Modeling Fouling Mitigation Options for Cellulosic Ethanol Distillation

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Abstract

This paper presents a techno-economic analysis of fouling mitigation options for a cellulosic ethanol process. A recent change upstream in the pretreatment step of the ethanol production process has resulted in the formation and build up of calcium sulphate scale further downstream in the distillation column reboiler. The rapid rate of fouling observed in the reboiler has lead to a large reduction in operational efficiency with significant process downtime and cleaning costs. The purpose of this report is to provide a thorough understanding of the fouling mechanism, construct an empirical model for predicting fouling and present mitigation strategies. Theory dictates that the major fouling mechanism in effect is precipitation fouling where calcium sulphate is supersaturated and crystallizes onto the heat transfer surface after the initial nucleation phase. The rate of fouling is strongly affected by the surface temperature in the process side of the exchanger, calcium sulphate concentration in the feed and fluid velocity through the reboiler. The construction of an empirical model used for predicting fouling tendency was based on collected data over a six month period which included a 2-month base period with no severe fouling and a 4-month period where fouling was most severe. The model identified that time, steam flow to reboiler and inlet temperature of the process fluid are significant parameters and no interactions between these variables were detected. A basic analysis was carried out to quantify some of the costs associated with fouling. Costs for steam, reboiler cleaning and lost revenue due to downtime were calculated. Three fouling mitigation strategies were proposed. The implementation of a predictive fouling control tool developed by combining the empirical regression model and real plant data to optimize the cleaning schedule of the reboiler was discussed. Also, the flow through the reboiler should be increased to decrease the rate of fouling and this can be achieved by simple pump modifications. Another mitigation strategy is the installation of a stand-by reboiler, which is an additional capital cost but may be necessary for continuous operation.

Keywords
Techno-economic analysis, ethanol distillation, fouling mitigation.

1. Introduction
The build-up of undesirable deposits within process equipment is a phenomenon known as fouling, and presents a major economic problem in many chemical plants. Fouling is known to have significant cost implications due to reductions in heat transfer efficiency and reduced throughput capacity. It has been roughly estimated that 15% of the maintenance costs of a process plant can be attributed to heat exchangers and boilers, and of this, half is probably attributable to fouling (Pitchard 1987). Cellulosic ethanol is a liquid biofuel made from agricultural waste such as wheat straw and corn stover and it is similar in composition to grain ethanol, which utilizes food sources such as corn and cane sugars as its feedstock. Cellulosic ethanol has significant advantages over conventional ethanol due to its use of abundant feedstock supply that does not compete with some of the world's most in-demand food sources. In addition to a feedstock that is in abundance, there is evidence that cellulosic ethanol also produces substantially less green house gases (GHG) compared to gasoline and grain ethanol (which has a high carbon footprint when feedstock farming is considered). However, one main disadvantage of cellulosic ethanol over grain ethanol is the difficulty of breaking down the plant fiber (lignocellulose) into sugar monomers to allow for ethanol fermentation.

In this work fouling mitigation issue due to using a calcium hydroxide as neutralization agent upstream of cellulosic ethanol process from Iogen Coporation was studied. The licensed process consists of three main steps: pretreatment and conversion of feedstock, fermentation and beer distillation In the pretreatment step, the lignocellulose is broken down to free the cellulose from the plant structure using a steam explosion technique under an acidic pH. In the next step, enzymes (produced in-house) are used to convert cellulose to glucose. Fermentation converts these glucose molecules into ethanol using advanced bio-reactions and microorganisms. Then as a final step, the beer produced from fermentation is distilled in a continuous distillation operation. At the distillation process, there is a use of calcium hydroxide which resulted in the formation of calcium sulphate in the process stream and led to fouling in distillation column reboiler. Even an anti-scaling agent is being added to the incoming beer stream leaving the fermentation tanks to help decrease the rate of deposition of calcium sulphate in the process equipment. The cleaning agents tested were mainly unsuccessful as only a maximum of 50% scalant removal was obtained and pressure cleaning was still required before reinstating the reboiler for normal operation. The rapid rate of fouling observed in the reboiler has led to a large reduction in operational efficiency of distillation with significant process downtime and costs due to the requirement for high pressure cleaning. Therefore, the purpose of this study is to provide a thorough understanding of the fouling mechanism, construct an empirical model for predicting fouling and finally present mitigation strategies.

2. Theory behind Fouling

Fouling is caused by any foreign material that deposits on to a heat transfer surface over time, introducing an additional heat transfer resistance. At Iogen, the scalant contributing to fouling is mostly comprised of calcium sulphate ($CaSO_4$). Severe fouling reduces the operational capability of the heat exchanger by decreasing the heat transfer rate and increasing the pressure drop across the reboiler. In order for fouling to be disruptive to a plant operation, three requirements need to be met; a foulant should be present in the system in relatively significant concentrations, operating conditions should favour the fouling mechanism and lastly fouling should occur on equipment that is prone to fouling.

Heat exchanger fouling refers to a physical deposit on the solid between the two heat transfer fluids and it causes a decrease in the rate of heat transfer across the solid boundary. There are several types of fouling categorized using their respective mechanisms. The major types are corrosion fouling, biofouling, particulate fouling, chemical fouling, and precipitation fouling. It is important to note that any of these mechanisms could exist in combination with another mechanism. For example, both particulate and precipitation fouling can be found in cooling water towers (Perry and Green 1984). As discusses previously, the major fouling mechanism present at Iogen is precipitation fouling due to an inversely soluble salt.

2.1 Operating Conditions and Fouling

The operating conditions also play a critical role in determining the intensity of fouling in addition to the fouling mechanism. The normal operating temperature of the beer bottoms reboiler (process side) is constantly above 100oC and therefore both ethanol and water in the process side are above their boiling temperature range. When a fluid has reached above its saturation temperature, bubbles form rapidly and this phenomenon contributes to a better heat transfer by agitating the thermal boundary layer (Malayeri and Müller-Steinhagen 2007). Figure 1 shows bubbling occurring at various heat fluxes. Heat transfer was highest when there were many small bubbles as it increases convective heat transfer forces.

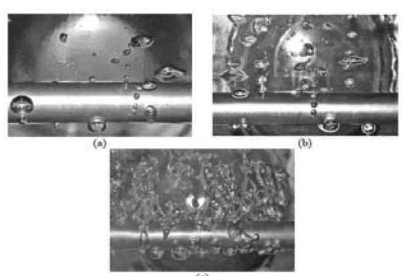


Figure 1: Bubbling due to boiling with increasing heat flux (Malayeri and Müller-Steinhagen 2007).

2.2 Fouling Mechanism

The fouling mechanism, when combined with operating conditions and equipment that is prone to fouling, determines the intensity of fouling in an operation. There are three main steps in the fouling mechanism that is present under bubbling heat transfer conditions: supersaturation, nucleation and crystal growth phase as shown in Figure 2. When boiling begins, first bubbles form just above the nucleation sites on the solid surface. The bubble size, shape and rising velocity are determined by the physical and chemical properties of the process fluid (mainly surface tension). Moreover, the bubble density is determined by the initial surface conditions such as roughness and availability of nucleation sites (pits and cracks).

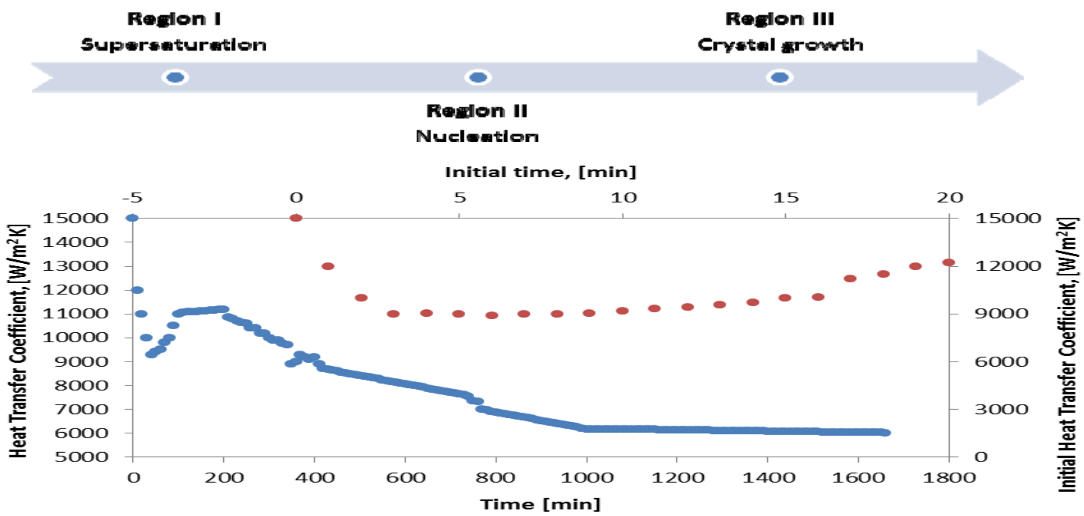


Figure 2: Typical Heat Transfer Coefficient Decay Curve (Mwaba et. al. 2006a).

In Region I, supersaturation occurs in a microlayer underneath the bubbles formed due to boiling. Supersaturation refers to increasing the amount of dissolved material in the solution than it would usually allow for under normal operating conditions. In this case, the solvent (water) is selectively evaporated by rapid boiling and this leads to supersaturated calcium sulphate in the process fluid. Moreover since the salt has inverse solubility characteristics, it is further supersaturated and the salt begins its precipitation first by nucleation.

Nucleation (Region II) refers to the first formation of stable crystalline phase on a solid surface. There are two types of nucleation, homogenous (unaided nucleation) and heterogeneous (aided nucleation). In heat exchangers such as the beer reboiler, heterogeneous nucleation is present as impurities on the surface aid the nucleation process. Nucleation is a function of interfacial tension and therefore the surface also plays a role in promoting or resisting the forming of the first crystalline phase. As more bubbles are formed, agitation occurs and this significantly increases the rate of heat transfer through the thermal boundary layer. Once this phase has formed, crystallization will occur if certain conditions are satisfied.

The crystallization phase (Region III) refers to growth of the fouling layer and it is directly affected by the bulk concentration of foulant in the process fluid and the surface temperature. As crystallization progresses, the heat transfer coefficient decreases gradually until it plateaus out at an equilibrium level where the removal of calcium sulphate is equal to the deposition rate (Mwaba et. al. 2006a).

The rate of fouling is also influenced by calcium sulphate concentration and surface temperature (Mwaba et. al. 2006b).The bulk concentration affects both supersaturation and crystallization phases. At low $CaSO_4$ concentrations, a long induction period will be in effect indicating that the process of supersaturation is slow and fouling is delayed. However, as the concentration is increased, the induction period becomes non-existent. During crystallization, high $CaSO_4$ concentrations would allow for the fouling layer to build, effectively preventing equilibrium between the deposition and removal rate of the foulants. The surface temperature also plays a critical role and as expected, a higher surface temperature resulted in an increased rate of fouling. It is important to note that the fluid velocity does not greatly affect $CaSO_4$ fouling as the crystallization phase is dependent more on the surface temperature.

However, an increased flow (at a constant heat input) would result in a lowering of the surface temperature and therefore reduce the rate of fouling.

3. Fouling Mitigation Model

The construction of a multiple linear regression model used for predicting fouling tendency consisted of three main steps: obtaining raw DCS data, filtering data and performing heat transfer calculations, and statistically analysis for the overall regression model.

3.1 Distillation DCS Data

Distillation data was obtained from Iogen's demonstration plant distributed control system (DCS) for each month in the year 2009. Of the 12 months of data, 6 months were chosen for analysis. During January and February, ammonium hydroxide was used as the neutralization agent in the pretreatment step of the process. These two months were selected to represent the baseline months for a normal operation period. Fouling in the reboiler was not known to be a problem in distillation during this period of time. Another four month, which were June, July, September and October, use calcium hydroxide and it results in the downstream formation of calcium sulphate ($CaSO_4$) which is the main fouling constituent in the distillation reboiler. Thus, these four months are referred to as the fouling months.
To track the operational quality of the reboiler, the overall heat transfer coefficient (U) and fouling resistance (R_f) of the reboiler was monitored over time. However, to assess this data properly, extensive filtering was required so that several subsets of pseudo-steady state periods could be isolated and analyzed. Filtering was required to eliminate data points attributed by outliers, disturbances, start-up and shut-down periods, etc. For the four months analyzed during the fouling period, eight subsets of data were analyzed. These periods represent operational periods after the reboiler was cleaned and extend until the reboiler is needed to be taken offline again for cleaning due to foulant build-up. The overall heat transfer coefficient could be determined using the following formula

$$U = \frac{Q}{A \cdot T_{lm}} \quad (1)$$

Where Q is heat transfer rate from the steam, A is reboiler area and T_{lm} is log-mean temperature across the reboiler. Also fouling resistance is calculated using Equation (2).

$$R_f = \left(\frac{1}{U}\right) - \left(\frac{1}{U_{clean}}\right) \quad (2)$$

Where U is overall heat transfer coefficient and U_{clean} is clean heat transfer coefficient.

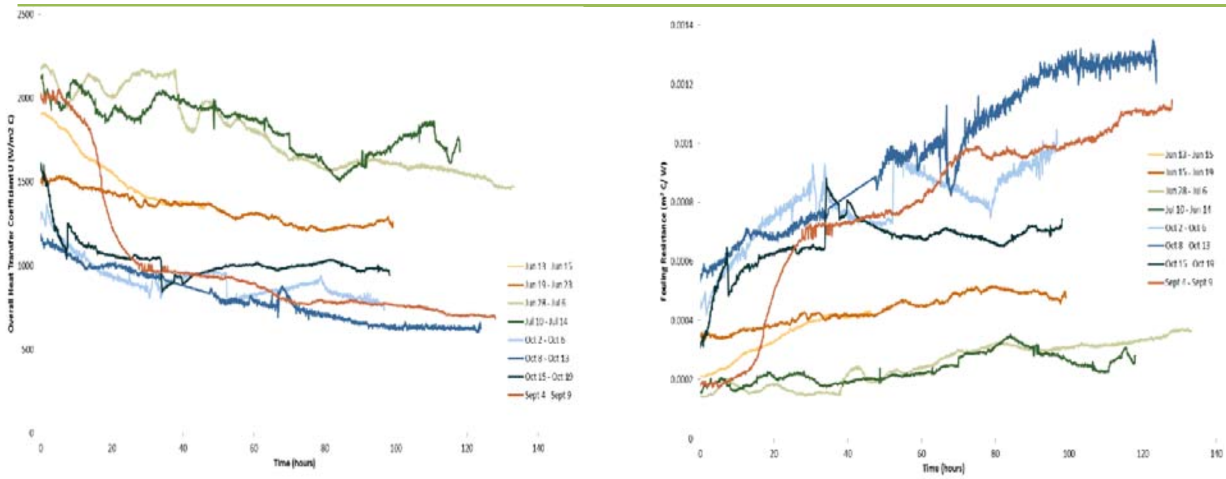
3.2 Diagnostic Evaluation of Data

From the filtered data sets general inferences can be made about the effect of different process conditions on the rate of fouling. Table 1 summarizes the process conditions for each of the isolated data sets and Figures 3 displays the overall heat transfer coefficients and fouling resistance curves respectively. As expected, the overall heat transfer coefficient and fouling resistance curves have an inverse relationship. This corresponds with theory because as the heat transfer decreases, the resistance to heat transfer increases due to the formation of foulant in the reboiler. From Table 1, Data set 1, 5, and 8 demonstrate the effect operating at a high reboiler pressure (>50 psig). Figure 3a) shows that for these three data sets, the overall heat transfer coefficient drops rapidly. On the other extreme it was also observed that operating at a low steam flow as seen in data sets 6 and 7 (<200 kg/hr), can result in poor reboiler performance. Figure 4 shows the reboiler inlet and outlet temperature for data set 6. The reboiler performance reaches the point where it is effectively useless, considering the outlet temperature is actually below the inlet temperature. The negative effects of operating at a high steam flow and a low steam flow suggest that there is an optimal operating steam flow between 200 and 300 kg/hr, correlating to a reboiler pressure of 35 to 50 psig.

To observe the effect of calcium sulphate concentration on the fouling, data sets 2 and 3 which have similar operating conditions were compared. Data set 3 with a higher concentration of calcium sulphate (0.77 g/l) demonstrates a decrease in the overall heat transfer coefficient of approximate 550 W/m^2 ^{o}C over the initial 100 hours of operation while data set 2 only showed a decrease of approximately 250 W/m^2 ^{o}C over the initial 100 hours of operation. This result corresponds with theory, which states that the solubility of calcium sulphate will decrease with a higher concentration, and will thus more readily form scale in the reboiler leading to increased fouling and lower heat transfer. However, since data is limited to only two data points every 24 hours it is difficult to make any generalizations about the effect of the concentration calcium sulphate on reboiler fouling.

Table 1: Process conditions for each isolated data sets.

	Start Date	End Date	Time Period	Steam Flow (avg)	Reboiler Pressure	Inlet Temp	[Ca^{2+}]	Cleaning
June Fouling								
Data Set 1	09-06-13	09-06-15	46:10:00	350-480 (407)	55	119	0.56	cleaned Jun 12 & Jun 15
Data Set 2	09-06-19	09-06-23	99:10:00	210-250 (222)	36	118.5	0.44	offline till 19th, cleaned Jun 24
July Fouling								
Data Set 3	09-06-28	09-07-06	195:00:00	220-330 (260)	37	119	0.77	cleaned July 6
Data Set 4	09-07-10	09-07-14	118:05:00	230-330 (305)	37	119	0.80	July 22
September Fouling								
Data Set 5	09-09-04	09-09-09	127:55:00	210-360 (258)	56	119	0.67	cleaned Sept 9th
October Fouling								
Data Set 6	09-10-02	09-10-06	102:50:00	130-230 (196)	36	119	0.63	cleaned Sept 30
Data Set 7	09-10-08	09-10-13	124:20:00	130-250 (179)	42	119	0.51	n/a
Data Set 8	09-10-15	09-10-19	98:10:00	200-300 (256)	51	119	0.69	cleaned Oct 19



a) Overall heat transfer coefficient vs time

b) Fouling resistance vs time

Figure 3: Overall heat transfer coefficient and fouling resistance of each data set.

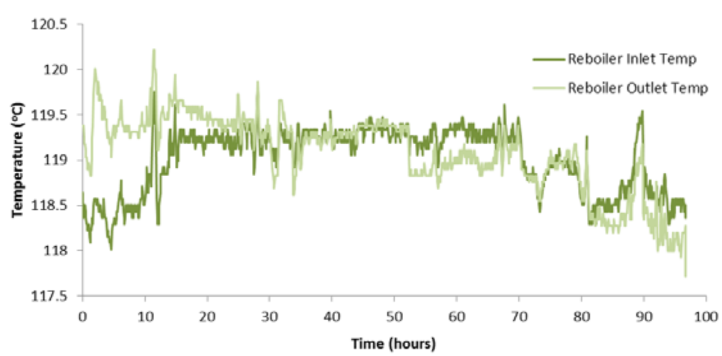


Figure 4: Reboiler inlet an outlet temperatures for data set 6 at low steam flow.

3.3 Multiple Linear Regression Model

In order to perform a multiple linear regression analysis to understand fouling tendency in the reboiler, The dependent variable for the regression analysis is the overall heat transfer coefficient in the reboiler. The overall heat transfer coefficient was selected as the dependent variable due to the fact that is a good indicator of the overall performance of the reboiler and is affected by several operating parameters including the buildup of foulant in the system. Multiple linear regression analysis was conducted using the regression analysis function from Excel's built in data analysis tool pack. Using the filtered data sets, we conducted several initial regression analyses to determine runs which independent variables were significant. The selected independent variables we decided to examine in the regression analysis are the steam flow to the reboiler, the inlet temperature of the beer and operational duration(time).

On all regression analyses conducted, several checks were done to ensure the statistical analysis was of good quality. An analysis of variance (ANOVA) was conducted with 95% confidence intervals on parameters. Parameters were also subjected to a t-test to test their significance. Residual plots and a normal probability plot were also conducted to check for any bias in the data. Interactions between regressor variables were examined the results indicate that these variables are mutually exclusive. Therefore, regression analysis was performed on each filtered data sets and an average of all the regression parameters from each model was calculated to obtain a single overall regression model to quantify the effect of regressor variables on the overall heat transfer coefficient of the reboiler. This overall regression model had a good fit with an R^2adj over 0.98. Table 2 shows the overall regression model parameters with 95% confidence intervals.

Table 2: Overall regression model parameters.

Label	Factor	Beta	Lower 95%	Upper 95%
Intercept	Initial U	-8092.44	-7635.60	-5310.24
X Variable 1	Time (hours)	-2.48	-2.09	-1.79
X Variable 2	Steam Flow (kg/hr)	3.79	3.51	3.93
X Variable 3	Beer Inlet Temp (oC)	70.84	61.05	80.63

The overall regression equation is shown below,

$$\hat{U} = -2.48X_{time} + 3.79X_{streamflow} + 70.89X_{inletTemp} - 8092.44 \qquad (3)$$

This regression model will be the basis for a predictive fouling model. This regression model can also be used to test different scenarios (i.e. various operating conditions) in order to find the best operating parameters which minimize the effect of fouling on the heat transfer of the reboiler.

3.4 Cost of Fouling

An extra cost due to the foulant buildup is incurred from three main sources: the increase in the amount of steam needed to increase heat transfer, the extra costs of having to clean the reboiler, and the loss of revenue (i.e. lack of ethanol production) during the down periods.

3.4.1 Average of Cost of Steam

As a buildup of calcium sulphate scale occurs on the wall of the reboiler, an increase in the resistance to heat transfer occurs. To counteract the reduced heat transfer, Iogen increases the flow of steam into the reboiler and directly injects some steam into the distillation column as well. To calculate the total cost of steam, the flow of steam through the reboiler and the flow of steam directly injected into the column were added up for each 5 minute interval data point. According to Iogen's Stationary Engineer, the cost of steam for the facility is around \$18.00 per 1000 lbs of steam. Therefore, the following calculation was performed for each 5 minute interval of data.

$$\text{cost of steam} = (\text{steam into rebolier} + \text{steam into column})\left[\frac{\text{kg}}{\text{hr}}\right] x \frac{2.20462\text{lbs}}{1\text{kg}} x \frac{\$18.00}{1000\text{lbs steam}} \qquad (4)$$

The comparison of the cost of steam during the baseline and fouling periods is summarized in Table 3. Therefore, it can be concluded that due to the calcium sulphate scale buildup, the cost of the extra steam that needs to be injected to maintain a constant heat transfer, is about $4.39/hour. This corresponds to about $105.36/day or a 30% increase in the cost of steam.

Table 3: Comparison of the cost of steam for baseline and fouling periods.

	Baseline Period	**Fouling Period**
Average Cost of Steam *($/hour)*	14.65	19.04
Difference of Costs Incurred Due to Fouling *($/hour)*	n/a	4.39

3.4.2 Average of Cost of Cleaning Rebolier

Iogen schedules a high pressure cleaning of the reboiler when the performance of the distillation system can no longer transfer the desired amount of heat under the desired operational conditions. This threshold is reached, on average, every one and a half (1.5) weeks.

There are labour costs associated with having the reboiler cleaned at such a high frequency. On average, the total downtime associated with cleaning the reboiler is 8 hours. Iogen hires an external vendor to pressure wash the reboiler. Cleaning the reboiler is a two-person task and the cost of labour is approximately $1500 for each cleaning (Bansal et.al.1993). The hourly cost associated with cleaning the reboiler is therefore calculated as follows,

$$\$1500\,(\text{cost of cleaning})\ \text{x}\ \frac{1}{1.5\ \text{weeks}\,(\text{frequency of cleaning})}\ \text{x}\ \frac{1\ \text{week}}{168\ \text{hours}} = \frac{\$5.95}{\text{hour}} \qquad (5)$$

During the baseline period, the reboiler and distillation column were never cleaned using a high pressure wash. Therefore the extra costs associated with cleaning the reboiler during the fouling period is $5.95 per hour.

3.4.3 Lost of Revenue

On average, Iogen's plant produces about 6000 L of ethanol per day assuming there are no shutdowns or other delays in production. Due to the downtime associated with cleaning the reboiler, the demonstration plant cannot produce ethanol. The current cost of ethanol is somewhere in the range of $3/gallon (Ethanol Prices and Pricing Information 2010). Assuming this price of $3/gallon, Equation (6) below shows the revenue made from ethanol production during a period of no shutdowns.

$$\frac{600\ \text{L}}{\text{day}}(\text{normal capacity})\ \text{x}\ \frac{254.17\ \text{gal}}{1000\ \text{L}}\ \text{x}\ \frac{\$3.00}{\text{gal}} = \frac{\$475.06}{\text{day}} = \frac{\$198.13}{\text{hour}} \qquad (6)$$

Therefore, because the reboiler is cleaned approximately once every one and a half weeks, with each cleaning resulting in approximately 8 hours of downtime, the total lost revenue resulting from the cleaning of the reboiler is $1585.02 every one and a half weeks. Therefore, the costs due to increased steam usage, cleaning the reboiler and lost revenue can be summed up and represented as an annual cost due to reboiler fouling for the year 2009 equal to $145,676.72 per year. It also would be beneficial to have some understanding of the costs of reboiler fouling in the near future if no actions are taken to mitigate the problem and if operating conditions, the cost of steam, the wage of workers, and the price of ethanol remain relatively constant. The future worth for the next five year using an interest rate of 2.5% were plotted in Figure 5. In five years time, Iogen can expect to be spending close to $165,000 toward reboiler fouling. This cost represents a significant amount of lost money that could be otherwise used toward other capital investments (opportunity costs).

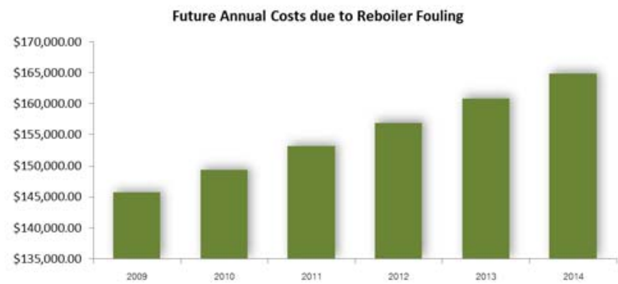
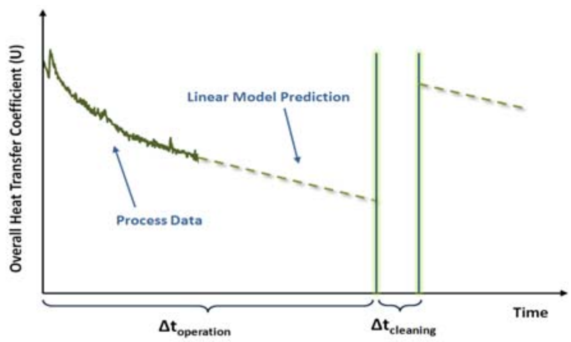


Figure 5: Future annual costs due to reboiler fouling

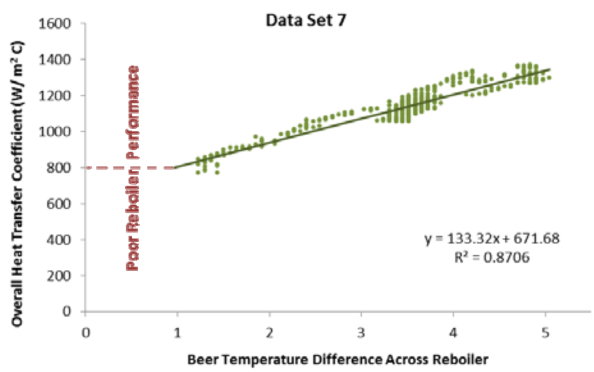
4. Mitigation Strategies

4.1 Predictive Control

One of the major problems experienced during reboiler fouling is the uncertainty regarding the time when the reboiler should be shut down and cleaned. Using a combination of current operating data and the linear regression model to forecast future decline in the overall heat transfer in the reboiler, a strategy can be implemented to better predict when the reboiler should be taken offline and cleaned. Figure 6a shows how a predictive strategy would combine operating data and a predictive model data to predict the next shut down period for the reboiler.



a) The operational data and predictive regression model



b) Critical reboiler performance

Figure 6: Predictive control strategy for overall heat transfer coefficient.

Before this predictive control scheme can be implemented, the critical overall heat transfer coefficient needs to be determined. In order to determine this coefficient, the temperature difference between the inlet and outlet beer from the reboiler was plotted against the overall heat transfer coefficient for all the isolated data sets in Table 1. Figure 6b shows this plot for data set 7 which shows that the difference between the inlet and outlet beer streams through the reboiler reaches about 1 ^oC at an overall heat transfer coefficient of approximately 800 W/m^2 ^oC. At this point, we will assume that the reboiler performance has reached a critically low performance. The predictive control model was constructed in Excel. First, the spreadsheet calculates the overall heat transfer coefficient for each input data point using the operational data surrounding the reboiler which are time, steam flow to the reboiler, reboiler steam pressure, beer inlet temperature to the reboiler and beer outlet temperature from the reboiler. Then, a linear model prediction is used to predict future changes in the overall heat transfer coefficient. These predictions are based on two user specified prediction parameters which are the steam flow and the beer inlet temperature to the reboiler. Based on the calculated and predicted heat transfer coefficient, a plot is automatically generated for visual inspection of the data (Figure 7).

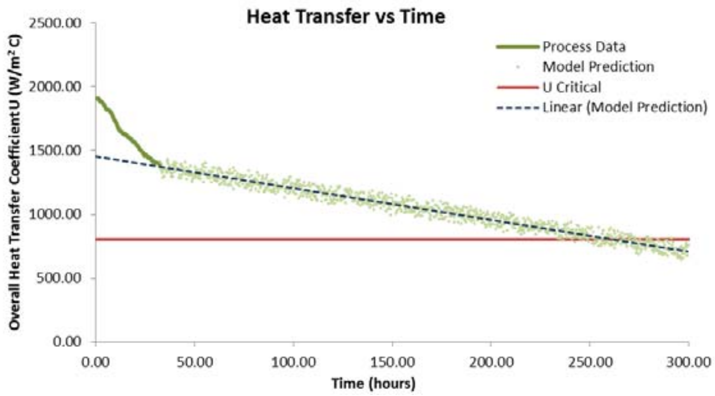


Figure 7: Excel predictive control plot.

From the above figure it can be predicted that the reboiler will need to be shut down for cleaning after approximately 260 hours of operation. The predictive ability of the model is clearly demonstrated here. With only about 33 hours of process data, the model can predict that approximately 230 hours (~9 days) later, the reboiler will need to be taken off-line for cleaning. This advanced knowledge, although not perfect, will give plant operations a better idea of when the shutdown will be required and they can then schedule operators or contractors with ample notice.

4.2 Increase Flow Rate through Reboiler

A mitigation strategy that could be implemented with a relatively low cost for reducing fouling is increasing the velocity of the beer through the column. A fluid velocity has a direct relationship with fouling reduction as it helps reduce the surface temperature in the reboiler. Therefore, as Bansal and Muller-Steinhagen discussed, increasing velocity results in decreased fouling resistance and the initial fouling rate (Sahdev and Mukesh 2010). Simple and cost effective set of solutions for increasing the velocity of the fluid through the pump are to increase the horsepower supplied to the pump and to increase the size of the impeller.

Currently, the beer stream is pumped into the reboiler using a centrifugal pump with an impeller of 8.3". For Case 1, increasing the horsepower with 8.3" impeller, the flow rate is limited to 1000 US GPM but a major caveat in this case is that the efficiency of the pump will be lowered to below 60% according to the pump curve. A low efficiency could result in vibrations, temperature rise, erosion and cavitation (Sahdev 2010). Moreover, the increase of horsepower will also increase the Net Positive Suction Head required (NPSHr) for the pump and it could present a problem if the pump was designed initially with a low tolerance for NPSHr. For Case 2, To maintain a BEP of 75% while also keeping the power demand increase relatively low, it is proposed to increase the impeller size to 9.8". According to the pump curve, this would require increasing the horsepower up to 20 hp from 11 hp (for 8.3" impeller). However, the larger impeller will result in an increased flow of up to 1200 US GPM while maintaining the same efficiency and with a small increase in the NPSHr. The cost of a larger impeller is expected to be relatively low in comparison to the savings it can present if fouling can be mitigated. Table 4 below summarizes the results of the analysis. Therefore, increasing the impeller size will have a significant impact on the velocity of the fluid and the pump operation will not deteriorate as a result of the increased flow.

Table 4: Summary of various scenarios for increasing fluid velocity.

	Current (8.3")	Case 1 (8.3")	Case 2 (9.8")
Horsepower	11 hp	12 hp	**20 hp**
BEP	75%	<60%	**73%**
$NPSH_r$	6 ft	14 ft	**10 ft**
Flow Rate	700 US GPM	1000 US GPM	**1000 US GPM**

4.3 Install Secondary Stand-by Reboiler

Due to the severity of fouling with the use of calcium hydroxide pretreatment, it is likely that fouling, although it can potentially be reduced, cannot be fully eliminated. Continuous operation is not necessarily imperative to a demonstration facility, but would be very important in a full scale cellulosic ethanol plant. In this case, it may be economically feasible to purchase a secondary stand-by reboiler. This stand by reboiler would serve as a reboiler in the event that the primary reboiler needed to be shut down for cleaning and maintenance. The stand-by reboiler could also implement a new reboiler type, which is better equipped to deal with fouling issues. Often shell and tube reboilers are used in fouling applications since they are much more common in industry, there is a lot of design knowledge that deals specifically with fouling applications. Spiral heat exchangers are another option, which greatly reduce the effect of fouling. However, a fouling exchanger can be considerable more cost.

5. Conclusions

This work presents a techno-economic analysis of fouling mitigation options for a cellulosic ethanol process. The study include a thorough understanding of the fouling mechanism, a construction of linear regression model for predicting fouling and finally presenting mitigation strategies. Theoretically, the major fouling mechanism is precipitation fouling where calcium sulphate is supersaturated and crystallizes onto the heat transfer surface after the initial nucleation phase. The rate of fouling is strongly affected by the surface temperature in the process side of the exchanger, calcium sulphate concentration in the feed and fluid velocity through the reboiler. The construction of an empirical model used for predicting fouling tendency was based on collected data over a six month period which included a 2-month base period with no severe fouling and a 4-month period where fouling was most severe. The model identified that time, steam flow to reboiler and inlet temperature of the process fluid are significant parameters and no interactions between these variables were detected. An extra cost incur due to the fouling were analyzed from three main sources: costs for steam, reboiler cleaning and lost revenue due to downtime. Three fouling mitigation strategies were proposed. The implementation of a predictive fouling control tool developed by combining the empirical regression model and real plant data to optimize the cleaning schedule of the reboiler was discussed. Also, the flow through the reboiler should be increased to decrease the rate of fouling and this can be achieved by simple pump modifications. Another mitigation strategy is the installation of a stand-by reboiler, which is an additional capital cost but may be necessary for continuous operation.

References

Bansal, B., et. al., Crystallization fouling in plate heat exchangers, *Journal of Heat Transfer*, vol 115, pp. 584-591, 1993.

Ethanol Prices and Pricing Information, *Chemical Industry News & Intelligence | ICIS.com.*, Available: http://www.icis.com/V2/Chemicals/9075312/ethanol/pricing.html>, April 09, 2010.

Malayeri, M. R., Müller-Steinhagen, H., Initiation of $CASO_4$ scale formation on heat transfer surfaces under pool boiling conditions, *Heat Transfer Engineering*, Retrieved April 03, 2010, from http://www.informaworld.com.proxy.lib.uwaterloo.ca/10.1080/01457630601066897, 2007.

Mwaba, M. G., Rindt, C. C. M., Van Steenhoven, A. A., and Vorstman, M. A. G., Experimental investigation of $CaSO_4$ crystallization on a flat plate, *Heat Transfer Engineering*, Retrieved April 03, 2010, from http://www.informaworld.com.proxy.lib.uwaterloo.ca/10.1080/01457630500458187, 2006a.

Mwaba, M. G., Rindt, C. C. M., Van Steenhoven, A. A., and Vorstman, M. A. G., Validated Numerical Analysis of $CaSO_4$ Fouling, *Heat Transfer Engineering*, Retrieved April 03, 2010, from http://www.informaworld.com.proxy.lib.uwaterloo.ca/10.1080/01457630600745160, 2006b.

Pictchard, A.M., Fouling science and technology, *Algarve, Portugal: North Atlantic Treaty Organization. Scientific Affairs Division*, print, 1987.

Perry, R. H., and Green, D. W., Chapter 11:Heat-Transfer Equipment, *Perry's Chemical Engineers' Handbook 6th edition*, McGraw-Hill, New York, 1984.

Sahdev M., Centrifugal Pumps: Basic Concepts of Operation, Maintenance, and Troubleshooting (Part-I), *Chemical Engineer's Resource*. Available: http://www.plant-maintenance.com/articles/centrifugalpumps.pdf, April 06, 2010.

Biography

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