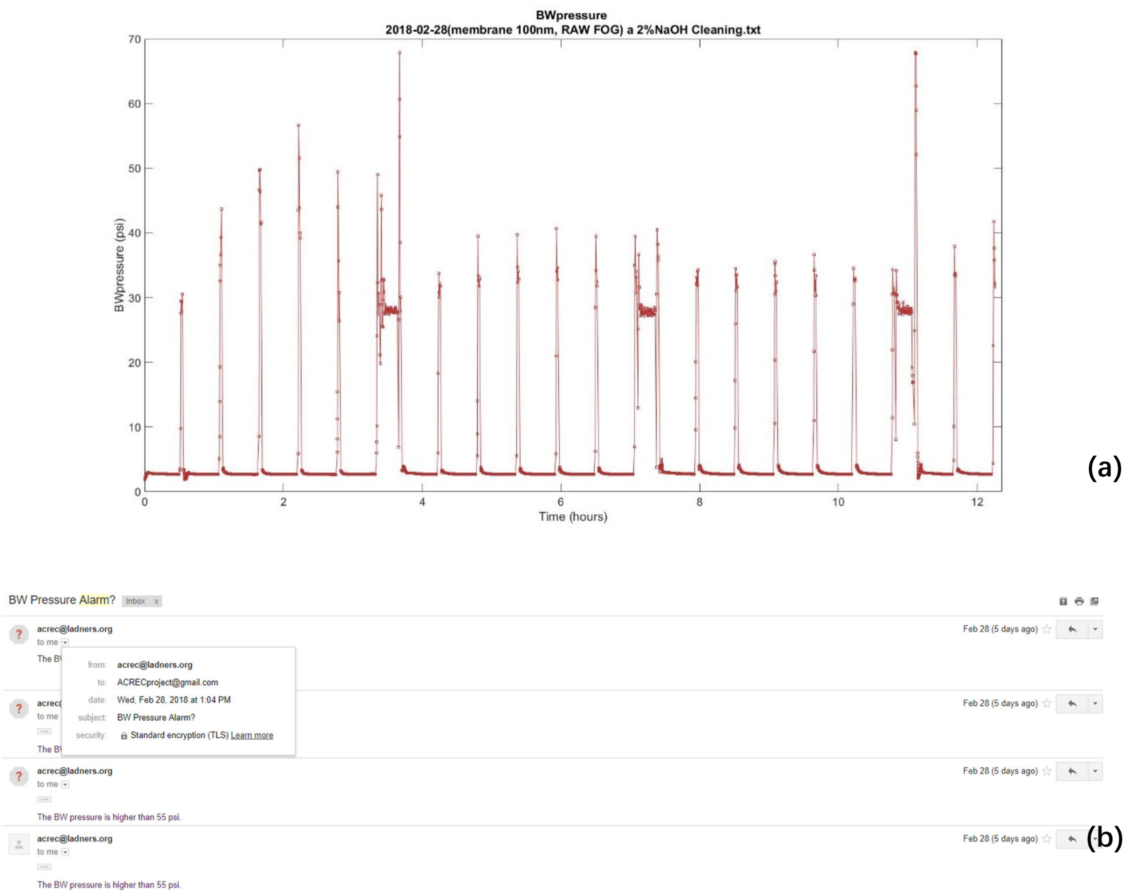


Figure 42. Alarm system performance – Permeate pressure Alarm. a) BW pressure, b) Alarm emails for BW pressure

The conductivity mostly was higher than 100 μs/cm when we used lake water, effluent from wastewater treatment plant, and FOG wastewater. The conductivity probe was always lower than water level in feed tank. Under unexpected circumstances, the probe was out of the water when some points in the system was leaking. In this condition, alarm emails were received. Figure 43–a and b below shows an example that the tubing in peristaltic pump head is ruptured that water level in feed tank is lower than conductivity probe. After received the alarm, the program was stopped manually which prevented water loss.

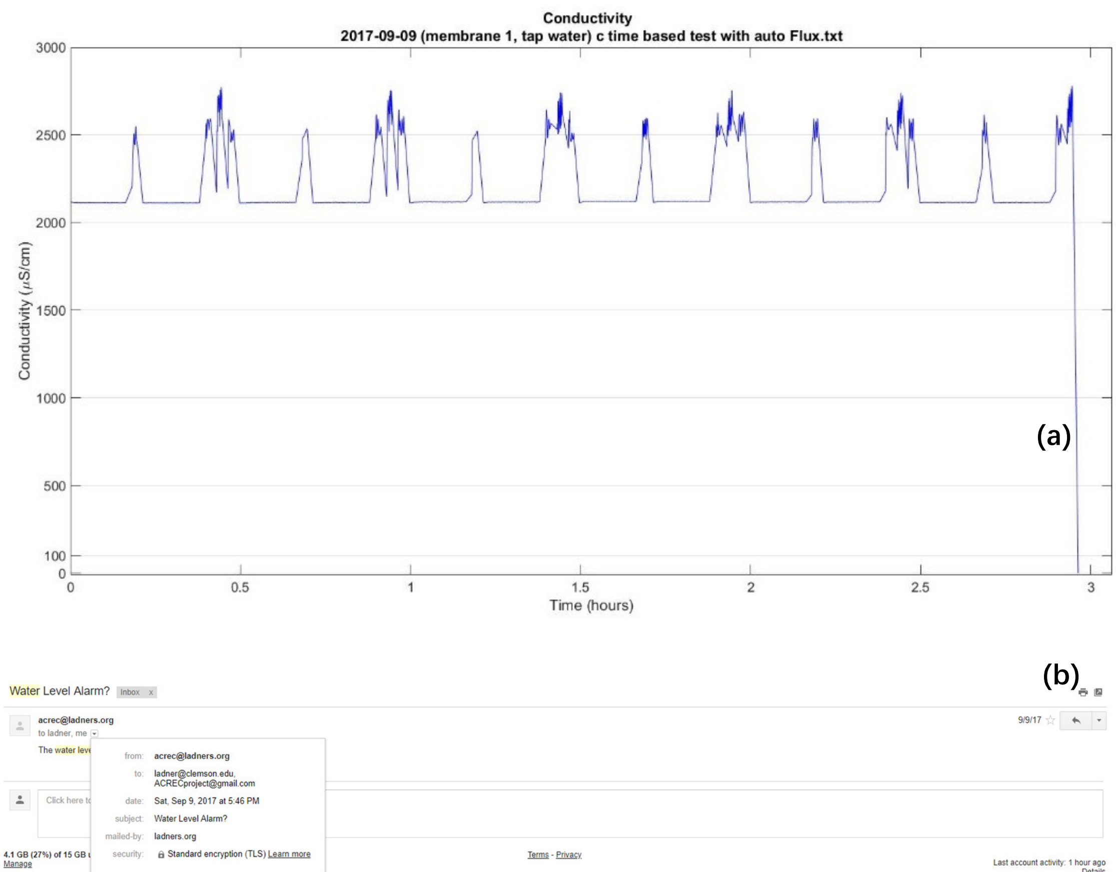


Figure 43. Alarm system performance – Conductivity Alarm. a) Conductivity results, b) Water level alarm emails

Email program also played an important role for monitoring the system. At beginning, an email was received at the 121st second that told the professor and the students that experiment was started. During the experiment, an email was sent at 10920, 21720, 32520, and 43320 seconds, which included the flux plots and data file that gave basic operational information and further details. At the end, the system was automatically stopped at 12.28 hour while an email was sent before stopped and deliver the message that the experiment was done and experimental data were attached. Figure 44 below shows an example of all the emails received at Mar./04/2018 when 12.28-hour experiment was running.

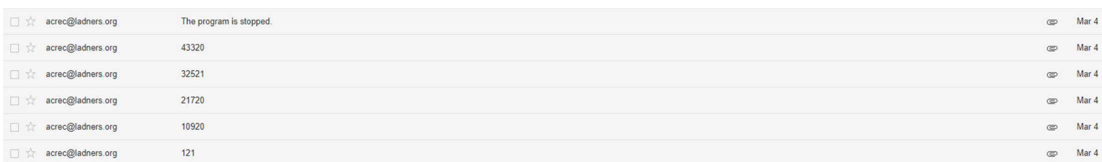


Figure 44. Emails from Data Acquisition and Presentation program.

4.1.3.2 Average program and balance flowrate calculation

An Average program was added to TMP control input for filtering extreme values. The results showed that this program provide a high stability of the TMP input value and sensitivity to TMP tendency. Figure 45-a presents real time TMP, and Figure 45-b, c, and d shows $TMP_{average}$ changed with the number of TMP used for average. Three, eight, and eighteen TMP values were tried for calculation of $TMP_{average}$, and the three-TMP calculation did not smooth the real-time TMP too much. And the eighteen-TMP average made the details blurred. The eight-TMP results had lower chaos than real-time TMP with obvious trend of TMP.

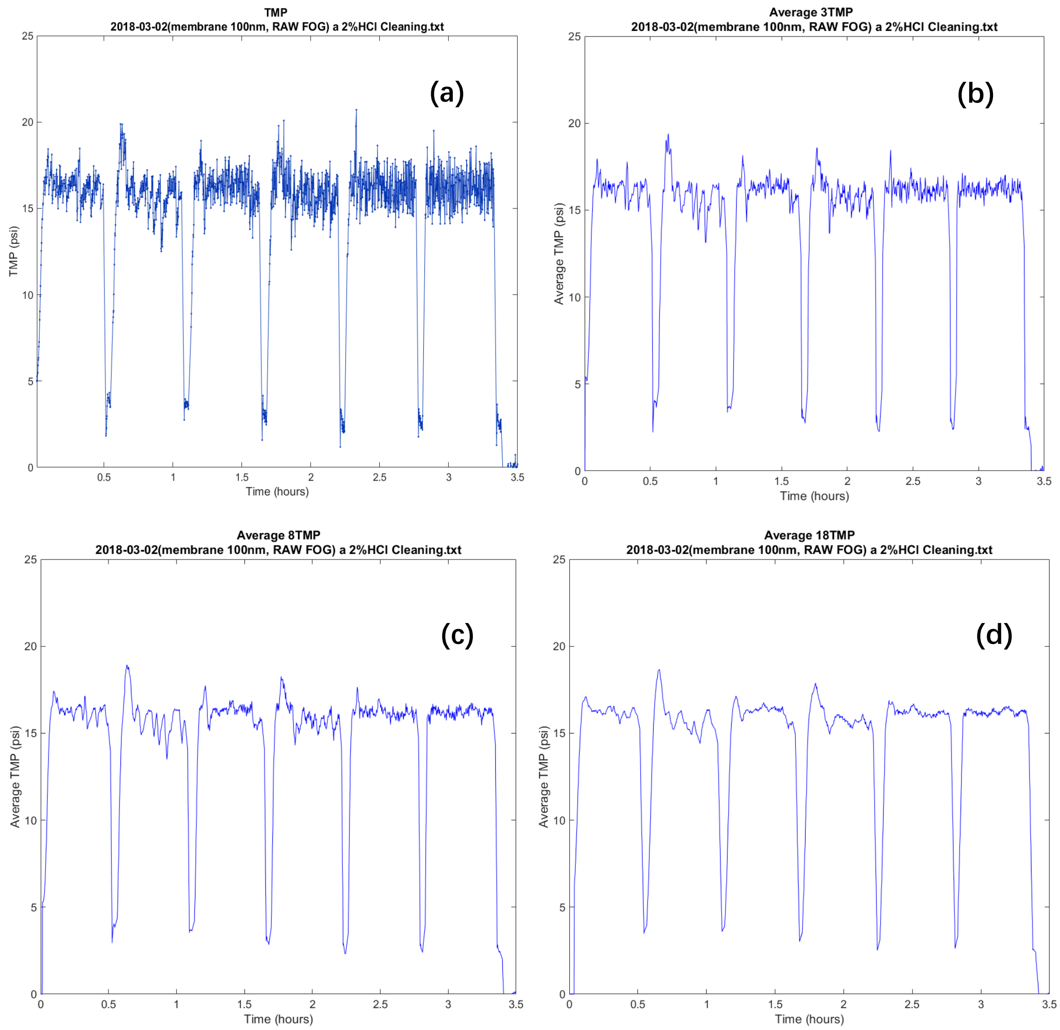


Figure 45. Average TMP performance. a) Real TMP; b) 3-TMP average results; c) 8-TMP average results; d) 17-TMP average results.

The balance flowrate was also recorded for comparing with flowrate from flowmeter (Figure 46). Blue dots were the balance flowrate which had the similar trend with flowrate from flowmeter (red line). However, the flowmeter could be influenced by interference factors like bubble or particles in permeate. This happened frequently like unreasonable declining at around 5.8 hour. On the other hand, the effective measurement range was to 50 ml/min, which meant the flowmeter could not give a

precise value at low flowrate. In the figure below, the flowrate from flowmeter was always be inaccurate when flowrate was lower than 10 ml/min. At a higher flowrate (higher than 10 ml/min), the flowrate was the same as balance flowrate.

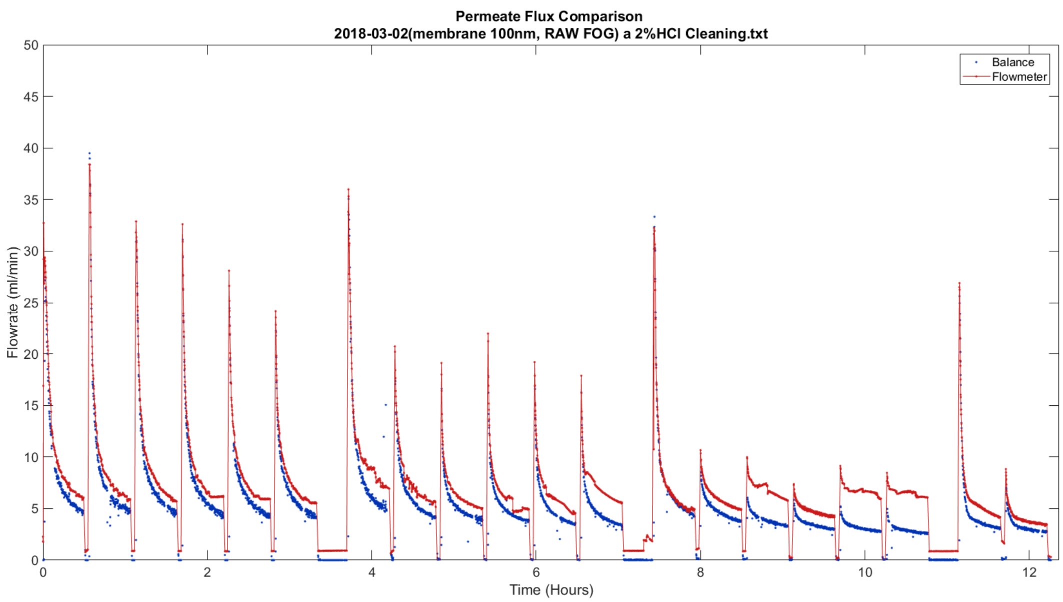


Figure 46. Balance flux performance. The blue line is balance flowrate, and the red line is the flowrate from flowmeter.

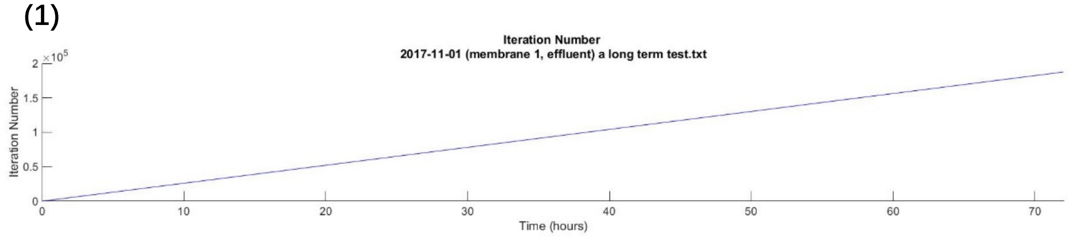
4.2 Data Processing Performance

4.2.1 Plots

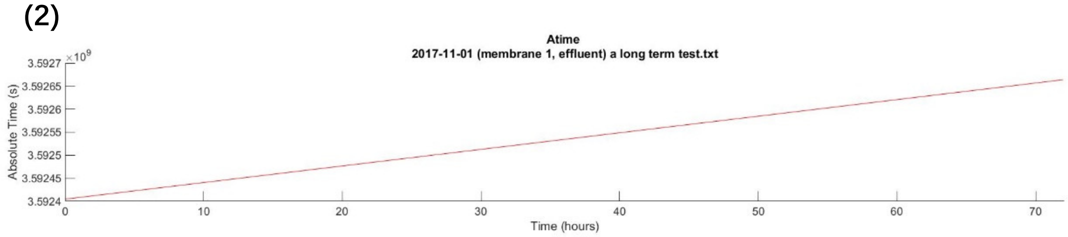
Plots from MATLAB program shows below (Figure 47-1 to Figure 47-31). Thirty-one figures were plotted at once, and twenty-one of them were one group of original data versus running time. And the rest of them were calculated value and comparations plotting which contained two or three groups of data in one figure. The calculated values

were Fouling Rate and running time calculated within MATLAB program. Relative time was compared with running time calculated in MATLAB for making sure the relative time shown in LabVIEW was precise. The comparison plots were TMP vs. flux from flowmeter; BW pump speed vs. BW pressure; target TMP vs. TMP; target flux vs. flux from flowmeter; actuator voltage vs. TMP (and target TMP); actuator voltage vs. flux from flowmeter (and target flux); TMP vs. flux from flowmeter; and permeate flux comparison. The plots from original data gave the outline of all the system characteristics. The comparison and calculation plots aimed to provide an insight of the experiment. Figure 47 below presented all of the plots for a 72-hour experiment at 2017-11-01 which was a typical running testing the stability of the system.

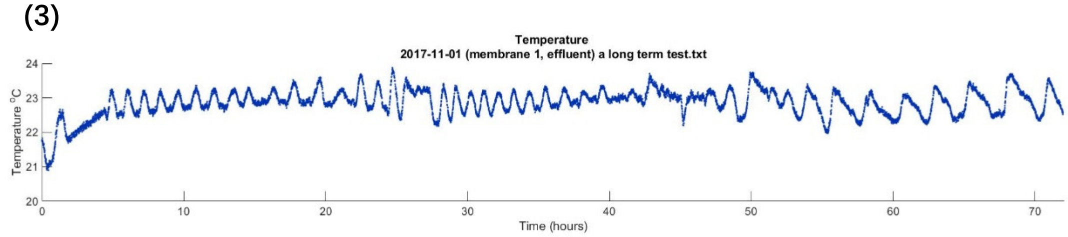
(1)



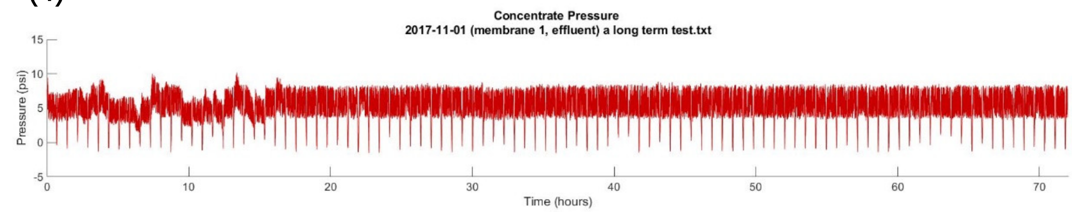
(2)



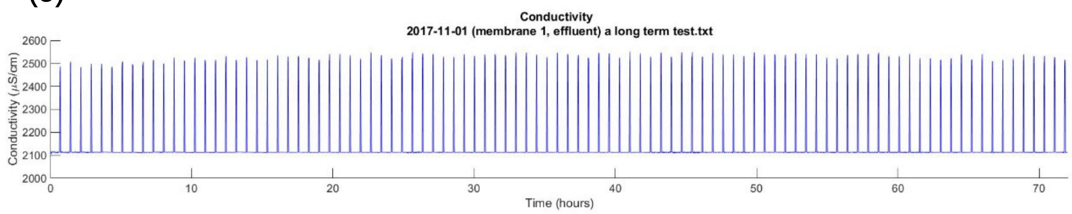
(3)



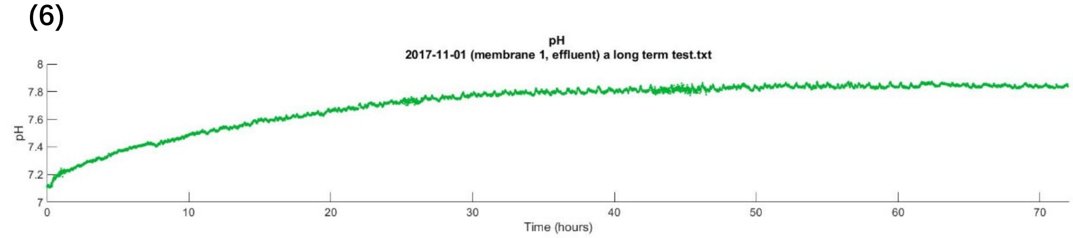
(4)


Concentrate Pressure
2017-11-01 (membrane 1, effluent) a long term test.txt
Pressure (psi)
Time (hours)

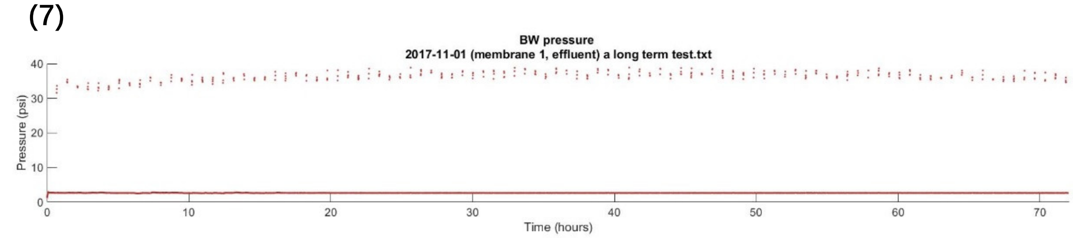
(5)


Conductivity
2017-11-01 (membrane 1, effluent) a long term test.txt
Conductivity (μS/cm)
Time (hours)

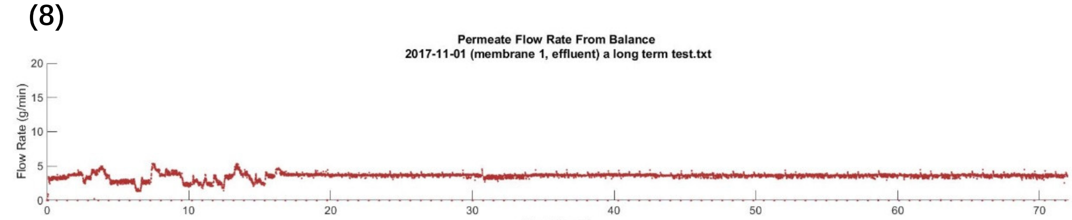
(6)


pH
2017-11-01 (membrane 1, effluent) a long term test.txt
pH
Time (hours)

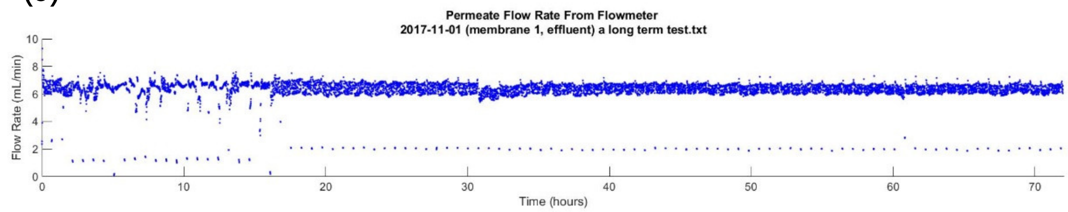
(7)


BW pressure
2017-11-01 (membrane 1, effluent) a long term test.txt
Pressure (psi)
Time (hours)

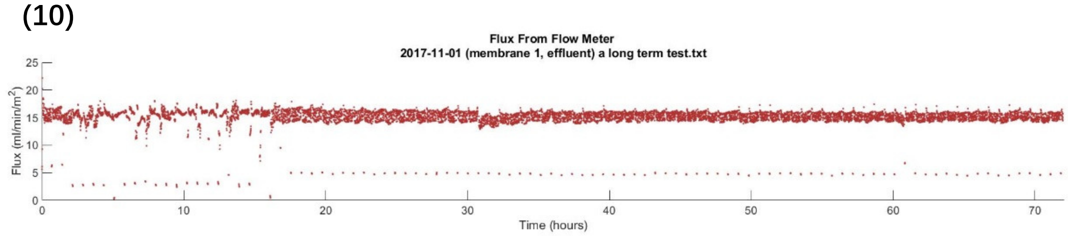
(8)


Permeate Flow Rate From Balance
2017-11-01 (membrane 1, effluent) a long term test.txt
Flow Rate (g/min)
Time (hours)

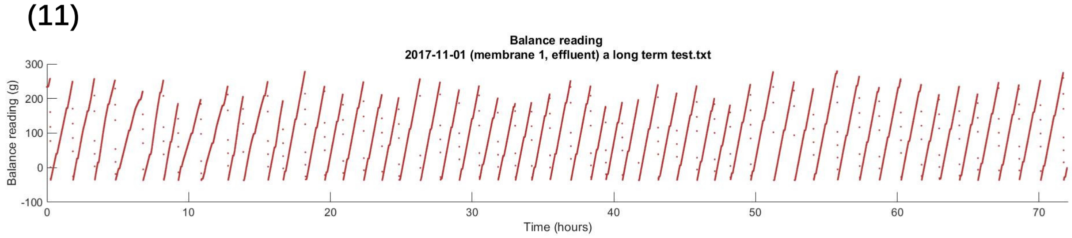
(9)


Permeate Flow Rate From Flowmeter
2017-11-01 (membrane 1, effluent) a long term test.txt
Flow Rate (mL/min)
Time (hours)

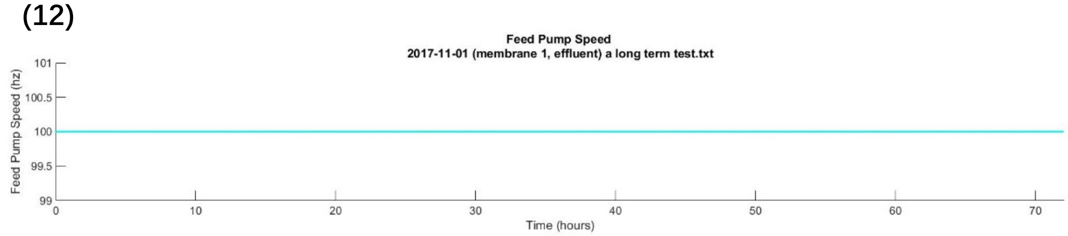
(10)


Flux From Flow Meter
2017-11-01 (membrane 1, effluent) a long term test.txt
Flux (ml/min/m2)
Time (hours)

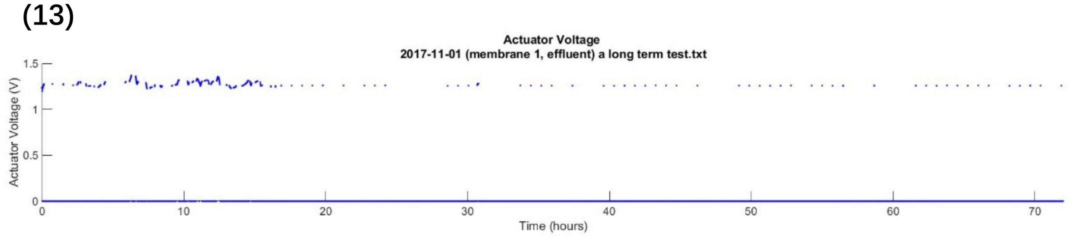
(11)


Balance reading
2017-11-01 (membrane 1, effluent) a long term test.txt
Balance reading (g)
Time (hours)

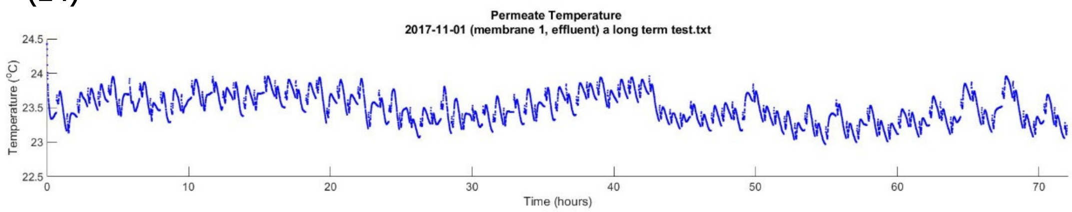
(12)


Feed Pump Speed
2017-11-01 (membrane 1, effluent) a long term test.txt
Feed Pump Speed (hz)
Time (hours)

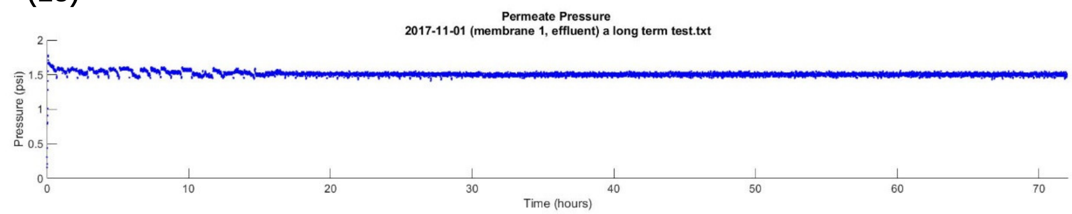
(13)


Actuator Voltage
2017-11-01 (membrane 1, effluent) a long term test.txt
Actuator Voltage (V)
Time (hours)

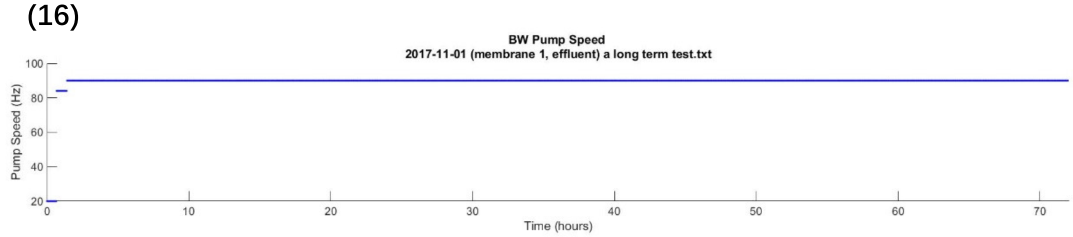
(14)


Permeate Temperature
2017-11-01 (membrane 1, effluent) a long term test.txt
Temperature (°C)
Time (hours)

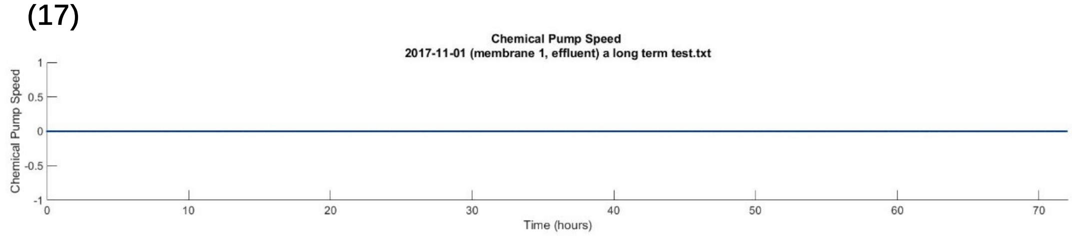
(15)


Permeate Pressure
2017-11-01 (membrane 1, effluent) a long term test.txt
Pressure (psi)
Time (hours)

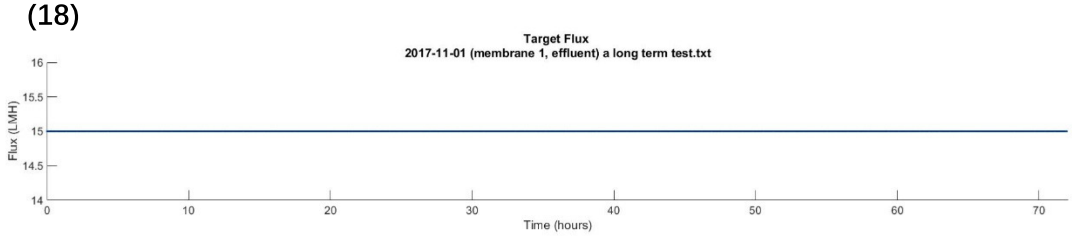
(16)


BW Pump Speed
2017-11-01 (membrane 1, effluent) a long term test.txt
Pump Speed (Hz)
Time (hours)

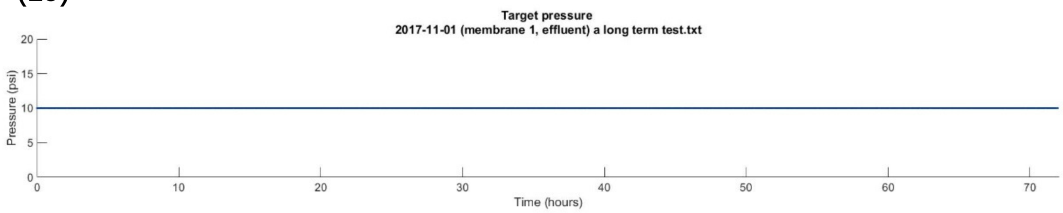
(17)


Chemical Pump Speed
2017-11-01 (membrane 1, effluent) a long term test.txt
Chemical Pump Speed
Time (hours)

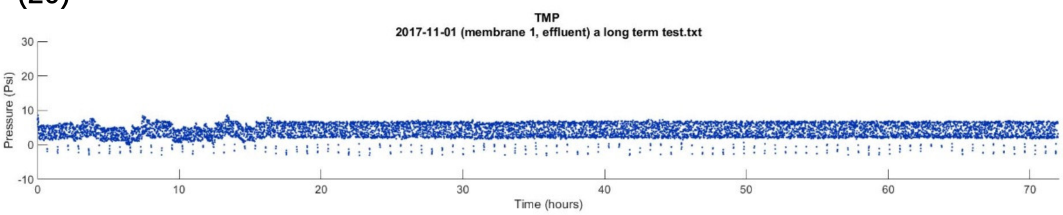
(18)


Target Flux
2017-11-01 (membrane 1, effluent) a long term test.txt
Flux (LMH)
Time (hours)

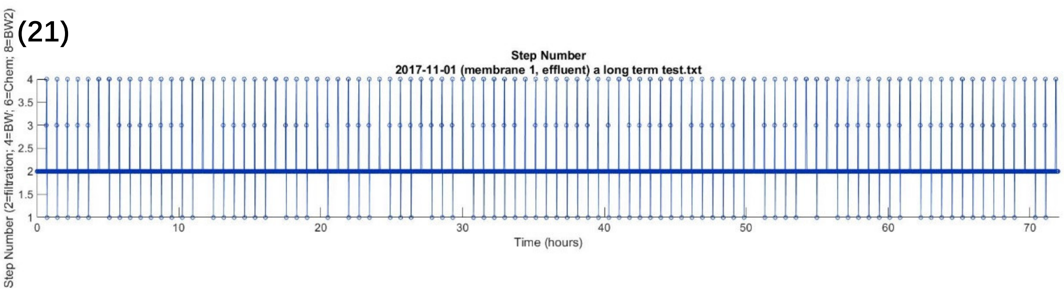
(19)


Target pressure
2017-11-01 (membrane 1, effluent) a long term test.txt
Pressure (psi)
Time (hours)

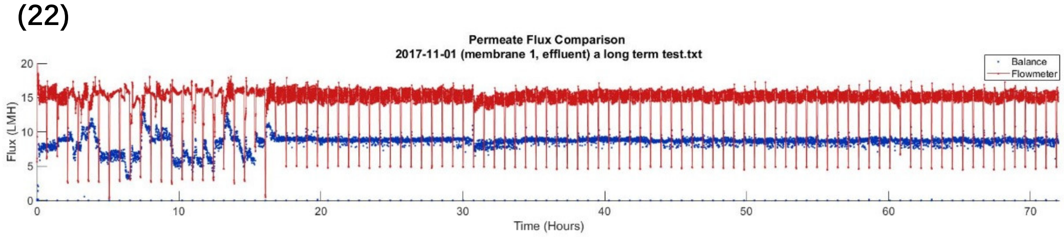
(20)


TMP
2017-11-01 (membrane 1, effluent) a long term test.txt
Pressure (Psi)
Time (hours)

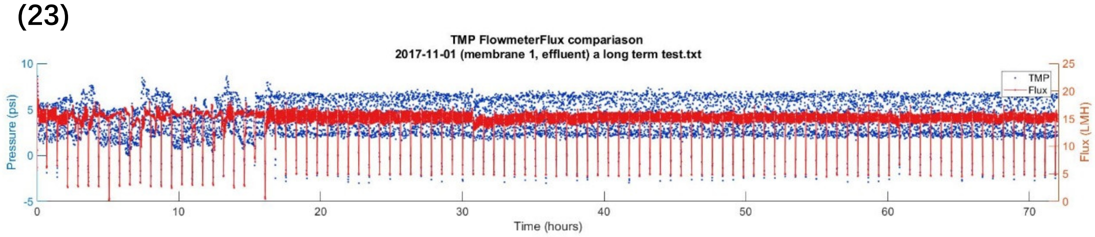
(21)


Step Number
2017-11-01 (membrane 1, effluent) a long term test.txt
Step Number (2=filtration; 4=BW; 6=Chem; 8=BW2)
Time (hours)

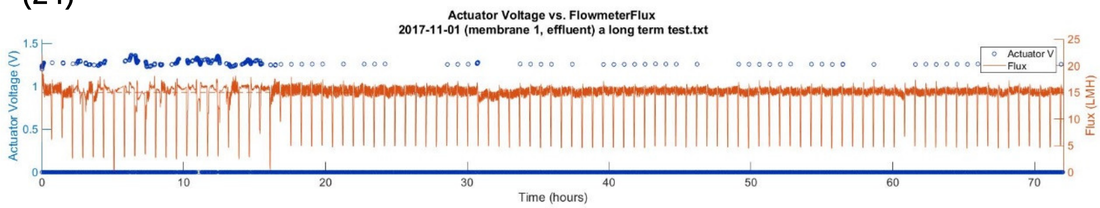
(22)


Permeate Flux Comparison
2017-11-01 (membrane 1, effluent) a long term test.txt
Balance
Flowmeter
Flux (LMH)
Time (Hours)

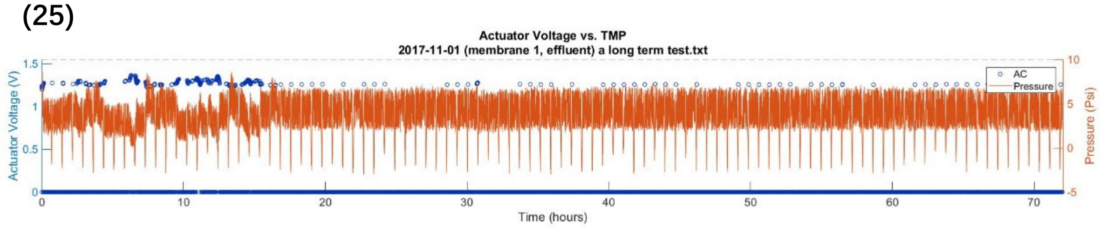
(23)


TMP FlowmeterFlux compariason
2017-11-01 (membrane 1, effluent) a long term test.txt
TMP
Flux
Pressure (psi)
Flux (LMH)
Time (hours)

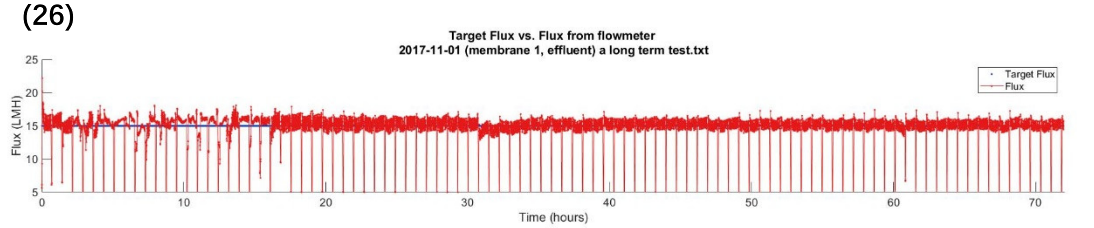
(24)


Actuator Voltage vs. FlowmeterFlux
2017-11-01 (membrane 1, effluent) a long term test.txt
Actuator Voltage (V)
Flux (LMH)
Time (hours)
Actuator V
Flux

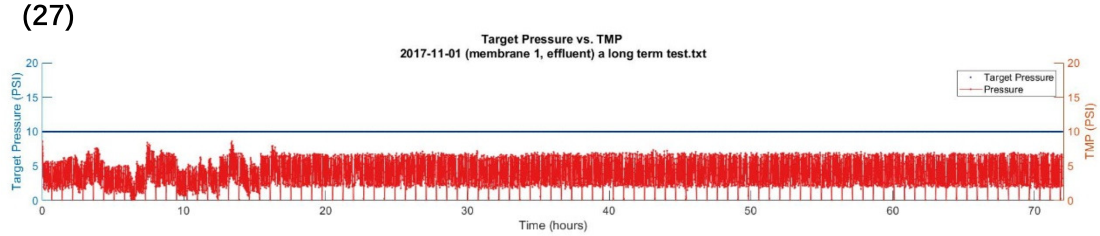
(25)


Actuator Voltage vs. TMP
2017-11-01 (membrane 1, effluent) a long term test.txt
Actuator Voltage (V)
Pressure (Psi)
Time (hours)
AC
Pressure

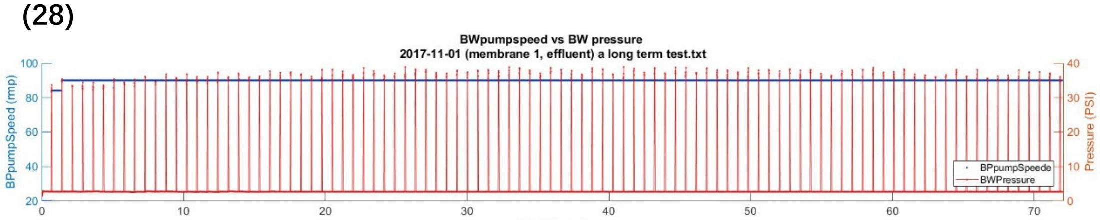
(26)


Target Flux vs. Flux from flowmeter
2017-11-01 (membrane 1, effluent) a long term test.txt
Flux (LMH)
Time (hours)
Target Flux
Flux

(27)


Target Pressure vs. TMP
2017-11-01 (membrane 1, effluent) a long term test.txt
Target Pressure (PSI)
TMP (PSI)
Time (hours)
Target Pressure
Pressure

(28)


BWpumpspeed vs BW pressure
2017-11-01 (membrane 1, effluent) a long term test.txt
BPpumpSpeed (rmp)
Pressure (PSI)
Time (hours)
BPpumpSpeede
BWPressure

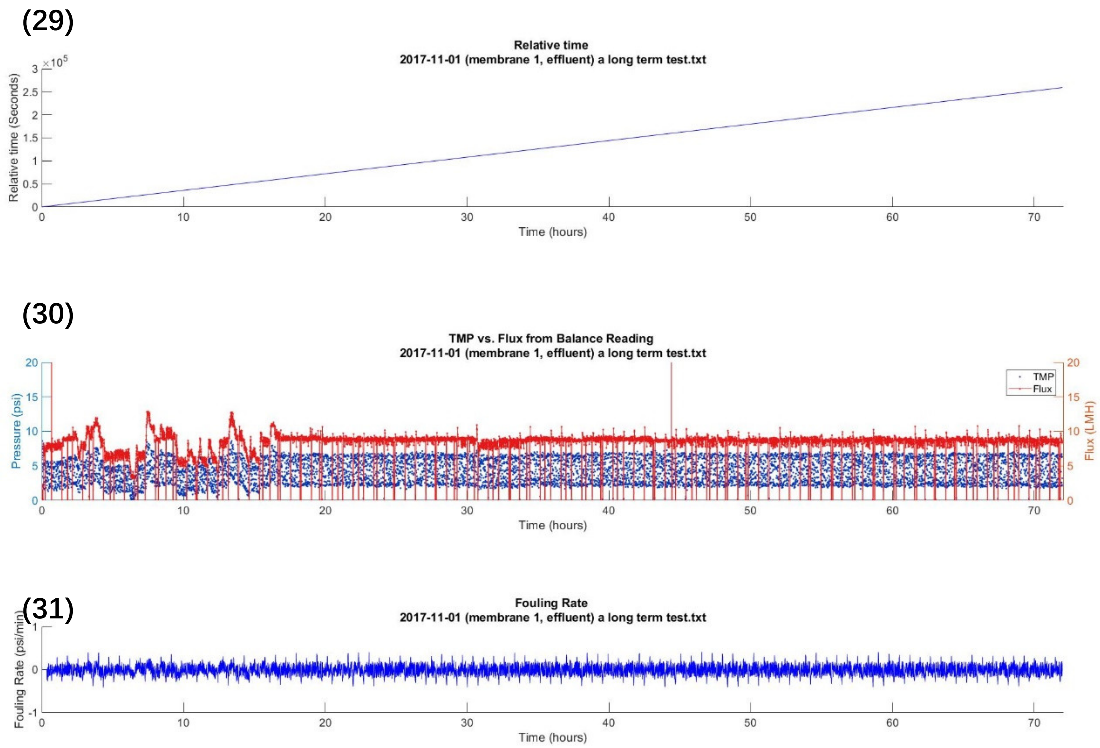
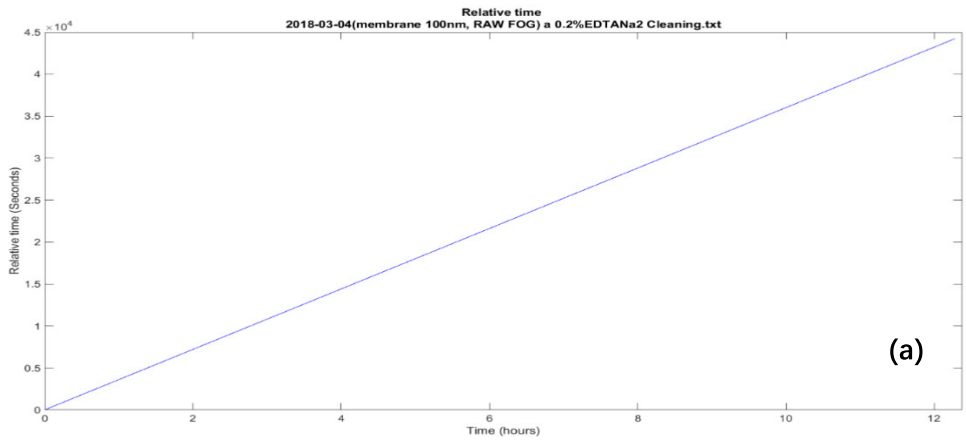


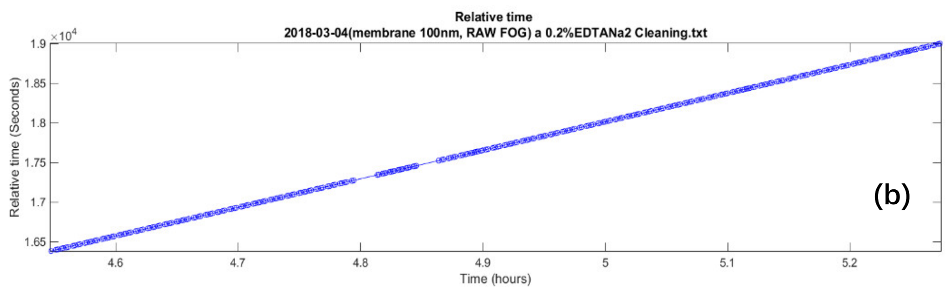
Figure 47. Plots from MATLAB program for data analysis. 1) Iteration Number; 2) Absolute time; 3) Feed water temperature, 4) Concentrate pressure; 5) Feed water conductivity; 6) Feed water pH; 7) Backwash pressure; 8) Balance flowrate; 9) Flowmeter flowrate; 10) Flux from flowmeter; 11) Balance reading; 12) Feed pump speed; 13) Actuator voltage; 14) Permeate temperature; 15) Permeate pressure; 16) Backwash/Chem pump speed; 17) Chem pump speed; 18) Target flux; 19) Target TMP; 20) Real TMP; 21) Step number; 22) Permeate flux comparison; 23) TMP and flux from flowmeter comparison; 24) Actuator voltage and flux from flowmeter comparison; 25) Actuator Voltage and TMP comparison; 26) Target flux and flux from flowmeter comparison; 27) Target TMP and TMP comparison; 28) Backwash pressure and backwash pump speed comparison; 29) Relative time; 30) TMP and flux from balance comparison; 31) Fouling rate.

4.2.2 Running Time

Relative time versus running time was also plotted in MATLAB program (Figure 48-a). Relative time from LabVIEW had the unit of second, and the running time was sin hour. The plot was a straight line which meant two variables had linear relationship. This result showed that the relative time from LabVIEW was precise. Figure 48-b and c zoom into 5.2 to 6.2 and 5.45 to 6.55 hour, respectively. In Figure 48-b, there are two blank periods between 4.8 and 4.9 hour, which are prepare steps for backwash and filtration. In these

prepare steps, data were not recorded since the prepare step was finished in one iteration, which lasted for 60 seconds. In Figure 48-c, the relative time points are inhomogeneous because the recording program in LabVIEW did not re-write the TXT file every 5 second precisely though the program is set to record every 5 second.





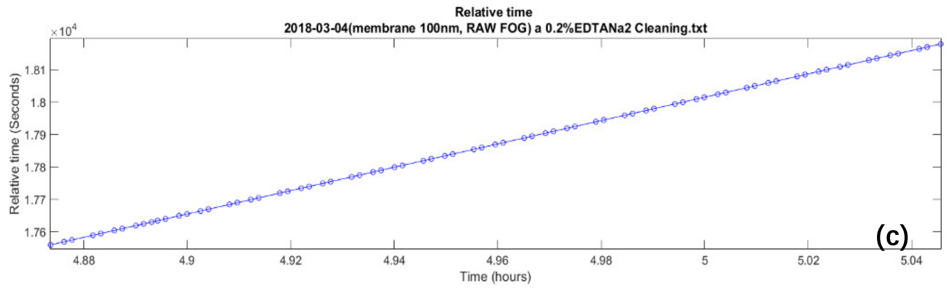


Figure 48. Running time performance; a) overall relative time, b) BW zoom in, c) details zoom in

4.2.3 Fouling Rate

Figure 49 shows the fouling rate that is the fouling formed on membrane. At the beginning of every filtration, the fouling rate was on the lowest point which means the flux-decrease rate was higher than any other time during one filtration. After a few minutes, the fouling rate decreased to a stable level close to zero, which proved that only a little fouling was formed after that.

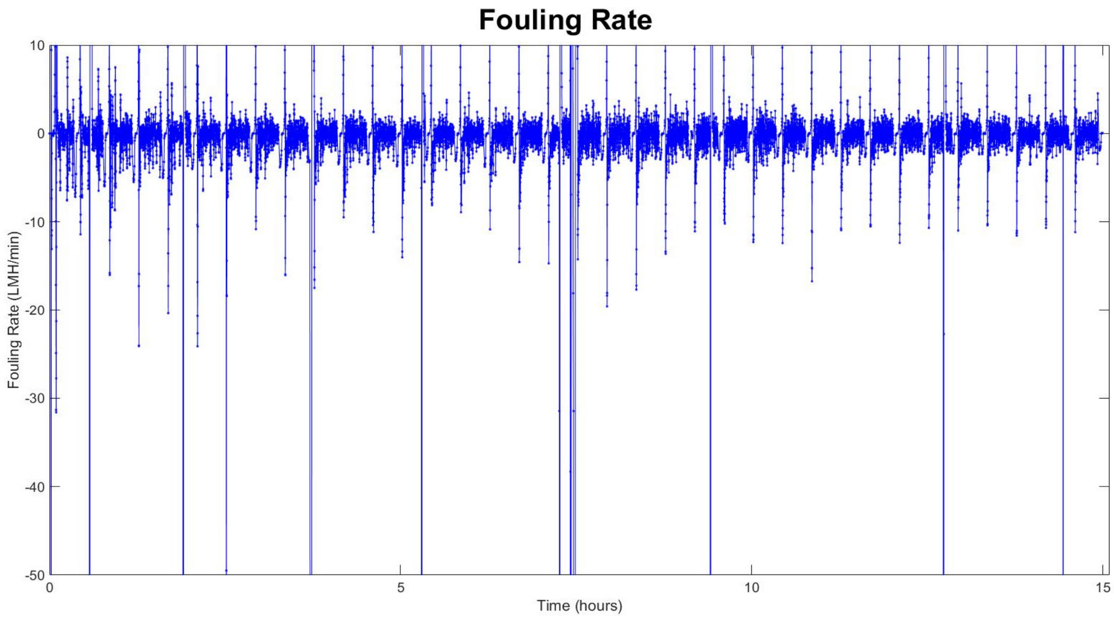


Figure 49. Fouling Rate calculated by MATLAB program.

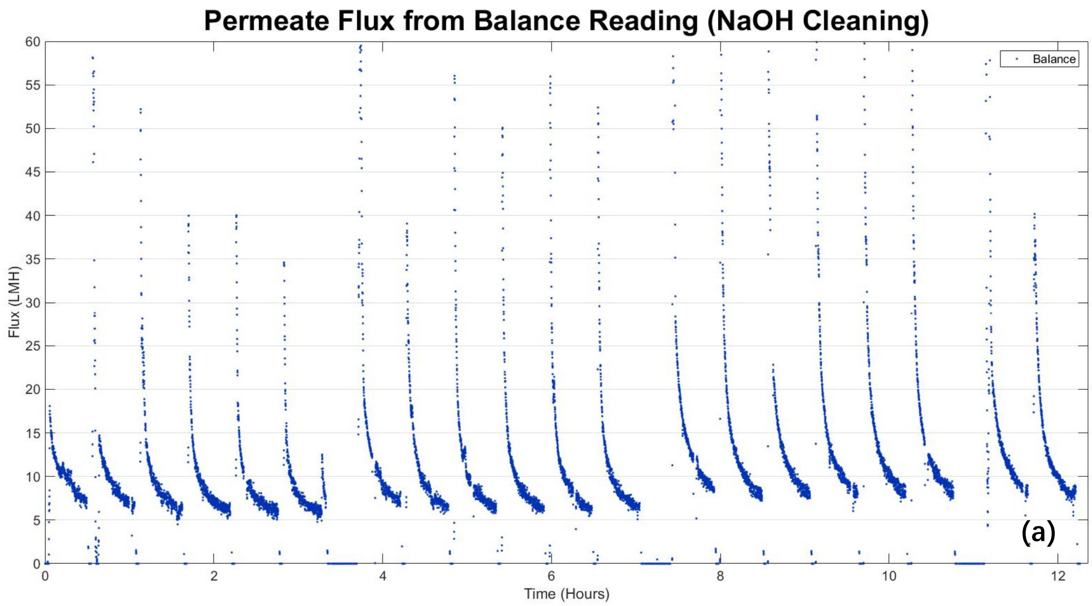
4.3 Chemical Cleaning Performance

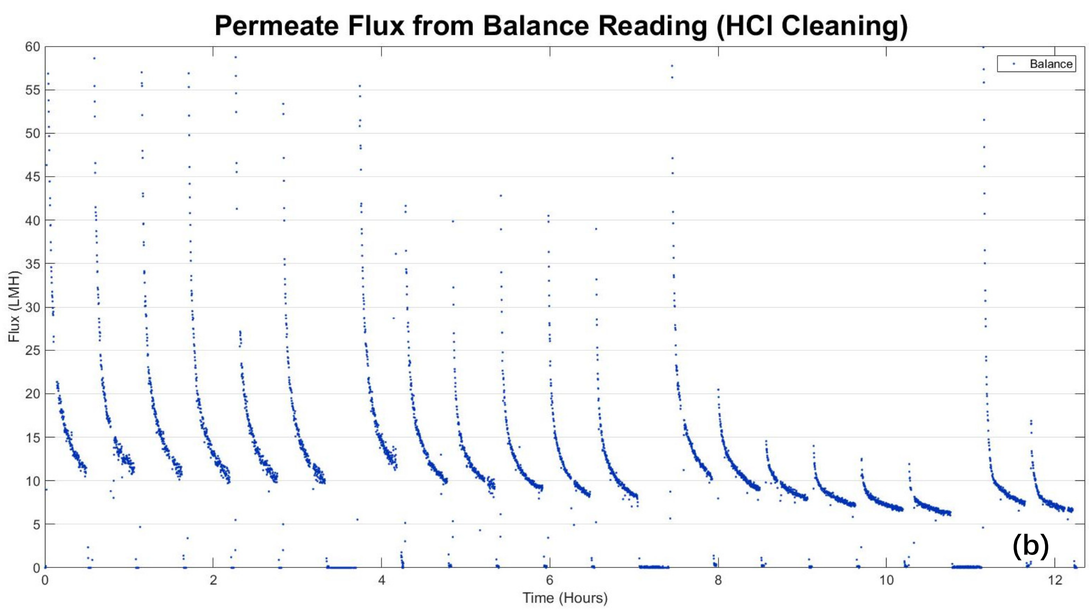
4.3.1 Flux behavior of membranes

The profile of the flux during three experiments are shown in Figure 50-a, b, and c. The TMP of all experiments were 15 psi, so the decreasing flux was for assessing the fouling. In all three experiments, the flux decreased sharply after the backwash, which indicated the reversible fouling formed right after the backwash. The filtrations right after the chemical cleaning had a lower tendency for reversible fouling. The overall flux increased from the first experimental day to the last experimental day, which was caused by TSS degrading.

HCl and Na_2EDTA experiments had the flux with declining tendency, even the backwash and chemical cleaning removed the reversible fouling and irreversible fouling. The declining tendency indicated these two cleaning agents did not remove all of the irreversible fouling. In this case, the irreversible fouling was accumulated on or in the membrane and caused a higher resistance which decreased the flux.

The NaOH experiment had an opposite result that the overall flux had a rising tendency. Two possible reasons might contribute to this situation. The first one was that the membrane was brand new. Although the membrane had rinsed before the experiment it was possible that the membrane had not been wetted totally, which meant bubbles could block the pores and decreased the flux. During the filtration, these bubbles were pushed out and the flux was recovered. Another reason was the membrane was destroyed by 2% NaOH solution. However, this possibility could be excluded because other research has been made using 2% NaOH at 70-80℃ for Al_2O_3 membrane cleaning, and the author had not observed any damage to the membrane. [4]


Permeate Flux from Balance Reading (NaOH Cleaning)
Balance
Flux (LMH)
Time (Hours)
(a)


Permeate Flux from Balance Reading (HCl Cleaning)
Balance
Flux (LMH)
Time (Hours)
(b)

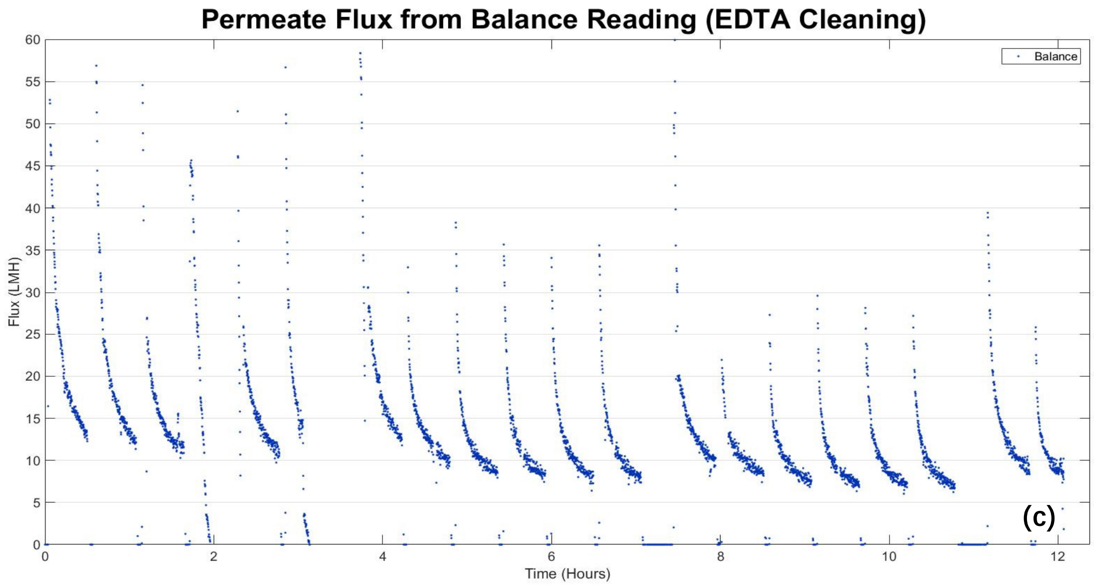


Figure 50. Flux of three cleaning experiments with the filtration raw rendering wastewater, a) NaOH, b) HCl, c) EDTA

The TMP details (Appendix C) from three experiments indicated that the system needed at least one minute after the FP step for stabilizing the TMP to 15 psi. Because of that, the first two minutes of data were not representative and ignored during analyzing. Also, the data from last one minute of the filtration were also ignored to avoid unstable factors. The extreme values would also influence the results, so several values but not only one point were collected for analysis. Flux values in 120 -180 second from each filtration were calculated for an average which was the flux at filtration beginning. Also, flux values from 1,710 to 1,740 second were calculated for an average as the end flux of each filtration. Table 6, Table 7, and Table 8 show the beginning and the end flux of each filtration from NaOH, HCl, and EDTA experiments, respectively. The raw data of collected flux are shown in Appendix B.

Table 6. Flux details of NaOH cleaning

Step	NaOH Cleaning			
	Begin Flux LMH	Time Hour	End Flux LMH	Time Hour
C0F1	41.587	0.054	7.126	0.495
C0F2		0.621	6.470	1.063
C0F3	21.411	1.187	6.291	1.629
C0F4	17.219	1.754	6.263	2.195
C0F5	15.071	2.321	6.168	2.763
C0F6	13.547	2.887	8.332	3.329
Chem 1				
C1F1	50.960	3.771	7.120	4.212
C1F2	22.027	4.337	6.500	4.779
C1F3	21.035	4.904	6.376	5.345
C1F4	21.263	5.471	6.278	5.912
C1F5	21.573	6.037	6.235	6.479
C1F6	21.799	6.604	6.205	7.045
Chem 2				
C2F1	42.685	7.487	8.452	7.929
C2F2	32.846	8.054	7.874	8.495
C2F3		8.620	7.918	9.063
C2F4	34.205	9.188	8.200	9.629
C2F5	35.158	9.753	8.258	10.196
C2F6	32.678	10.321	8.356	10.762
Chem 3				
C3F1	42.630	11.177	8.208	11.645
C3F2	27.324	11.771	8.012	12.212

Table 7. Flux details of HCl cleaning

Step	HCl Cleaning			
	Begin Flux LMH	Time Hour	End Flux LMH	Time Hour
C0F1	62.275	0.053	11.257	0.496
C0F2	44.206	0.621	11.093	1.063
C0F3	44.033	1.187	10.724	1.630
C0F4	37.523	1.753	10.330	2.195
C0F5		2.321	10.266	2.763
C0F6	28.813	2.887	10.094	3.328
Chem 1				
C1F1	51.094	3.770		4.213
C1F2	27.083	4.338	9.850	4.779
C1F3	19.953	4.903	9.278	5.345
C1F4	21.582	5.470	9.299	5.913
C1F5	20.388	6.037	8.421	6.478
C1F6	17.756	6.604	8.265	7.045
Chem 2				
C2F1	38.947	7.487	10.657	7.929
C2F2	16.048	8.054	8.511	8.496
C2F3	11.919	8.619	7.822	9.062
C2F4	10.362	9.188	7.251	9.629
C2F5	9.517	9.754	6.747	10.195
C2F6		10.320	6.197	10.762
Chem 3				
C3F1	25.089	11.203	7.393	11.645
C3F2	10.750	11.771	6.567	12.211

Table 8. Flux details of EDTA cleaning

Step	EDTA Cleaning			
	Begin Flux LMH	Time Hour	End Flux LMH	Time Hour
C0F1	93.320	0.053	13.219	0.495
C0F2	47.580	0.621	12.618	1.062
C0F3		1.187	11.876	1.628
C0F4	42.812	1.754		2.195
C0F5		2.320	11.251	2.762
C0F6	28.308	2.888	11.111	3.329
Chem 1				
C1F1	39.593	3.770	12.634	4.213
C1F2	19.669	4.336	9.619	4.780
C1F3	21.286	4.904	8.499	5.346
C1F4	23.132	5.470	8.374	5.912
C1F5	22.324	6.037	7.840	6.478
C1F6	21.657	6.602	7.931	7.044
Chem 2				
C2F1	31.664	7.487	9.794	7.929
C2F2	16.103	8.053	8.329	8.496
C2F3	15.750	8.619	7.159	9.063
C2F4	17.370	9.186	7.308	9.630
C2F5	19.046	9.755	7.051	10.195
C2F6	17.069	10.320	6.915	10.763
Chem 3				
C3F1	25.637	11.204	9.135	11.645
C3F2	15.343	11.770	8.600	12.040

Several flux values were not recorded since the self-empty device on the balance needed tens of seconds to drain out all the water and started another accumulation. The

colored cells were the unrecorded values in which the green meant these values would not influence the calculation. The yellow filled cells were the predicted values since these results played an important role during the calculation.

The predication was based on the linear fitting of other flux values and related time. The beginning flux of the first filtration before the first chemical cleaning in NaOH experiment equaled to zero, which was impossible during the filtration. There was a long tubing between the permeate port and the self-empty device on the balance. The water would not enter the self-empty device for weighting until it full filled the tubing first. The flux at the beginning could be predicted by other flux values at different filtrations. The Figure 51-a shows the linear fitting of flux versus relative time. The equation of the trendline is

$$\text{Flux} = -4.5431 * \text{Relative time} + 26.068 \tag{11}$$

The flux at the beginning of the first filtration could be calculated by using the relative time corresponded to the collecting point, which was 0.537 hour. Then, the predicted flux was 25.82 LMH. With the same mechanism, another predicted value was derived according to the trend line in Figure 51-b, which was the flux at the end of last filtration before the first chemical cleaning at EDTA experiment.

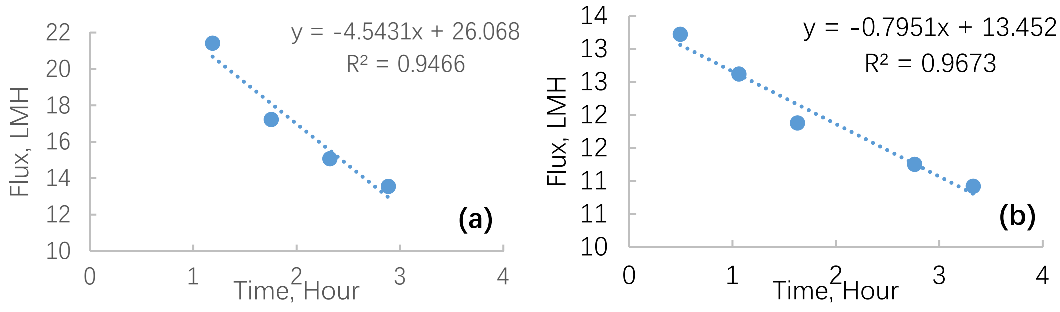


Figure 51. Trendline of a) beginning flux of C0F1 in NaOH experiment, b) end flux of C0F6 in EDTA experiment

4.3.2 Reversible Fouling

The reversible fouling formed on each step is shown in Table 9. The yellow cells are the reversible fouling formed at sixth filtration before the chemical cleaning. These values could not be measure since no other filtration happened after the backwash. These values were the average of reversible fouling formed in the first 5 filtrations. In the second filtration after the third chemical cleaning (C3F2), the reversible fouling was also impossible to calculate. However, no prediction was required since this reversible fouling has not been used for chemical flux recovery calculation.

Table 9. Reversible fouling formed in each step

Step	Reversible Fouling, LMH		
	NaOH	HCl	EDTA
C0F1		32.949	34.361
C0F2	14.941	32.940	
C0F3	10.929	26.799	30.935
C0F4	8.808		
C0F5	7.379	18.546	17.057
C0F6			
Chem 1			
C1F1	14.906		7.036
C1F2	14.535	10.103	11.666
C1F3	14.887	12.304	14.633
C1F4	15.295	11.089	13.950
C1F5	15.564	9.336	13.817
C1F6			
Chem 2			
C2F1	25.359	8.560	8.616
C2F2		3.866	7.697
C2F3	25.585	1.743	8.751
C2F4	25.970	0.329	9.860
C2F5	22.924		7.314
C2F6			
Chem 3			
C3F1	19.116	3.357	6.207
C3F2			

The reversible fouling of EDTA and HCl experiment were decreasing from the beginning to the end. This was caused by low irreversible fouling removal. The irreversible fouling was accumulated in the membrane which limited the backwash efficiency. The plots of pump speed (Figure 52) could prove this. The Chem pump speeds of two experiments were decreased from 1st to 3rd chemical cleaning, which indicated that the resistance of the membrane during chemical cleaning was increasing. Also, the backwash pump speeds in two experiments were decreased, which also supported this.

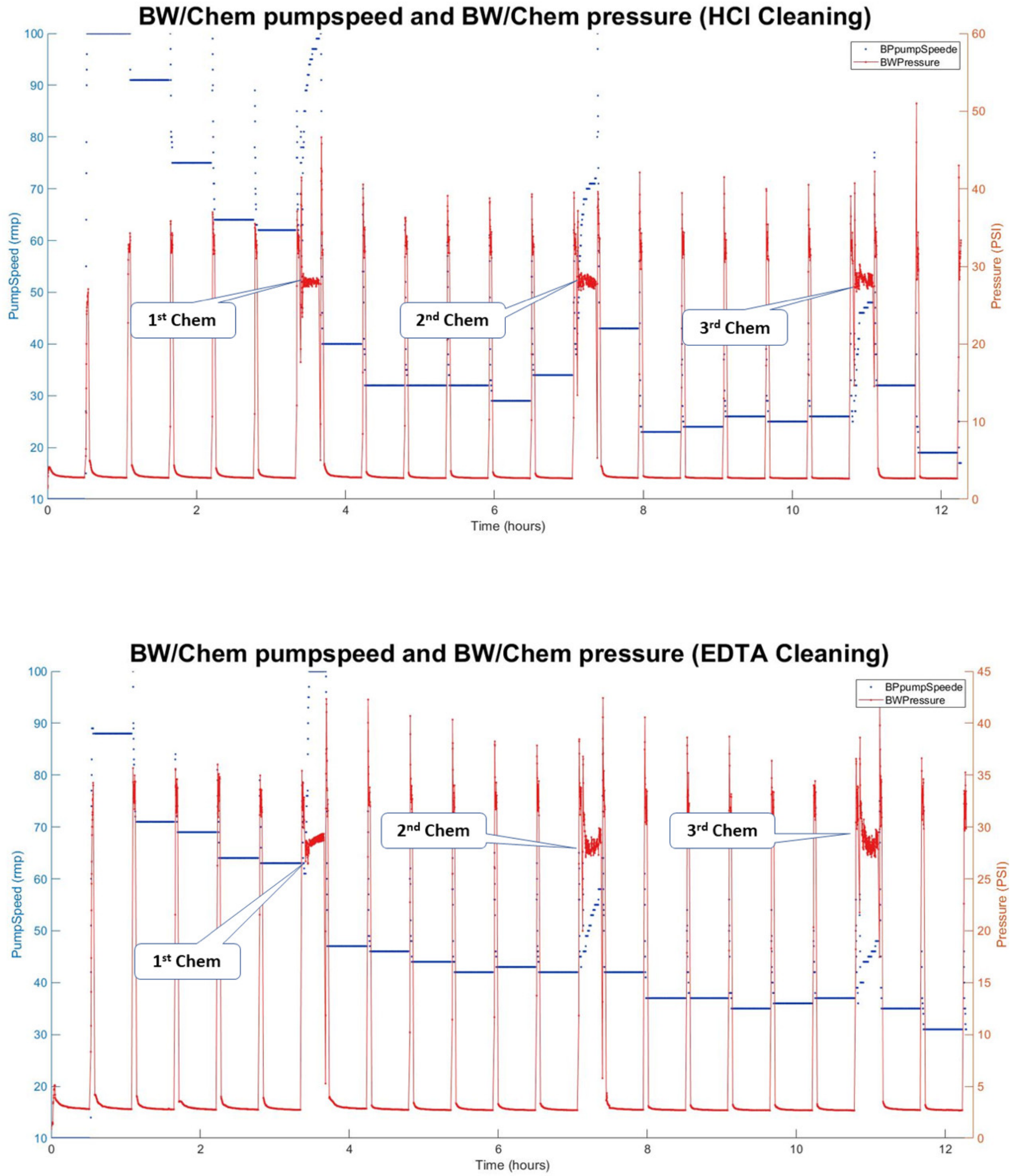


Figure 52.BW/Chem pump speed and BW/Chem pressure of a) HCl experiment, b) EDTA experiment.

The NaOH experiment shows different pattern (Figure 53). The Chem pump speed was increased from 1st to 3rd chemical cleaning, which meant the resistance of the membrane was reduced. Also, the BW pump speed at 5 backwashes between two chemical cleanings proved this again. With the same time, this plot gives the same basic pattern as flux rising during the experiment.

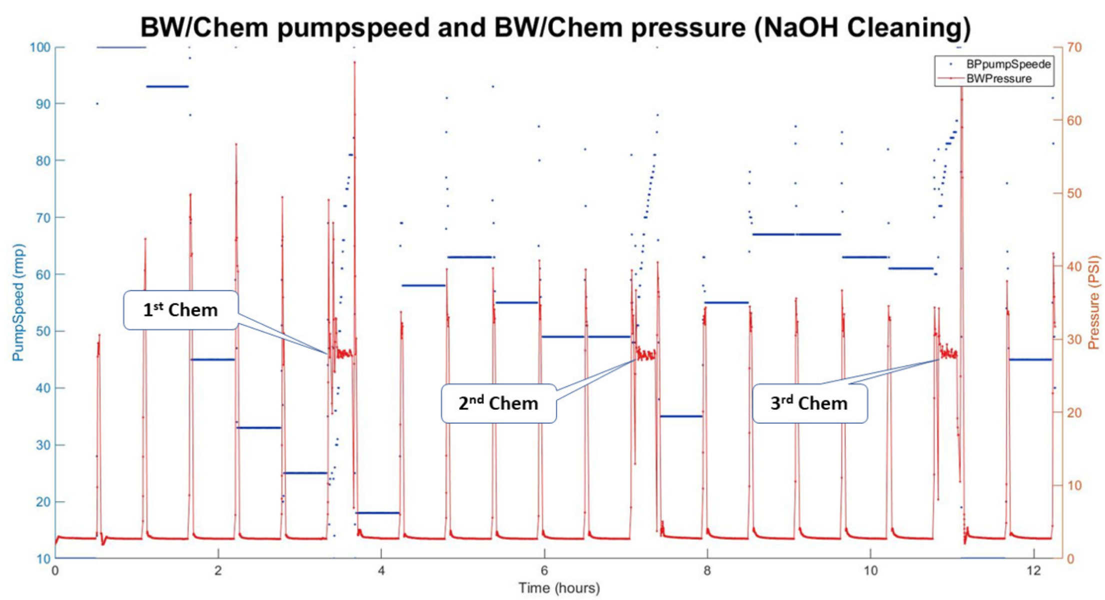


Figure 53. BW/Chem pump speed and BW/Chem pressure of NaOH experiment.

4.3.3 Chemical Flux Recovery

The chemical flux recovery and its efficiency are shown in Table 10 which also contains the calculation results of several main steps. Two extreme values from the first chemical cleaning in NaOH and EDTA experiments are in red. The extreme values from NaOH experiment might be due to the unstable beginning, which might underestimate the initial

flux. The extreme values from EDTA experiment was due to the hysteresis of TMP (Figure 54). The TMP after the first chemical cleaning increased slowly, which leaded to the flux was lower than the regular flux and undermine the total flux recovery. We could take several flux values after this hysteresis; however, the fouling was formed during this period which would also influence the results.

Table 10. Chemical flux recovery efficiency of three experiments.

Item	NaOH			HCl			EDTA		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Irreversible Fouling from 6 filtrations	15	35	12	40	40	47	78	22	18
Reversible Fouling from 6th filtration	11	15	25	28	11	4	27	12	8
Flux recovered	43	36	34	41	31	19	29	24	19
Irreversible Fouling Removed	32	21	9	13	20	15	1	12	10
Flux Recovery Efficiency	218%	61%	78%	33%	50%	33%	2%	53%	59%

NaOH had the highest chemical flux recovery efficiency while EDTA had the second position. NaOH could hydrolyze the fat, oil and grease in wastewater, which destroyed the irreversible fouling. EDTA was a kind of surfactant which had limited cleaning efficiency. The HCl had the lowest recovery efficiency for organic fouling and was mostly

used for inorganic fouling.

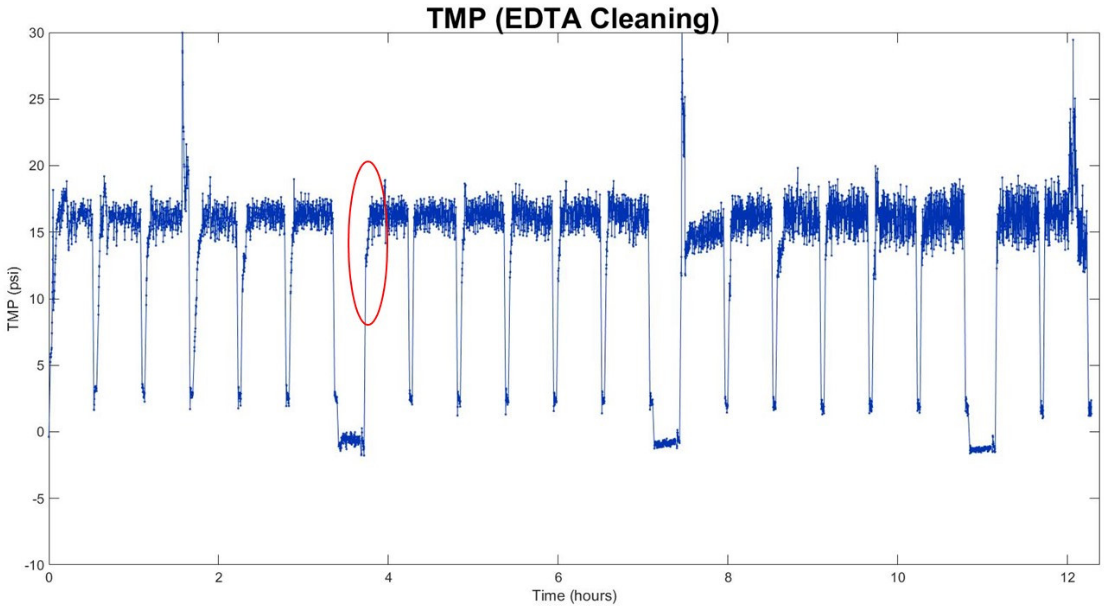


Figure 54. TMP of EDTA cleaning experiment.

5 Conclusions and Future Work

An automated membrane system was created for treatment of FOG wastewater. The software interface written in LabVIEW showed high reliability and flexibility. Three main programs presented satisfactory results from the test filtrations with tap water, lake water, effluent water, and FOG wastewater: Filtration Loop Control, Actuator Auto Adjustment, and Data Acquisition and Presentation. Other programs like alarm system and auto-stop program protected the system from leaking and breaking down. The data analysis program created in MATLAB brought much convenience during data analyzing. One limitation was that the filtration system controls were not as advanced as might be

desirable for robust optimization; the system was operated with a time-based program, rather than one that could perform backwash and cleaning based on flux and/or TMP. Sodium hydroxide showed the best chemical flux recovery efficiency, which is 70% compared with 39% recovery efficiency of HCl and 56% of EDTA. NaOH was effective because the fats, oils, and grease in the wastewater can be hydrolyzed under alkaline conditions.

In future work, a decision program will replace the Step Choose program. Right now, the actions of each step during filtration is in a case structure which has eight cases corresponding to eight steps in filtration. The case running at any given time depended on the Time-based Step Choose program. When we built the whole program, we had thought that other step choose program would replace the Time-Based Step Choose program for “Smart Control”. Thus, we built the Time-Based Step Choose program as an independent program which means we won't have to do any update to the case structure when Time-based Step Choose program is replaced by other programs. The Time-based Step Choose program is a time-based program which can only reach non-manual operation, but it is hard to achieve "Smart Control". In future work, we can easily use another program like "TMP-Based" or "Flux-Based" program to replace it, which means the backwash and chemical cleaning are triggered by TMP of Flux. Even, we will build our new standard (more efficient standards than TMP of Flux) to trigger the backwash and chemical cleaning. Then, "Smart Control" will be achieved. The "TMP/Flux-Based" program is important for practical deployment since the rendering wastewater has different flowrate and TSS concentrations during a day. Only the “Smart Control” program can handle this.

Another effort that should be undertaken is to evaluate other chemical agents for cleaning. Although the NaOH shown a satisfactory result, it still has disadvantages. NaOH may damage the membrane, even though the ceramic membrane has high chemical resistance. Future work will use low-concentration NaOH with elevated temperature to clean the membrane, which can decrease the NaOH cost and the damage to the membrane. Supersaturated carbon dioxide will also be evaluated for its cleaning potential. However, these cleaning procedures are only for the unmodified membrane. Other method for mitigating the fouling of the membrane is to modified membrane. For example, Daniel Wandera created a polymer-modified membranes for the treatment of rending wastewater, which processed 26% more permeate compared with unmodified membranes.[9] Husson used modified membrane to treat the produced water, which could achieved 100% flux recovery after a cold water rise, compared with 81% flux recovery of unmodified membrane.[16] These studies shown that the modified polymer membranes had a good mitigation of fouling during oily wastewater filtration. Thus, other researches on modification of ceramic will be on process also.

6 Acknowledgements

Firstly, I would like to express my sincere gratitude to my advisor Dr. Ladner for the continuous support of my research for his patience, motivation, and immense knowledge. His guidance helped me during all the master time from the beginning that the system was initialized to the end that the thesis was corrected and reviewed.

Besides my advisor, I would like to thank other committee members: Dr. Popat and Dr. Zheng for their insightful comment and farsighted suggestions.

Then, I would like to thank Inopore, who provided the ceramic membranes. Aniruddha Sawant made initial contact with Inopore and helped in the membrane acquisition. Jiayu Liu built an initial ceramic membrane flow system and Joe Batts built the frame and installed much of the hardware for the current system. I also would like to thank Matt McKinney for his help during installation of other hardware and rebuilding the software interface; Matt brought me new ideas when the new system was built.

Appendices

Appendix A - Calculation Example

The figure below shows the permeate flux of NaOH experiment. The filtrations between the first and second chemical cleaning are chosen since the filtrations before first chemical cleaning show an unstable result.

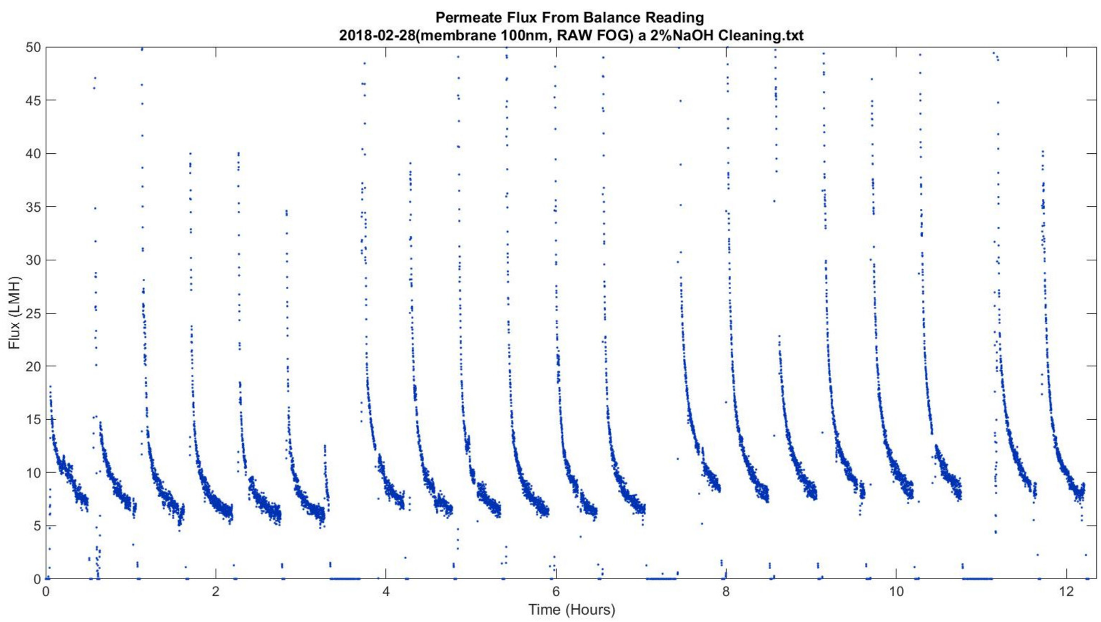


Figure 55. Flux from balance reading of NaOH experiment.

1. Reversible Fouling

Reversible fouling is the fouling can be removed by backwash. The equation below shows the calculation of reversible fouling.

$$F_{reversible} = Flux_{after\ BW} - Flux_{before\ BW}$$

$$F_{reversible\ 1st\ BW} = Flux_{after\ 1st\ BW} - Flux_{before\ 1st\ BW}$$

$$F_{reversible\ 1st\ filtraion} = 22.03\ LMH - \ 7.12\ LMH = 14.91\ LMH$$

The reversible fouling of other four filtrations can also calculated based on process above. The average of five-reversible fouling is 15.04 LMH which is the prediction value of the reversible fouling in the sixth filtration.

2. Irreversible Fouling

Irreversible fouling is the fouling can be removed by chemical cleaning.

$$F_{irreversible} = \ (Flux_{begin\ of\ 1st\ F} - \ Flux_{begin\ of\ 6th\ F}) * \frac{6}{5}$$

$$F_{irreversible\ in\ first\ 5\ filtration} = 50.96\ \mathrm{LMH} - \ 21.80\ LMH = 29.16\ LMH$$

The irreversible fouling from first five filtrations is 29.16 LMH. The irreversible fouling from sixth filtration can be predicted as the average values of the first five filtrations'.

$$F_{irreversible\ in\ 6\ filtrations} = 29.16\ LMH * \frac{6}{5} = 34.99\ LMH$$

The total irreversible fouling from six filtrations is 34.99 LMH.

3. Chemical Flux Recovery

The total flux recovery is the difference between the flux values before and after the second chemical cleaning, which contains the chemical flux recovery and backwash flux recovery.

$$Total\ Flux\ Recovery = Flux_{after\ 2nd\ Chem} - Flux_{before\ 2nd\ Chem} = 36.48\ LMH$$

Since the backwash can removal all reversible fouling, which means the backwash flux recovery is same as the predicted reversible fouling in sixth filtration. Thus, the chemical flux recovery is calculated as below:

$$Chem\ Flux\ Recovery = Total\ Flux\ Recovery - BW\ Flux\ Recovery = 21.44\ LMH$$

The chemical flux recovery after second chemical cleaning is 21.44 LMH.

4. Chemical Flux Recovery Efficiency

The chemical flux recovery efficiency is the ratio of the chemical flux recovery to the total irreversible fouling from six filtrations.

$$Chemical\ Flux\ Recovery\ Efficiency = \frac{Chemical\ Flux\ Recovery}{Total\ Irreversible\ Fouling} = 61\%$$

The recovery efficiency is 61% which means 61 percent of the irreversible can be removed after the second chemical cleaning.

Appendix B - Raw Data of Collected Points

Green cells mean that the values in the cells won't influence the calculation. Yellow cells mean that the value in the cells will influence the calculation and the predicted values are used.

Table 11. Flux data collection point at the beginning of NaOH experiment

Fitration Begin														
	Schedule	Start Time	End time	Flux										Ave Flux
		Hour		LMH										
F1	0.02	0.05	0.06	0	0	0	0	0	0	0	0	0		-0.02
F2	0.58	0.62	0.62	15	10	5	2	1	2	3	3			5.10
F3	1.15	1.18	1.19	22	21	21	20	20	21	22	23	24		21.41
F4	1.72	1.75	1.76	18	17	18	17	17	17	17	16	16		17.22
F5	2.28	2.32	2.32	16	16	15	15	15	15	15	15			15.07
F6	2.85	2.88	2.89	15	15	14	14	14	14	13	12	12		13.55
Chem 1														
F1	3.73	3.77	3.77	60	59	56	51	48	46	45	43			50.96
F2	4.30	4.33	4.34	23	23	22	22	22	21	22	21	21		22.03
F3	4.87	4.90	4.91	23	22	22	22	21	20	20	20	20		21.03
F4	5.43	5.47	5.47	23	22	22	22	21	21	21	21	20		21.26
F5	6.00	6.03	6.04	23	22	23	22	22	21	21	21	20		21.57
F6	6.57	6.60	6.61	22	22	23	23	23	22	22	21	21	20	21.80
Chem 2														
F1	7.45	7.48	7.49	66	61	52	45	39	35	31	28	27		42.69
F2	8.02	8.05	8.06	36	34	34	33	33	32	32	31	31		32.85
F3	8.58	8.62	8.63	-414	-438	-434	-431	-427	-426	-417	-415	-411		-423.65
F4	9.15	9.18	9.19	35	36	35	35	34	34	34	33	33		34.21

F5	9.72	9.75	9.76	37	36	36	35	34	35	35	34	34		35.16
F6	10.28	10.32	10.33	33	32	32	32	33	34	33	32	32		32.68
Chem 3														
F1	11.17	11.18	11.18	93	56	31	27	26	23					42.63
F2	11.73	11.77	11.77	29	27	28	27	28	27	27	26	27		27.32

Table 12. The time of Flux data collection point at the beginning of NaOH experiment

Filtration Begin														
	Schedule	Start Time	End time	Relative Time Corresponding to the Points										Ave Time
	Hour			Hour										
F1	0.02	0.05	0.06	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1		0.05
F2	0.58	0.62	0.62	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6			0.62
F3	1.15	1.18	1.19	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2		1.19
F4	1.72	1.75	1.76	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8		1.75
F5	2.28	2.32	2.32	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3			2.32
F6	2.85	2.88	2.89	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9		2.89
Chem 1														
F1	3.73	3.77	3.77	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8			3.77
F2	4.30	4.33	4.34	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3		4.34
F3	4.87	4.90	4.91	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9		4.90
F4	5.43	5.47	5.47	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5		5.47
F5	6.00	6.03	6.04	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0		6.04
F6	6.57	6.60	6.61	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.61	6.60
Chem 2														
F1	7.45	7.48	7.49	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5		7.49
F2	8.02	8.05	8.06	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1		8.05

F3	8.58	8.62	8.63	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6		8.62
F4	9.15	9.18	9.19	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2		9.19
F5	9.72	9.75	9.76	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8		9.75
F6	10.28	10.32	10.33	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3		10.32
Chem 3														
F1	11.17	11.18	11.18	11.2	11.2	11.2	11.2	11.2	11.2					11.18
F2	11.73	11.77	11.77	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8		11.77

Table 13. Flux data collection point at the end of NaOH experiment

Filtration End													
	Schedule	Start Time	End time	Flux									Ave Flux
	Hour			LMH									
F1	0.52	0.49	0.50	7	7	7	7	7	8	7	7	7	7.13
F2	1.08	1.06	1.07	7	6	6	6	7	7	7	7	7	6.47
F3	1.65	1.63	1.63	6	6	6	7	6	6	6	7		6.29
F4	2.22	2.19	2.20	6	6	6	6	6	6	7	6	6	6.26
F5	2.78	2.76	2.77	6	7	6	6	6	6	6	6	7	6.17
F6	3.35	3.33	3.33	8	9	9	8	8	9	8	8	8	8.33
Chem 1													
F1	4.23	4.21	4.22	7	8	8	7	7	7	7	7	7	7.12
F2	4.80	4.78	4.78	6	7	7	6	6	7	7	7	6	6.50
F3	5.37	5.34	5.35	6	6	6	7	6	7	6	6	7	6.38
F4	5.93	5.91	5.92	6	6	6	6	6	7	6	6	6	6.28
F5	6.50	6.48	6.48	6	6	6	6	6	6	6	6	6	6.24
F6	7.07	7.04	7.05	5	5	7	6	6	7	6	6	7	6.21
Chem 2													
F1	7.95	7.93	7.93	8	8	8	8	8	9	9	9	8	8.45

F2	8.52	8.49	8.50	7	7	8	8	8	8	9	8	7	7.87
F3	9.08	9.06	9.07	7	8	8	8	8	8	7	8	9	7.92
F4	9.65	9.63	9.63	8	8	8	9	9	8	8	8	8	8.20
F5	10.22	10.19	10.20	8	8	9	9	8	8	8	9	8	8.26
F6	10.78	10.76	10.77	9	9	8	8	8	7	8	9	9	8.36
Chem 3													
F1	11.67	11.64	11.65	9	8	8	8	8	8	8	9	8	8.21
F2	12.23	12.21	12.22	8	8	8	8	8	8	8	8	8	8.01

Table 14. The time of Flux data collection point at the end of NaOH experiment

	Schedule	Start Time	End time	Relative Time Correspoding to the Points									Ave Time
		Hour		Hour									
F1	0.52	0.49	0.50	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.50
F2	1.08	1.06	1.07	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.06
F3	1.65	1.63	1.63	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6		1.63
F4	2.22	2.19	2.20	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.20
F5	2.78	2.76	2.77	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.76
F6	3.35	3.33	3.33	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.33
Chem 1													
F1	4.23	4.21	4.22	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.21
F2	4.80	4.78	4.78	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.78
F3	5.37	5.34	5.35	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.35
F4	5.93	5.91	5.92	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.91
F5	6.50	6.48	6.48	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.48
F6	7.07	7.04	7.05	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.05

Chem 2													
F1	7.95	7.93	7.93	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.93
F2	8.52	8.49	8.50	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.50
F3	9.08	9.06	9.07	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.06
F4	9.65	9.63	9.63	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.63
F5	10.22	10.19	10.20	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.20
F6	10.78	10.76	10.77	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.76
Chem 3													
F1	11.67	11.64	11.65	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.65
F2	12.23	12.21	12.22	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.21

Table 15. Flux data collection point and corresponded time point at the beginning of HCl experiment

Filtration Begin													
	Schedule	Start Time	End time	Flux				Ave Flux	Relative Time Corresponding to the Points				Ave Time
	Hour			LMH					Hour				
F1	0.02	0.05	0.06	63	63	61		62.27	0.1	0.1	0.1		0.05
F2	0.58	0.62	0.62	45	46	41		44.21	0.6	0.6	0.6		0.62
F3	1.15	1.18	1.19	47	43	42		44.03	1.2	1.2	1.2	1.2	1.19
F4	1.72	1.75	1.76	39	37	36		37.52	1.8	1.8	1.8	1.8	1.75
F5	2.28	2.32	2.32	-381	-376	-362		-373.28	2.3	2.3	2.3	2.3	2.32
F6	2.85	2.88	2.89	30	29	28	28	28.81	2.9	2.9	2.9	2.9	2.89
Chem 1													
F1	3.73	3.77	3.77	54	51	48		51.09	3.8	3.8	3.8	3.8	3.77
F2	4.30	4.33	4.34	28	28	26		27.08	4.3	4.3	4.3	4.3	4.34
F3	4.87	4.90	4.91	21	20	19	19	19.95	4.9	4.9	4.9	4.9	4.90
F4	5.43	5.47	5.47	22	22			21.58	5.5	5.5			5.47
F5	6.00	6.03	6.04	21	21	19		20.39	6.0	6.0	6.0	6.0	6.04

F6	6.57	6.60	6.61	19	16	18		17.76	6.6	6.6	6.6		6.60
Chem 2													
F1	7.45	7.48	7.49	41	39	37		38.95	7.5	7.5	7.5		7.49
F2	8.02	8.05	8.06	16	16	16		16.05	8.1	8.1	8.1		8.05
F3	8.58	8.62	8.63	12	12	12		11.92	8.6	8.6	8.6		8.62
F4	9.15	9.18	9.19	10	11	10		10.36	9.2	9.2	9.2	9.2	9.19
F5	9.72	9.75	9.76	9	9	10		9.52	9.8	9.8	9.8	9.8	9.75
F6	10.28	10.32	10.33	-324	-475	-466		-421.55	10.3	10.3	10.3	10.3	10.32
Chem 3													
F1	11.17	11.18	11.18	28	24	24		25.09	11.2	11.2	11.2		11.20
F2	11.73	11.77	11.77	11	11	11		10.75	11.8	11.8	11.8		11.77

Table 16. Flux data collection point and corresponded time point at the end of HCl experiment

Filtration End													
	Schedule	Start Time	End time	Flux				Ave Flux	Relative Time Corresponding to the Flux				Ave Time
	Hour			LMH					Hour				
F1	0.52	0.49	0.50	11	11	12		11.26	0.5	0.5	0.5		0.50
F2	1.08	1.06	1.07	11	11	11	11	11.09	1.1	1.1	1.1	1.1	1.06
F3	1.65	1.63	1.63	10	11	11		10.72	1.6	1.6	1.6		1.63
F4	2.22	2.19	2.20	10	11	10		10.33	2.2	2.2	2.2		2.20
F5	2.78	2.76	2.77	11	10	10	10	10.27	2.8	2.8	2.8	2.8	2.76
F6	3.35	3.33	3.33	10	11	10		10.09	3.3	3.3	3.3		3.33
Chem 1													
F1	4.23	4.21	4.22	-458	-455	-433		-448.52	3.8	3.8	3.8	3.8	4.21
F2	4.80	4.78	4.78	10	10	10	10	9.85	4.3	4.3	4.3	4.3	4.78
F3	5.37	5.34	5.35	9	9	9		9.28	4.9	4.9	4.9	4.9	5.35
F4	5.93	5.91	5.92	9	9	9	9	9.30	5.5	5.5			5.91
F5	6.50	6.48	6.48	8	8	8		8.42	6.0	6.0	6.0	6.0	6.48
F6	7.07	7.04	7.05	8	8	8		8.26	6.6	6.6	6.6		7.05

Chem 2															
F1	7.95	7.93	7.93	11	11	10			10.66	7.9	7.9	7.9			7.93
F2	8.52	8.49	8.50	8	9	9			8.51	8.5	8.5	8.5			8.50
F3	9.08	9.06	9.07	8	8	8			7.82	9.1	9.1	9.1			9.06
F4	9.65	9.63	9.63	7	7	7	7		7.25	9.6	9.6	9.6	9.6		9.63
F5	10.22	10.19	10.20	7	7	7			6.75	10.2	10.2	10.2			10.20
F6	10.78	10.76	10.77	6	6	6	6	6	6.20	10.8	10.8	10.8	10.8	10.8	10.76
Chem 3															
F1	11.67	11.64	11.65	7	7	7	7		7.39	11.2	11.2	11.2			11.64
F2	12.23	12.21	12.22	7	7	6	7		6.57	11.8	11.8	11.8			12.21

Table 17. Flux data collection point and corresponded time point at the beginning of EDTA experiment

Filtration Begin															
	Schedule	Start Time	End time	Flux					Ave Flux	Relative Time Corresponding to the Points					Ave Time
	Hour			LMH						Hour					
F1	0.02	0.05	0.06	96	93	94	96	87	93.32	0.1	0.1	0.1	0.1	0.1	0.05
F2	0.58	0.62	0.62	51	48	44			47.58	0.6	0.6	0.6			0.62
F3	1.15	1.18	1.19	-402	-397				-399.48	1.2	1.2				1.19
F4	1.72	1.75	1.76	44	44	41			42.81	1.8	1.8	1.8			1.75
F5	2.28	2.32	2.32	11	8	-456			-145.83	2.3	2.3	2.3			2.32
F6	2.85	2.88	2.89	29	28	28	28		28.31	2.9	2.9	2.9	2.9		2.89

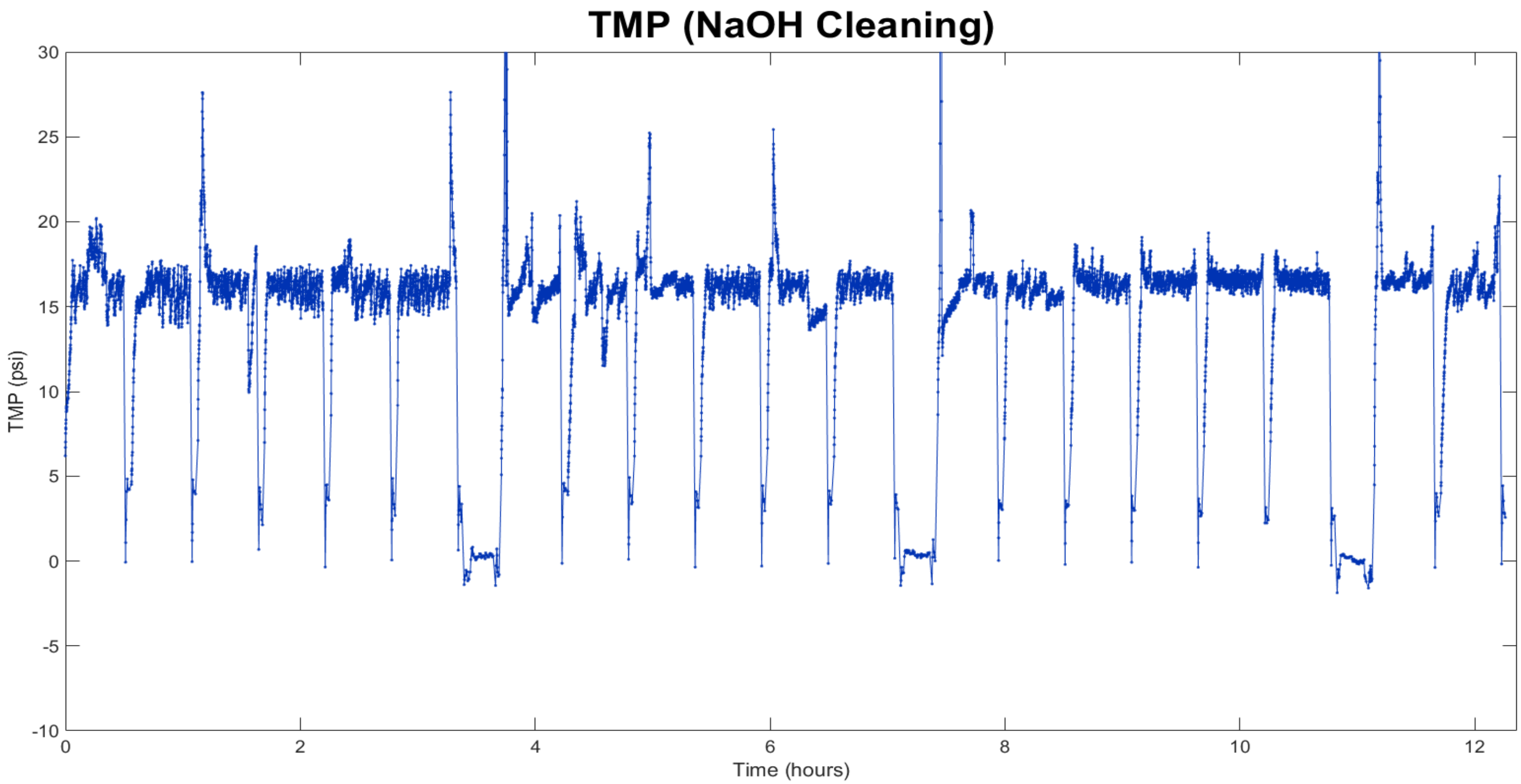
Chem 1															
F1	3.73	3.77	3.77	42	41	39	37		39.59	3.8	3.8	3.8	3.8		3.77
F2	4.30	4.33	4.34	20	20	19	20		19.67	4.3	4.3	4.3	4.3		4.34
F3	4.87	4.90	4.91	21	21	21	22		21.29	4.9	4.9	4.9	4.9		4.90
F4	5.43	5.47	5.47	24	23	23	23		23.13	5.5	5.5	5.5	5.5		5.47
F5	6.00	6.03	6.04	24	23	21	22	21	22.32	6.0	6.0	6.0	6.0	6.0	6.04
F6	6.57	6.60	6.61	22	21	22			21.66	6.6	6.6	6.6			6.60
Chem 2															
F1	7.45	7.48	7.49	33	32	30			31.66	7.5	7.5	7.5			7.49
F2	8.02	8.05	8.06	17	16	16			16.10	8.1	8.1	8.1			8.05
F3	8.58	8.62	8.63	16	16	15			15.75	8.6	8.6	8.6			8.62
F4	9.15	9.18	9.19	18	18	17	17		17.37	9.2	9.2	9.2	9.2		9.19
F5	9.72	9.75	9.76	20	19	19			19.05	9.8	9.8	9.8			9.75
F6	10.28	10.32	10.33	18	18	16	17		17.07	10.3	10.3	10.3	10.3		10.32
Chem 3															
F1	11.17	11.18	11.18	27	25	24			25.64	11.2	11.2	11.2			11.20
F2	11.73	11.77	11.77	16	15	15			15.34	11.8	11.8	11.8			11.77

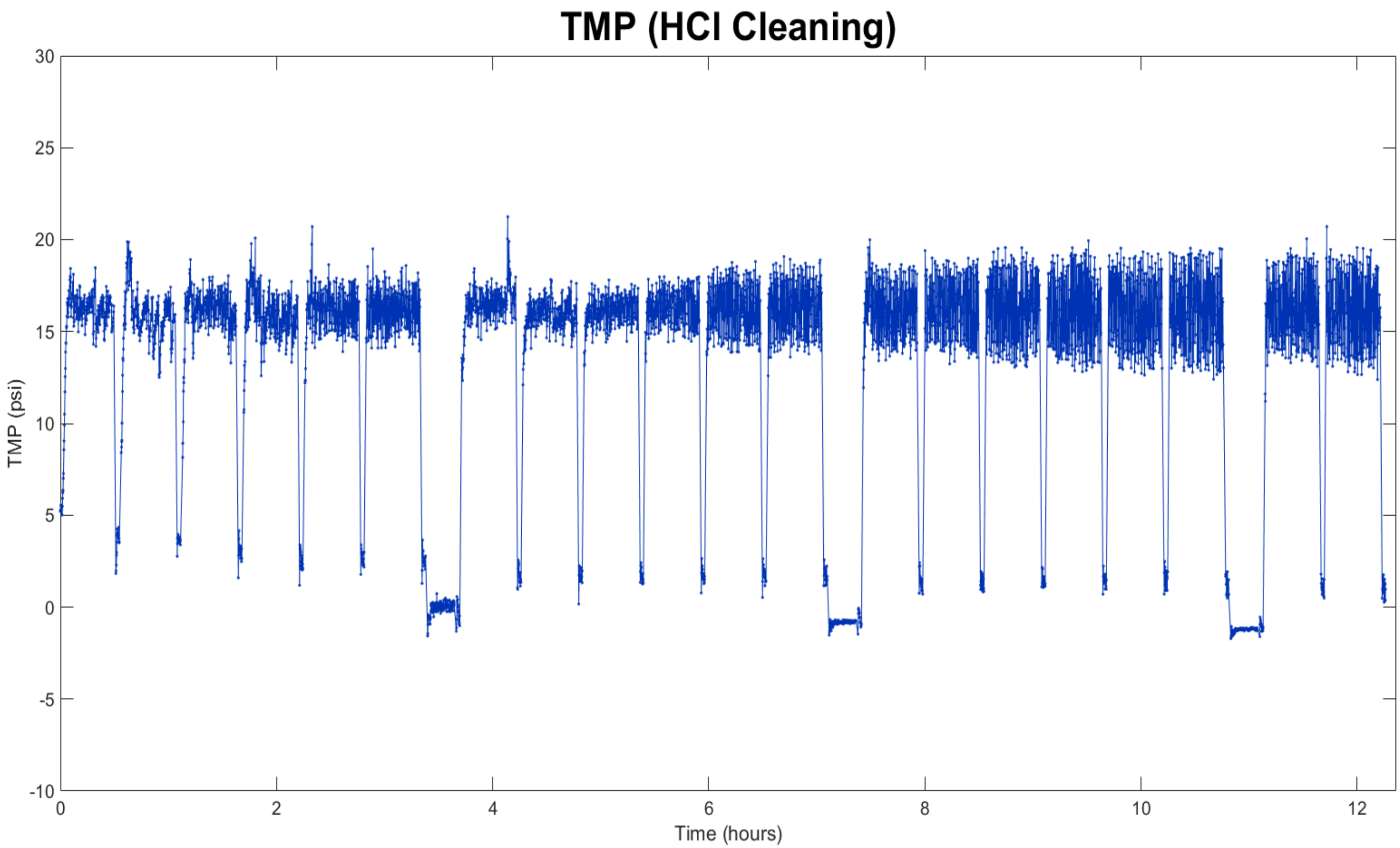
Table 18. Flux data collection point and corresponded time point at the end of EDTA experiment

Filtration End															
	Schedule	Start Time	End time	Flux					Ave Flux	Relative Time Corresponding to the Flux					Ave Time
	Hour			LMH						Hour					
F1	0.02	0.05	0.06	13	13	13	13	13	13.22	0.5	0.5	0.5	0.5	0.5	0.50
F2	0.58	0.62	0.62	12	13	13			12.62	1.1	1.1	1.1			1.06
F3	1.15	1.18	1.19	12	12	12			11.88	1.6	1.6	1.6			1.63
F4	1.72	1.75	1.76	-1	-1	0	-1	0	-0.82	2.2	2.2	2.2	2.2	2.2	2.20
F5	2.28	2.32	2.32	11	12	12	10		11.25	2.8	2.8	2.8	2.8		2.76
F6	2.85	2.88	2.89	-2	-2	-3	-2		-2.09	3.3	3.3	3.3	3.3		3.33
Chem 1															
F1	3.73	3.77	3.77	13	13	13	12		12.63	4.2	4.2	4.2	4.2		4.21
F2	4.30	4.33	4.34	9	10	10			9.62	4.8	4.8	4.8			4.78
F3	4.87	4.90	4.91	9	8	8			8.50	5.3	5.3	5.3			5.35
F4	5.43	5.47	5.47	8	8	8			8.37	5.9	5.9	5.9			5.91
F5	6.00	6.03	6.04	9	9	8	6		7.84	6.5	6.5	6.5	6.5		6.48
F6	6.57	6.60	6.61	8	8	8			7.93	7.0	7.0	7.0			7.04
Chem 2															
F1	7.45	7.48	7.49	10	10	9			9.79	7.9	7.9	7.9			7.93
F2	8.02	8.05	8.06	9	7	9			8.33	8.5	8.5	8.5			8.50
F3	8.58	8.62	8.63	8	7	7			7.16	9.1	9.1	9.1			9.06
F4	9.15	9.18	9.19	7	7	7			7.31	9.6	9.6	9.6			9.63
F5	9.72	9.75	9.76	7	7	7	7		7.05	10.2	10.2	10.2	10.2		10.19
F6	10.28	10.32	10.33	7	7	6			6.91	10.8	10.8	10.8			10.76

Chem 3											
F1	11.17	11.18	11.18	10	8	9	9.14	11.6	11.6	11.6	11.65
F2	11.73	11.77	11.77	-3	-4	-3	8.60	12.2	12.2	12.2	12.04

Appendix C – TMP of three experiments




TMP (HCl Cleaning)
TMP (psi)
Time (hours)
30
25
20
15
10
5
0
-5
-10
0
2
4
6
8
10
12

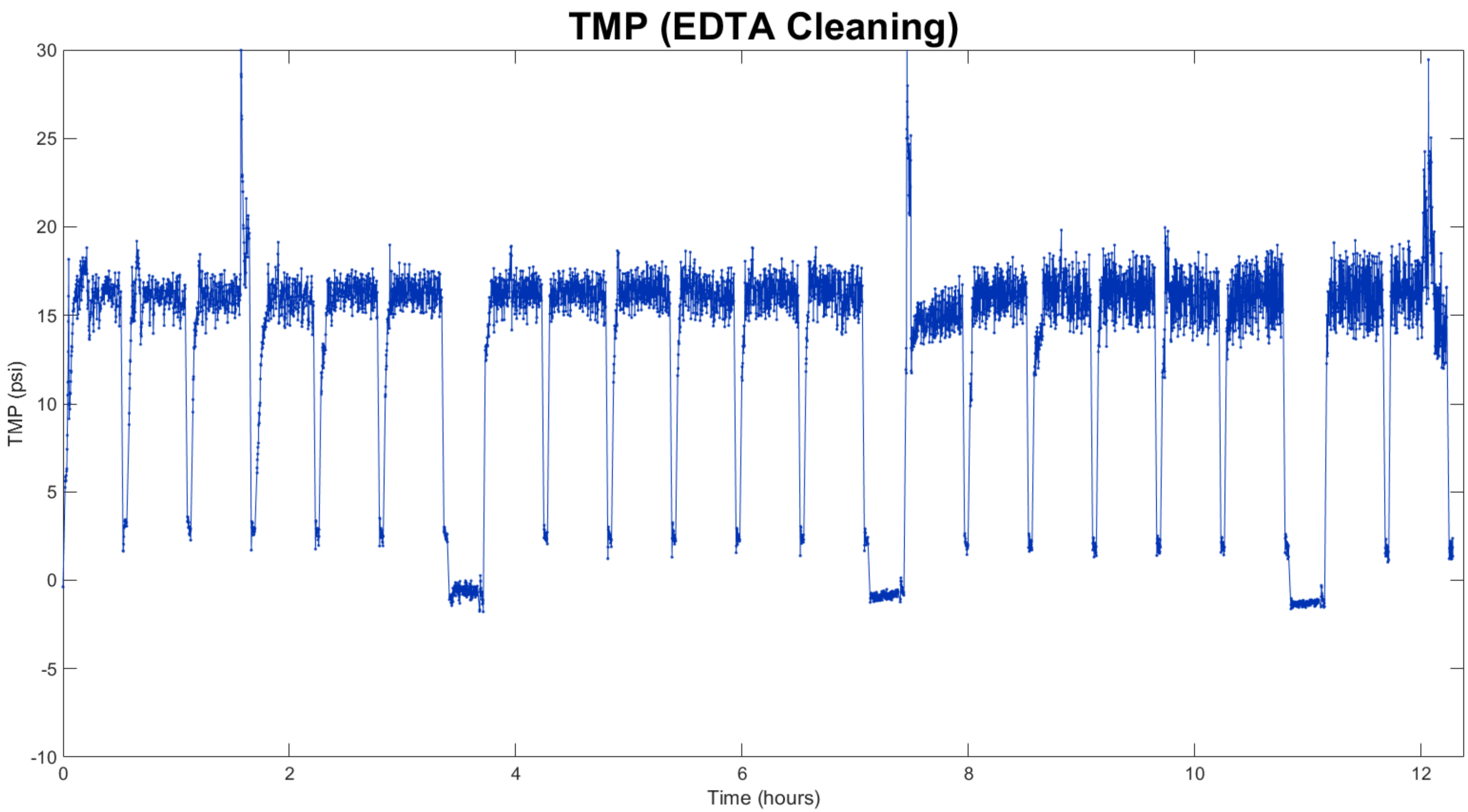


Figure 56. TMP of a) NaOH experiment, b) HCl experiment, and c) EDTA experiment

Appendix D – Components

Table below shows the components for system control and data recording.

Table 19. Components

Name	Purpose	From	#	Price, $	Purchase from	#	price
Peristaltic Pump 1	Feed flow	Cole Parmer	07551-20	2418			
Peristaltic Pump 2	Backwash	Cole Parmer	7551-20	2418			
Peristaltic Pump 3	Chemical Cleaning	Cole Parmer	07551-20	2418			
Solenoid Valve 1	Concentrate entering	Parker			McMASTER-CARR	4639K62	119.43
Solenoid Valve 2	BW entering	Parker			McMASTER-CARR	2660K12	148.27
Solenoid Valve 3	Permeate output	Parker			McMASTER-CARR	4639K62	119.43
Solenoid Valve 4	Chemical Cleaning entering	Parker			McMASTER-CARR	2660K12	148.27
Solenoid Valve 5	Wastewater to feed tank	Parker			McMASTER-CARR	4639K62	119.43
Solenoid Valve 6	Wastewater to waste tank	Parker			McMASTER-CARR	2660K12	148.27
USB - 232/4	USB to RS 232	National Instruments	778473-04	523.8			

USB - 232/2	USB to RS 232	National Instruments	778473-02	363.6			
cDAQ-9171	Control solenoid valve	National Instruments	781425-01	277.2			
NI 9482	Control solenoid valve	National Instruments	783906-01	169.2			
USB-6009 *2	Reading Data/ Control AC valve	National Instruments	191039D-01L		ebay		220
Alpha pH 500	pH transmitter pH sensor	Eutech	TSPHCTP0500		Cole Parmer	EW-56717-20	405
CX100	Conductivity transmitter Conductivity sensor	Sensorex	CX100	551.25			
A-10*2	Pressure sensor	Wike	50535196		Amazon		155
Pressure Gauge	concentrate pressure	ASHCROFT	63-1008-SL-02L-30#		ebay		60
Pressure Gauge	BW and CHEM pressure	UCI					
Flowmeter	measure permeate flow	ALICAT	L-50CCM-D	1165			

Reference

(1) Waeger, F.; Delhaye, T.; Fuchs, W. The use of ceramic microfiltration and ultrafiltration membranes for particle removal from anaerobic digester effluents. *Sep. Purif. Technol.* **2010**, *73* (2), 271–278.

(2) Zhang, W.; Ding, L.; Jaffrin, M. Y.; Tang, B. Membrane cleaning assisted by high shear stress for restoring ultrafiltration membranes fouled by dairy wastewater. *Chem. Eng. J.* **2017**, *325*, 457–465.

(3) Wang, Z.; Ma, J.; Tang, C. Y.; Kimura, K.; Wang, Q.; Han, X. Membrane cleaning in membrane bioreactors: A review. *J. Memb. Sci.* **2014**, *468*, 276–307.

(4) Abadi, S. R. H.; Sebzari, M. R.; Hemati, M.; Rekabdar, F.; Mohammadi, T. Ceramic membrane performance in microfiltration of oily wastewater. *Desalination* **2011**, *265* (1–3), 222–228.

(5) Hwang, K. J.; Chan, C. S.; Tung, K. L. Effect of backwash on the performance of submerged membrane filtration. *J. Memb. Sci.* **2009**, *330* (1–2), 349–356.

(6) Mutamim, N. S. A.; Noor, Z. Z.; Hassan, M. A. A.; Yuniarto, A.; Olsson, G. Membrane bioreactor: Applications and limitations in treating high strength industrial wastewater. *Chemical Engineering Journal*. 2013.

(7) Mutamim, N. S. A.; Noor, Z. Z.; Hassan, M. A. A.; Olsson, G. Application of membrane bioreactor technology in treating high strength industrial wastewater: A performance review. *Desalination* **2012**, *305*, 1–11.

(8) Mekonnen, T.; Mussone, P.; Bressler, D. Valorization of rendering industry wastes and co-products for industrial chemicals, materials and energy: Review. *Crit. Rev. Biotechnol.* **2016**, *36* (1), 120–131.

(9) Wandera, D.; Husson, S. M. Assessment of fouling-resistant membranes for additive-free treatment of high-strength wastewaters. *Desalination* **2013**, *309*, 222–230.

(10) Nisola, G. M.; Cho, E. S.; Shon, H. K.; Tian, D.; Chun, D. J.; Gwon, E. M.; Chung, W. J. Cell Immobilized FOG-Trap System for Fat, Oil, and Grease Removal from Restaurant Wastewater. *J. Environ. Eng.* **2009**, *135* (9), 876–884.

(11) Creamer, K. S.; Chen, Y.; Williams, C. M.; Cheng, J. J. Stable thermophilic anaerobic digestion of dissolved air flotation (DAF) sludge by co-digestion with

swine manure. *Bioresour. Technol.* **2010**, *101* (9), 3020–3024.

(12) Bouhabila, E. H.; Ben A??m, R.; Buisson, H. Fouling characterisation in membrane bioreactors. *Sep. Purif. Technol.* **2001**, *22–23*, 123–132.

(13) Silalahi, S. H. D.; Leiknes, T. Cleaning strategies in ceramic microfiltration membranes fouled by oil and particulate matter in produced water. *Desalination* **2009**, *236* (1–3), 160–169.

(14) Lee, H.; Amy, G.; Cho, J.; Yoon, Y.; Moon, S. H.; Kim, I. S. Cleaning strategies for flux recovery of an ultrafiltration membrane fouled by natural organic matter. *Water Res.* **2001**, *35* (14), 3301–3308.

(15) Chen, V.; Li, H.; Li, D.; Tan, S.; Petrus, H. B. Cleaning strategies for membrane fouled with protein mixtures. *Desalination* **2006**, *200* (1–3), 198–200.

(16) Wandera, D.; Wickramasinghe, S. R.; Husson, S. M. Modification and characterization of ultrafiltration membranes for treatment of produced water. *J. Memb. Sci.* **2011**, *373* (1–2), 178–188.

(17) Kim, J.; DiGiano, F. A. A two-fiber, bench-scale test of ultrafiltration (UF) for investigation of fouling rate and characteristics. *J. Memb. Sci.* **2006**, *271* (1–2), 196–204.

(18) Robles, A.; Ruano, M. V.; Ribes, J.; Ferrer, J. Advanced control system for optimal filtration in submerged anaerobic MBRs (SAnMBRs). *J. Memb. Sci.* **2013**, *430*, 330–341.

(19) Ferrero, G.; Monclús, H.; Buttiglieri, G.; Comas, J.; Rodriguez-Roda, I. Automatic control system for energy optimization in membrane bioreactors. *Desalination* **2011**, *268* (1–3), 276–280.

(20) Zadeh, L. A.; Introduction, I.; Navy, U. S. Fuzzy Sets * -. **1965**, *353*, 338–353.

(21) Villarroel, R.; Delgado, S.; González, E.; Morales, M. Physical cleaning initiation controlled by transmembrane pressure set-point in a submerged membrane bioreactor. *Sep. Purif. Technol.* **2013**, *104*, 55–63.

(22) Field, R. W.; Wu, D.; Howell, J. A.; Gupta, B. B. Critical flux concept for microfiltration fouling. *J. Memb. Sci.* **1995**, *100* (3), 259–272.

(23) Howell, J. A. Sub-critical flux operation of microfiltration. *J. Memb. Sci.* **1995**, *107* (1–2), 165–171.

(24) Kwon, D. Y.; Vigneswaran, S. Influence of particle size surface charge on critical flux of crossflow microfiltration. *Water and Science Technology*. 1998, pp 481–488.

(25) Kwon, D. Y.; Vigneswaran, S.; Fane, A. G.; Aim, R. Ben. Experimental determination of critical flux in cross-flow microfiltration. *Sep. Purif. Technol.* **2007**, *19* (2000), 169–181.

(26) Monclús, H.; Ferrero, G.; Buttiglieri, G.; Comas, J.; Rodriguez-Roda, I. Online monitoring of membrane fouling in submerged MBRs. *Desalination* **2011**, *277* (1–3), 414–419.

(27) Diez, V.; Ezquerra, D.; Cabezas, J. L.; García, A.; Ramos, C. A modified method for evaluation of critical flux, fouling rate and in situ determination of resistance and compressibility in MBR under different fouling conditions. *J. Memb. Sci.* **2014**, *453*, 1–11.

(28) David A. Ladner. Effects of bloom-forming algae on fouling of integrated membrane systems in sewater desalination. **2009**.