The Canadian Society for Bioengineering
The Canadian society for engineering in agricultural, food, environmental, and biological systems.

CSBE | SCGAB

La Société Canadienne de Génie Agroalimentaire et de Bioingénierie
La société canadienne de génie agroalimentaire, de la bioingénierie et de l'environnement

Paper No. CSBE16-116

Accelerated Aging of Whisky using a Packed Bed Bioreactor

Sheldon Amichand[1], Geoffrey Beamish[1], Bryan Melchior[1], Ping Wu[1,2]

1. School of Engineering, University of Guelph, Guelph, ON, Canada, N1G 2W1
2. Ontario Ministry of Agriculture, Food and Rural Affairs, Guelph, ON, Canada, N1G 4Y2

Written for presentation at the
CSBE/SCGAB 2016 Annual Conference
Halifax World Trade and Convention Centre
3-6 July 2016

ABSTRACT This report examines the design steps that were taken in order to create a bioreactor that utilizes continuous flow in order to increase the rate at which whisky ages. Currently, whisky aging occurs through the use charred oak barrels which provides phenolic compounds when whisky is stored within the barrels. This reaction occurs due to the diffusion and provides very distinct and important flavour that is highly desired by consumers. In order to design a bioreactor that would be able to accelerate this aging process a variety of bioreactors were examined such as a plug flow bioreactor and a packed bed bioreactor. Once a bioreactor was chosen, we designed and constructed our bioreactor so that we could began testing our hypothesis and the effectiveness of the system. Multiple trials were completed in order to check the change in absorbance throughout each trial in comparison to both the control and prior samples. In addition, mass transfer calculations were completed in order to have an idea of what magnitude the convective mass transfer had on the aging of our system. Our whisky, was then tested in comparison to a control in order to identify if there was any noticeable difference in the bioreactor aged product.

Keywords Bioreactor, Whisky, Accelerated, Aging, Packed Bed, Spectrophotometry, Mass Transfer

INTRODUCTION The production and consumption of alcohol has played an important role in the culture and society of humans since its discovery thousands of years ago. It is believed that alcoholic beverages first began as a mistake, fruits rich in fermentable sugars were left in sealed vessels with yeast for long enough for a fermentation to take place. This basic form of fermentation has been documented up to 10,000 years ago. Similar products have even been observed in the animal kingdom with the ingestion of semi-fermented fruits by various animals.

The development of distillation has been documented as early as the second millennium BCE by the Babylonians for the production of perfumes. The earliest records of the distillation of alcohol place its conception in Italy around the 13th century, at this time alcohol was distilled from wine. The practice of distillation spread to Scotland and Ireland around the 15th century where the production of whisky was popularized and spread out to the masses. At this time the whisky produced was not aged or diluted, this raw product was very potent and lacked much of the smooth flavors noted in today's whiskys.

From the 15th century whisky grew greatly in popularity, production was spread across multiple locations and the volume produced rose greatly. As the production rose so did the taxation of the product, several English taxes were introduced until a breaking point was reached in 1725 with the introduction of the English malt tax. These taxes made the production of whisky on a mass scale uneconomical thus forcing production into a series of illegal, underground stills. Stills were hidden and fear of persecution forced them to operate at night under the light of the moon giving them the name of moonshine. It is estimated that at this point in history around fifty percent of whisky produced was done so illegally in the moonshine style.

As time progressed whisky grew in popularity and its production was transported around the world on the backs of whisky lovers. Many governments struggled with the control of whisky, forcing production underground numerous times over the course of history. To

this day the high taxation of alcohols drives an illegal production market estimated at fifty-six million liters of alcohol in Ontario alone.

From traditional fermented beverages in clay vessels to the highly controlled fermentations and distillations of today, the production of alcohol for beverages has progressed along with the furtherment of modern technologies. Today Canadian whisky makes up 14.7% of alcohol sold or thirteen million liters at LCBO stores. This volume correlates to a 400 million dollar market in Ontario alone.

PRODUCTION METHODS Whisky starts from a heated slurry of water and grains (typically a mixture or wheat, rye, corn and barley). These grains are mixed into the water and heated as to allow for the partial digestion of the complex sugars within the grains. The heat allows for natural enzymes within the grains to be activated and to break the complex starches within the grains into simpler sugars. At this stage additional enzymes can be added in order to allow for a more complete breakdown of the starches into simpler sugars. The more complete the breakdown of starch is the easier it will be for the fermentation to take place later on.
The product of the mashing is called the wort, this dark liquid is what is used in the fermentation stage of production. The wort is transferred into the fermentation vessel, in which brewers yeast is added in order to convert the simple sugars within the wort into ethanol. The length of the fermentation varies depending on different factors including the temperature, humidity, pH and availability of oxygen.

After the fermentation takes place the result is an alcoholic substance similar to beer. This beer like substance lacks many of the desired favours of beer as in order to produce a desirable product the effects of distillation on the favours of the whisky must be considered. The fermented product is then moved to a distillation column. Distillation is used in order to evaporate desired compounds from a mixture containing numerous compounds. The fermented product is raised in temperature slowly, the distillation column has a condensing element in order to capture the evaporated liquids from the mixture and condense them into a separate vessel. The resulting alcohols from the

distillation process are separated by the times they were obtained from the column. The result from this stage is highly concentrated ethanol.

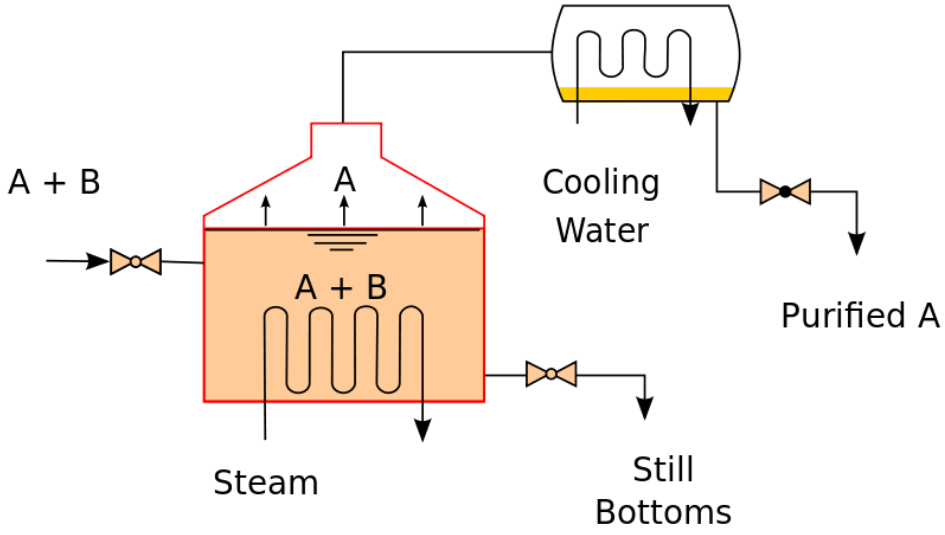

Figure 1. Modern batch distillation process (Distillation, 2016)

This concentrated ethanol must be diluted to a lower percentage before being stored for some time before they are available for retail. The duration of stay within the barrel depends in the quality of the product. The longer the alcohol stays within the barrel the more its flavours are imparted on the alcohol, creating a more desirable product.

AGING METHODS Of the production of whisky, no step is costlier than that of aging. In order for the product to be properly aged the aging vessel must be kept at very specific conditions in order to insure that the product achieves its desired flavours and colour. At large scale whisky is often stored within large wooden barrels of up to 80 liters in volume. These barrels are often highly costly, making them a significant cost to start-up distilleries. In an attempt to make a more cost effective product for start-up distilleries different technologies have evolved in order to produce a similar aged product for a cheaper price and at an accelerated rate.

One promising new aging technology implores wooden spirals as a replacement for barrels. These spirals are placed within a contained and after some time is allowed to pass, sold to customers. The shape of the spiral allows for a high surface area per volume which causes the spiral to be aged at a rate faster than that experienced in

traditional barrel aging. The measurement of surface area per volume can be used to accurately quantify the rate of aging in diffusion based aging methods. The more area available for the unaged whisky to make contact with allows for more interaction between the spiral and whisky thus aging at a faster rate.

The greatest cost associated with aging is the time required to produce an aged product. The tight requirements to age the product demands energy intensive equipment to adhere to its strict climate guidelines. Long term operation of this equipment can be extremely costly to the extent that there exists a window for the invention of a novel accelerated aging system.

In a case study using the same climate control systems a comparison of traditional and novel aging methods were compared. In this theoretical case study a 20L climate control system was run for differing amounts of time in order to produce products of comparable ages. An accelerated system utilizing a pump along with a cooling system can produce a more cost competitive produce as shown in the figure below.

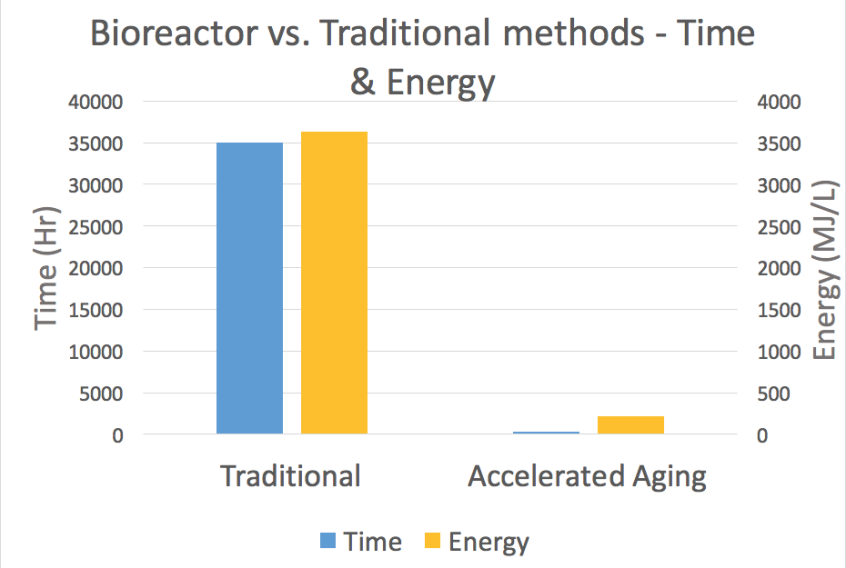

Figure 2. Cost and Energy comparison of traditional and accelerated aging

The aging process takes place as compounds housed within the wooden barrel seep out into the whisky. This transfer of mass can be imparted by means of convection or diffusion. In the case of diffusion the transfer relies on a concentration gradient to drive

the particles from a region of high concentration into a region of low. In driving the particles from high to low concentration an equilibrium can be reached in which there is a uniform concentration of particles throughout the container.

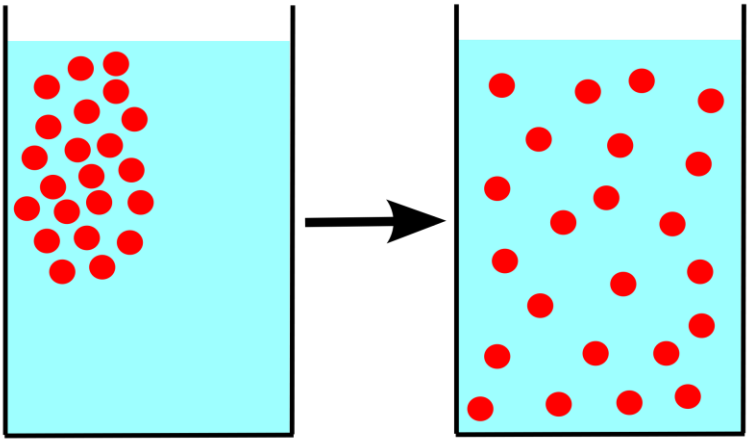

Figure 3. Diffusion illustration (Diffusion, 2016)

In the case of whisky aging the concentration gradient within the barrel is driven by slight changes in temperature within the place of aging.

In the case of convective mass transfer a fluid is circulated past a solid, this flow acts an effective driving force that allows for mass transfer to occur. The addition of gradients by which to drive mass transfer can combine to produce a more effective method of aging. In the case of whisky a convective element like a pump to circulate whisky, combined with a large surface area for the whisky to pass by can create a situation ideal for rapid mass transfer.

BIOREACTOR TYPES AND CURRENT LANDSCAPE When analyzing the current landscape for mass transfer applications in the whisky and spirit industry most of the current bioreactors are setup in a batch reactor setup. This is the case as spirits and other alcoholic beverages such as beer require very exact conditions in order to survive and have the proper chemical reactions occur.

Our first idea was to force the whisky through the wood at a faster rate while circulating it through the system. We believe this could be achieved by utilizing a plug flow bioreactor. Plug flow bioreactors utilize the force of a flowing medium typically a liquid, to flow through a pipe and reach a blockage or plug which prevents medium from freely flowing through or around. In order to pass it and continue flowing, the medium reacts with the material in the plug and forms a gradient with respect to the distance travelled through the plug. As the distance travelling through the gradient increases the rate of reaction decreases. The problem that this type of reactor faces however, is that it requires a very strong and precise system that would be difficult to build given our limited budget and need to switch out our wood product between different trials. This would cause a problem as the samples may differ in size and shape slightly would not provide maximum usage of the potential of a plug flow bioreactor.

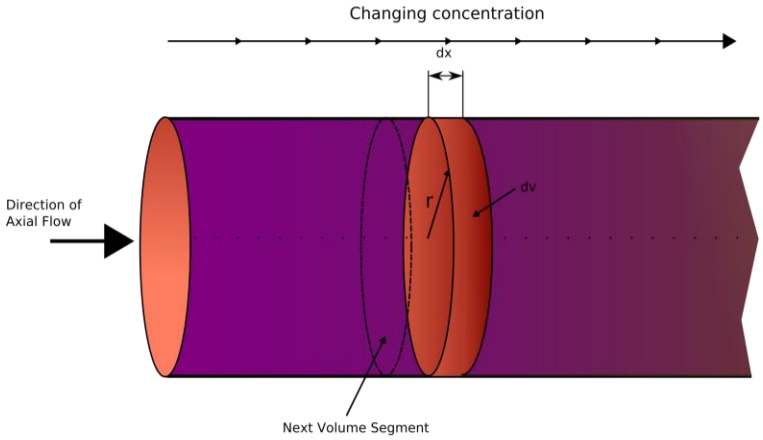

Figure 4- Basic diagram of a plug flow reactor (Plug Flow reactor model, 2016)

The next type of bioreactor that we attempted to design our project on was packed bed bioreactor. A packed bed bioreactor utilizes a porous layer that is typically a catalyst for a desired reaction inside of a reaction chamber. This type of bioreactor is typically very effective in a wide range of chemical and pharmaceutical products. Typically they are utilized to catalyze gas reactions utilizing solid catalysts, however the theory of running a fluid through a solid bed of particulates in order to catalyze a reaction seemed very close to the application we were designed towards. Some of the problems that occur with packed bed reactors are focused around the heat transfer and

mass transfer that occurs within the reaction chamber and ensuring that an optimized reaction is occurring. If the system is designed poorly excess heat due to poor heat transfer design or poor mass transfer due to poor flow may occur.

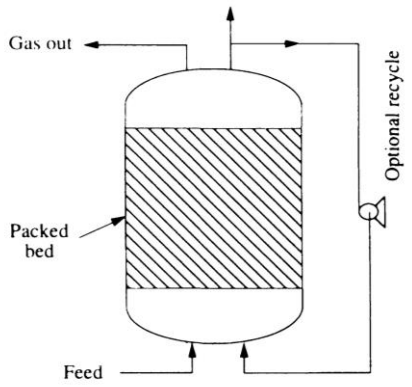

Figure 5- Basic diagram of a packed bed reactor (Packed bed reactors, 2016)

The last bioreactor that fit out our specifications was a fluidized bed bioreactor. This type of bioreactor contains a two-phase mixture of particulate solid and material and fluid. It is commonly used in many industrial applications such as carbonization and the gassing of coal. The benefit of this bioreactor types is that it provides a high surface area to volume so chemical reactions are encouraged to occur as well as high levels of intermixing of the particulate phase.

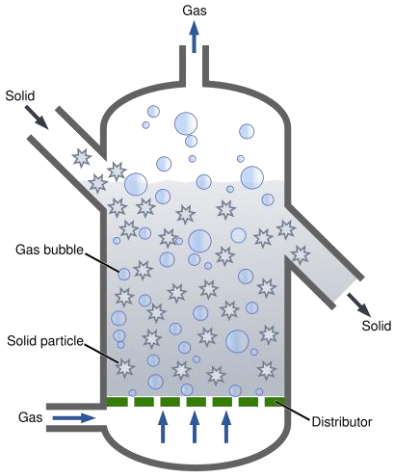

Figure 6. Fluidized bed reactor (Fluidized Bed, 2016)

Currently, distilleries including our industry contact and provider Dixon`s Distillery utilize barrels as their main means of aging their whisky. Through this method they place the unaged whisky into charred oak barrels in order to begin the aging process. In Canada, whisky is required to stay within a barrel for a minimum of three years before being able to be sold as Canadian whisky. Other countries have much less strict rules on this besides a few exclusive cases such as Scotch and Bourbon which have very exact standards. With this design however, adaptations could be made to circulate the whisky within the barrel at a low flow rate in order to maintain the barrels structural integrity but provide the additional convective mass transfer. Another application for distilleries such as Dixon`s, would be using a bioreactor to give the whisky a kick-start and equivalently age it to an older product before placing it in the barrel for three years so that the product produced at the end is of a higher quality than a regular three year whisky.

EXPERIMENTAL SET-UP & BIOREACTOR CONSTRUCTION

Looking at the simplified P&ID diagram on the right, the basic concept of the system can be seen. The flow is indicated by the arrow on the pump symbol. The dotted and solid lines connected to the pump are to represent that the system is being kept in a cool environment. There are drain and fill valves on the top and bottom of the system respectively. The real system is shown in figure 10 below. Ball valves were used over

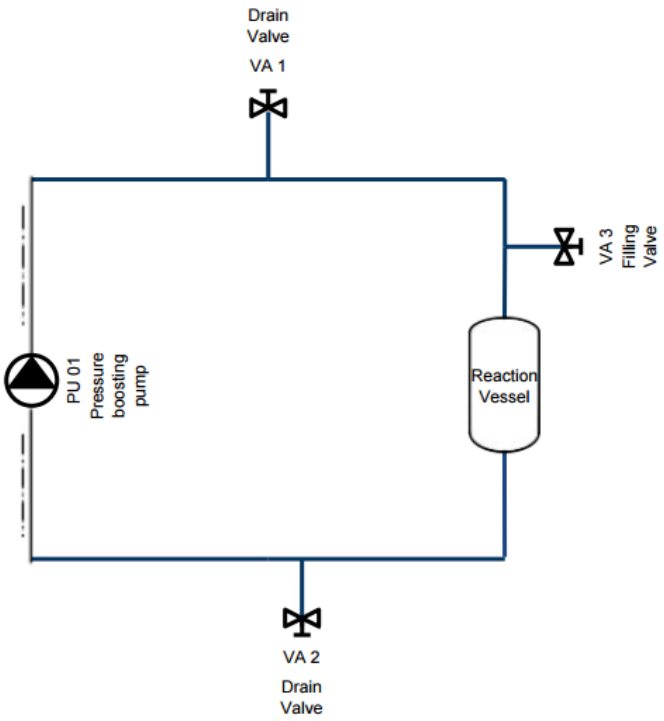

Figure 7. P & ID diagram of the experimental bioreactor

globe valves as they introduce less friction losses than globe valves. The pump is a pressure boosting pump that is commonly used in household applications like boosting shower pressure. The reason that this pump was selected over other pumps was because it is made entirely of metallic components. Many other pumps at this price point feature plastic impellers, this plastic could have leached into the alcohol effectively ruining the product. The majority of the tubing used in this reactor was ½ inch diameter copper piping. This excludes the reaction chamber which was made from a much wider copper piping. Inside of the reaction chamber has a section of ¾ inch diameter copper piping. The purpose of this will be explained in depth later within this report. It can be seen that the reaction chamber section requires numerous fittings to merge everything together.

Initially, the thought was to run this system at room temperature. Upon initial testing the system get too hot, maxing out the recommended operation temperature in a matter of minutes. For example, when the temperature of the pump was measured, it was in excess of 50°C. In order to overcome this effect, the system was placed in a walk-in

cooler that had a maintained temperature of 4°C. To make sure that the pump was not overheating within the cooler, various temperatures were taken of the pump. The temperature readings within the cooler never got above 40°C. This was important because the pump itself had a maximum heat rating of 40°C. To further ensure that the pump would not overheat, a heat sink was placed on the rear end of the pump to aid in further heat dissipation.

Another issue that was found was the optimal location of the wooden spiral. Initially the spiral was hanging inside of the reaction chamber. However, after the first batch was run, it was observed that the colour was not as dark as expected. It was determined this location for the wooden spiral was not effective and thus had to be changed. One further complication was that the pump was not self-priming. This meant that before flow was started, the pump had to be primed. This is explained further later in this section of the report.

This reactor is a continuous flow packed bed reactor. This means that the whisky is to flow through the system continuously whilst going through a charred wooden spiral which is the packed bed. The pump is in place to circulate the whisky through the reactor. The wooden spiral is placed inside of the ¾ inch diameter pipe mentioned before. This method ensures that the whisky is being forced through the wood spiral, which in turn leads to increased mass transfer between the whisky and wooden spiral. Operation of the reactor is simple as there are few steps required to operate it. First, the wooden spiral must be placed within the ¾ inch diameter pipe. This must be done when the reaction chamber is disconnected. Once the wood spiral is within the reaction chamber, re-assemble the section by screwing the pieces together. Next, the whisky needs to be filled into the fill valve. Around 650 mL filled the system due to our dimensions of the copper piping. Next, the pump needs to be primed before the whisky will begin circulation. To do this, the pump must be turned on and then the drain valve after the pump must immediately be opened. This drain valve must be opened fully and around 100 mL of whisky must be drained out to initiate the flow of whisky. When performing this procedure, the fill valve must be opened so that the flow will initiate. If

this fill valve is not opened during this step, then the flow will not start. As seen in figure 11 the pump is being primed by opening the drain valve immediately after the pump is turned on. This was required as the pump that we had was not self priming, therefore the need to prime it manually.

Once the flow of whisky has been started, close all valves and run for the desired time. Once the desired time is complete, the reactor must be drained. To do this, open one drain valve and place container under it. As with priming, the fill valve should be opened during this process to speed up the draining process.

Once the whisky seems drained, close the drain valve and open the other drain valve to drain that side of the reactor. Once the system is completely drained, the wooden spiral must be removed from the reaction chamber. This can be done by unscrewing the reaction chamber and simply removing the wooden spiral. This process is shown in figure 12 to the right. If the system is being stored, then it should be filled with water or unaged whisky so that corrosion of the copper piping does not occur.

Figure 8. Colour change over time Taken from multiple samples

Numerous samples of 10 mL were taken at various times throughout the experiment. The samples were taken from the fill valve through the use of a pasteur

pipette. These samples were then placed in the spectrophotometer to obtain the absorbance curve from 400nm to 800 nm. For the first trial, samples were taken at 90 minute intervals to see the colour change at different time increments. In order to simulate fair results, a control experiment was setup alongside the reactor setup. The control was simply a wooden spiral placed inside a bottle of 650 mL. This bottle was then placed inside the same cooler that the reactor was placed in. Samples were also taken at 90 minute intervals and compared against the reactor samples. This was done to see if the reactor had darker colour over the same time period. As shown in figure 9 it can be seen how the colour of the samples changes over time.

The initial design featured stainless steel as the primary material for the construction of this bioreactor. Stainless steel was selected as it is food safe and widely used in the food industry. It was then determined that stainless steel would be too expensive as an option for this project. After consulting with some industry experts, it was agreed upon that copper would be the primary building material for the bioreactor. This material is food safe and removes sulphur from the whisky.

Figure 91. Spiral aged whisky (Barrel Aged In a Bottle - Oak Infusion Spiral, 2016)

Copper was used as it provided a cheaper alternative to stainless steel and glass and is used within industry for different distilling processes. In addition, lead-free solder should be used for the soldering of all joins and fittings. This system has a width of 40 centimeters, length of 50 centimeters, and an overall height of 60 centimeters. This system is capable of running 650 mL of fluid. Finding a suitable pump for this

application took a long time as many of the pumps contained materials that could not be used with alcohol. Most pumps are made from plastic materials that would likely leach into the alcohol. After searching for a while, a suitable pump was found. This pump is made from all metallic components and would work well with alcohol. This particular pump is used in household applications for boosting the flow of water. The materials list for the construction of this reactor is in the Appendix.

When this method is compared to industry, there are a few crucial differences that can be observed. First, as mentioned whisky is typically aged within barrels. This method is proven as it is widely used and has shown to be effective. However, barrel aged whisky takes a long time to age. This is because the barrels have such a large volume and majority of that volume does not touch the charred sides of the barrel. This was shown in figure 5 as there is only mass transfer occurring through diffusion. Because this process takes so much time, there are other methods being tried to see if the aging time can be reduced. For example, spiral aging is now being used within industry.

There are multiple variations in this method. The first variation is simply putting a small wooden spiral within 750 mL of unaged whisky and allowing it to sit. A picture of this method is shown in figure 15. This spiral is allowed to sit within the product for a 4 month period, and then it is sold. The other variation of using wooden spirals is by placing a number of bigger wooden spirals within an actual barrel and allowing it to sit. Typically this method is aged for around 3 months and then sold. The thought is that multiple big wooden spirals would significantly increase the mass transfer within the barrel, thus speeding up the aging process. A picture of this method is shown in figure 16.

RESULTS

After the accelerated aging process was allowed to run for a set period of time the fluid was recovered from the reactor and given some time to settle. After a sufficient settling time samples were taken from the settling vessel and tested using different analysis methods.

SPECTROPHOTOMETRY

In the analysis of whisky spectrophotometry serves as a quantitative measurement of the transmission properties of a material as a function of wavelength. When utilizing the wavelengths of 400 to 800 nm the visible light spectrum can be obtained. In aged whiskys the colour of the whisky is very important to consumers as it is believed that the darker a whisky is the more aged it must be.

In the estimation of the age of the whisky samples both the slope from 400-600 nm and the maximum absorbance was used in order to determine the relative age of the whisky samples. From literature it was found that the slope of the abs vs. wavelength plot in the region of 400-600 nm can be used in order to estimate the approximate age of the sample. For traditional aging methods, this method works well as the slope is uniform in this region but in our samples it was determined that within the region of 400-600 nm there existed a peak in all accelerated aged samples. This peak threw off the slope in this region making it seem lower than it should be. In order to quantify the aging of samples over time the slope of the 400-600 nm band was taken at set increments and plotted against time. The slope of this plot is units of (abs/wavelength)/time can then be thought of as the aging rate of the whisky and be used to compare aging methods.

Figure 10: Traditional spectrophotometric curve

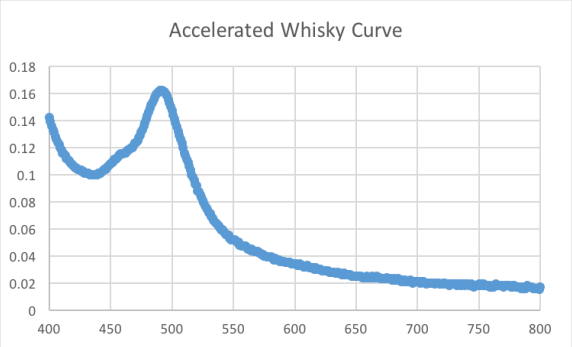

Figure 11: Accelerated aging spectrophotometric curve

The table below shows the results from three separate reactor trials along with a control trial. This data is then compared in the statistical portion following it to show the inaccuracy in the data caused in part by the peak behaviour explained above. The raw data and charts for all of this data can be found in the appendix.

Table 1 Slope of each samples absorption curve

Sample	Slope-Age (abs/wavelength*time)
Control (B)	0.000005
Reactor Sample A	0.00001
Reactor Sample X	0.0000002
Reactor Sample Y	0.0000004

Table 2: Statistical Variation between each samples and the control

	Bioreactor	Control
Average	0.0000035	0.000005
Standard Deviation	0.0000046	-
Percent Variation	129%	-

From this data we can see that there is are great variations in the data obtained. In an effort to account for this tendency of variation the maximum absorbance reading was counted over the entire range of 400-800 nm. In all obtained data sets this maximum observed at the wavelength of 400 nm, serving as a baseline for comparison.

Table 3: Absolute absorbance of each samples absorption curve

Sample	Abs-Age (max-abs/time)
Control (B)	0.0029
Reactor Sample A	0.0073
Reactor Sample X	0.0053
Reactor Sample Y	0.0097

Table 4: Absolute absorbance between each samples and the control

	Bioreactor	Control
Average	0.0074	0.0029
Standard Deviation	0.0018	-
Percent Variation	24%	-

From the statistical analysis conducted above we can see that the method of quantification using the maximum absorbance is more accurate than that of the slope. When both of these methods are compared to each other it can be seen that on average the reactor is about two times faster than the control method.

Samples were provided by industry at the four month mark. These samples were aged in a similar method to that of the control but at a larger scale. Samples were tested by the same measures as the previous samples in order to determine the effective age relative to samples obtained from the reactor.

Table 5: Comparisons of time slope of absorption curves and max absorbance of samples, control and Industry samples

Sample	Time Aged (Hr)	Slope-Age (abs/wavelength*time)	Abs-Age (max-abs/time)
Control (B)	48	0.000005	0.0029
Industry Control	2190	0.0033	1.02
Reactor Sample A	48	0.00001	0.0073
Reactor Sample X	48	0.0000002	0.0053
Reactor Sample Y	48	0.0000004	0.0097
Industry Barrel	2190	0.0009	0.287

The graph above displays the time aged for each sample as well as the industry control and an industry barrel aged sample. These samples are compared both to the slope age which is taken from the absorbance graph that was created for each sample divided by the wavelength and time for the wavelengths of 400-800 nm. Additionally, the absorbance max value from our range which occurs at 400 nm was divided by the time in order to give a value that reflects the maximum absorbance rating in the 400-800 nm wavelength range. From these samples we can see that for the reactor to produce a product comparable to those provided by industry the samples must be aged beyond the forty-eight hours they were circulated within the reactor for.

MASS TRANSFER

As stated early in the report the process of aging whisky relies on the mass transfer of the phenolic compounds found within the charred oak wood being diffused into the whisky. In typical barrel aging diffusion occurs with the charred surface of the barrel that provides whisky with its distinctive woody flavour and aroma. Small temperature and specific gravity gradients throughout the volume of the barrel help circulate the aged product with the unaged product. In terms of mass transfer, the transfer of these compounds occurs through the process of diffusion. Diffusion occurs due to a species concentration gradient which in this case is caused by the high concentration of phenolic compounds on the surface of the charred wood and the relatively low

concentration in the whisky. However, by utilizing our experiments setup the whisky will no longer only slowly diffuse and circulate based on the concentration gradient but will be circulated with the use of the pump creating a higher exposure of whisky to the surface off the charred oak. In order to maintain continuity of our experiments we compared the whisky that was created by our bioreactor with a control that had the same volume and was held at the same temperature for the same amount of time with the same ratio of surface area to volume. It was also compared to a finished product supplied by our contact Dixon's Distillery which aged it for three months with the same volume to surface area ratio but at room temperature instead of the walk in chiller temperature that we were confined to.

CALCULATIONS

Diffusion Mass Transfer

This section details the steps taken to calculate the rate of mass transfer that occurs when whisky is subjected to charred oak and the mass transfer that occurs in order to age it. This type of mass transfer is the bases of aging spirits and occurred in both our control and our bioreactor. In order to calculate values in the mass transfer calculations, assumptions must be made in order to simplify the equations. The two most assumptions that are made when doing the following calculations are that the mass diffusion is constant and steady operating conditions exist, this would include no large fluxuations in temperature or pressure.

Mass Diffusivity, **D**: $7*10^{-8}$ m^3/s
Surface area of Wood Spiral, A_W: 0.004572 m^2
Density of 3 month aged product from Dixon's $\rho = 882.95$ kg/m^3
Density of unaged whisky $\rho_i = 823.4$ kg/m^3

$$\dot{m}_{conv} = -\left(\frac{823.4\ kg}{m^3}\right) * \left(7 * 10^{-8}\frac{m}{s}\right) * (0.004572\ m^2) * \frac{d * \left(\frac{823.4}{882.95}\right)}{dx} = 2.6352 * 10^{-7} kg/(m * s) \quad (1)$$

Convective Mass Transfer

This section will detail the steps taken in order to calculate the rate of mass transfer for the convective mass transfer that occurred within our bioreactor.

Diameter of spiral, $\mathbf{d_s}$: 15.24 mm
Diameter of pipe, $\mathbf{d_p}$: 19.05 mm = Characteristic length $\mathbf{L_c}$
Kinematic Viscosity, v: $1.8*10^{-6}$ m^2/s
Mass Diffusivity, **D**: $7*10^{-8}$ m^2/s
Flow rate, **Q**: 0.0002624 m^3/s
Surface Area of Spiral = 0.004572 m^2
$\Delta\rho_{A,e}$ = Density of 3 month aged product from Dixon's - Density of 48 hour sample from reactor
= 882.95 kg/m^3 -857.75 kg/m^3 =25.2 kg/m^3
$\Delta\rho_{A,i}$ = Density of 3 month aged product from Dixon's - Density of unaged whisky
= 882.95 kg/m^3 -823.4 kg/m^3 = 59.55 kg/m^3

$$Area\ of\ Flow: A_T = A_p - A_s = \pi d_p - \pi d_s$$
$$= \pi * (0.01905\ m)^2 - \pi * (0.01524\ m)^2 = 4.10 * 10^{-4} m^2 \quad (2)$$

$$Velocity, v = \frac{Q}{A_T} = \frac{0.00026242\ m^3/s}{4.10 * 10^{-4} m^2} = 0.6393\ m/s \quad (3)$$

$$Schmidt\ Number, Sh = \frac{Kinematic\ Viscosity}{Mass\ Viscosity} = \frac{1.8 * 10^{-6} m^2/s}{7 * 10^{-8} m^2/s} = 25.71 \quad (4)$$

$$Hydraluic\ Diameter, D_H = \frac{4 * A_P}{Perimeter} = \frac{4 * 1.14 * 10^{-3} m^2}{0.0598\ m} = 0.0762m \quad (5)$$

$$Reynold\ Number, Re = \frac{v * D_H}{Kinematic\ Viscosity} = \frac{0.6393 \frac{m}{s} * 0.0762m}{1.8 * 10^{-6} m^2/s} = 26960 \quad 6)$$

$$Sherwood\ number, Sh = 0.3 + \left(\frac{0.62 * 26960^{1/2} * 25.71^{1/3}}{\left[1 + \left(\frac{0.4}{25.71}\right)^{2/3}\right]^{1/4}} \right) * \left[1 + \left(\frac{26960}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} = 349.7 \quad (7)$$

$$h_{mass} = \frac{Sh * D_{AB}}{L_c} = \frac{349.7 * 7 * 10^{-8} m^2/s}{0.01905\ m} = 1.285 * 10^{-3} m/s \quad (8)$$

$$\dot{m}_{conv} = (1.285 * 10^{-3} m/s) * (0.004572\ m^2) * \frac{\Delta\rho_{A,e} - \Delta\rho_{A,i}}{ln\left(\frac{\Delta\rho_{A,e}}{\Delta\rho_{A,i}}\right)} = 2.35 * 10^{-4} m/s \quad (9)$$

COMPARISON OF MASS TRANSFER

As seen from the calculations above the convective mass transfer that is present in the reactor provide a very significant increase in the total mass transfer in comparison the diffusivity mass transfer is very small in comparison and orders of magnitude smaller than the convective mass transfer. This makes sense as there was a very noticeable colour difference between the control sample and the 48 hour sample. Additionally, after a long period of time the mass transfer rate of just the diffusivity should be able to reach that of the bioreactor mass transfer. Additional research needs to be done in order to determine the exact diffusivity of the charred oak in whisky at it diffuses.

SENSORY EVALUATION

After completing our first test trial with our whisky, we were able to perform a sensory evaluation comparing our control and our reactor samples through the use of a triangle test. A triangle consists of serving a participant three samples of the product two of which are from the same source while the other is from a different source and having them identify the different sample. It does not matter if the participants are given 2 reactor samples and 1 control sample or 1 reactor sample and 2 control samples as the goal is not necessary to identify what sample is which but instead to focus on the differences between them. For sensory evaluation we gave samples to twenty different people with a variety familiarity with whisky and has them attempt to identify the difference. Using the equation: $X^2 = \Sigma(|O - E|)^2/E$ where O is the observed number of correct responses and E is the expected number of correct responses if guessed by random selection.

n=20

O_c= Observed number of correct responses=12

E_c= n(1/3)=(20)(1/3)=7
O_I= observed number of incorrect responses=8
E_I= n(2/3)=(20)(2/3)=13
α= risk of a Type I error=0.10
From a chi- square distribution chart $X^2_{1,0.10}$ = **2.706**
X2 = $((12-7)^2)/7$ = **3.57**

Since this number is greater than the expected 2.706 this shows that there is a significant difference from the control. Furthermore, after our first trial we adjusted the location of our wood spiral and obtained better results in observed spectrophotometry and would most likely showed even higher correct responses if tested against the control again.

CONCLUSION

In summary, this report details both the current technology that is used to age whisky as well as an application of bioreactor usage in order to accelerate the aging process. By utilizing this bioreactor and process we will be able to improve the flavour of the product produced but also change the way in which whisky producers create their whisky. By taking a more scientific and engineering approach to aging and increasing the chemical reactions in the aging process, a better understanding of flavour will be produced. This research also provides a starting point for other spirits that age the product in barrels or rely on diffusive mass transfer in order to improve flavour. Moving forward with this product there are many areas in which this research can expand into from creating a pilot scale version to additional testing methods to changing variables such as the size and shape of the wood, the surface area to volume ratio and temperature. This research is only just the first step towards a promising advancement in whisky and spirit technology.

REFERENCES

Annual Report 2014–15. 2015. LCBO. Available at: http://www.lcbo.com/content/dam/lcbo/corporate-pages/about/pdf/LCBO_AR14-15-english.pdf . Accessed 21 April 2016

Barrel Aged In a Bottle - Oak Infusion Spiral. 2016. UntoldGoods LLC. Available at: http://untoldgoods.com/products/barrel-aged-in-a-bottle-oak-infusion-spiral. Accessed 21 April 2016.

Diffusion. 2016. Wikipedia. Available at: https://en.wikipedia.org/wiki/Diffusion. Accessed April 21,2016

Distillation. 2016. Wikipedia. Available at https://en.wikipedia.org/wiki/Distillation. Accessed April 21,2016

Filippone P. 2016. Whiskey History - The History of Whisky: About.com Food. Available at: http://homecooking.about.com/od/foodhistory/a/whiskeyhistory.html. Accessed 21 Apr. 2016.

Fluidized Bed. 2016 Thermopedia. Available at http://www.thermopedia.com/content/46/. Accessed 21 April 2016

Foley, A. 2016. What Is a Packed Bed Reactor: Comsol. Available at https://www.comsol.com%2Fblogs%2Fpacked-bed-reactor%2F. Accessed 21 April 2016

Food and Drug Regulations (C.R.C., C. 870). 2016 Legislative Services Branch. Available at: http://laws-lois.justice.gc.ca/eng/regulations/C.R.C.,_c._870/section-B.02.020.html. Accessed 21 April 2016.

The Whisky Success Story. 2016. Whisky.com. Available at: https://www.whisky.com/history.html. Accessed 21 April 2016

Tubular Reactor or Plug Flow Reactor. 2016 Bioreactors for Metal Bearing Wastewater Treatment. Available at: http://www.metal.ntua.gr/~pkousi/e-learning/bioreactors/page_07.htm. Accessed 21 April 2016

Zandona E. 2013. Whiskey vs Whiskey: Dictionaries & Definitions : EZdrinking. Available at: http://www.ezdrinking.com/ezdrinking/2013/4/30/whiskey-vs-whisky-dictionaries-definitions. Accessed 21 April 2016

Appendix

Trial Plots (All plotted against reaction time)

The graphs seen below depict aging metric in relation to absorbance values time periods throughout testing. The first four plots depict the slope of the absorbance curve that were created from the absorbance values between 400 and 600 nm for each of the sample points taken throughout the aging process. The following four graph depict the maximum absorbance within the same range at each sample time throughout the aging period.

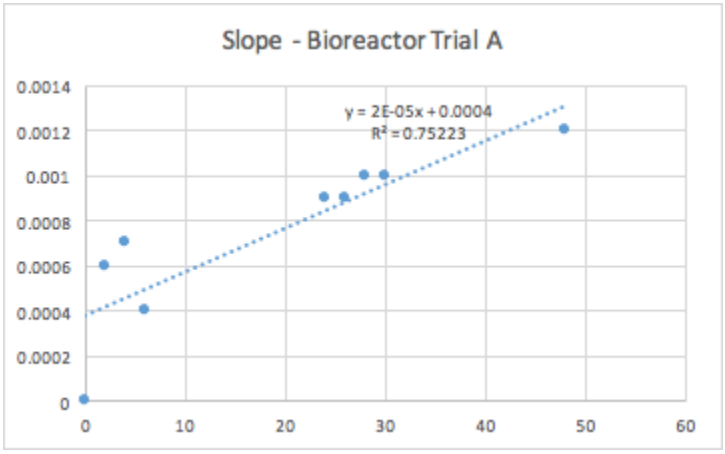

Figure 12: Absorbance slope vs Time for Bioreactor Trial A aged over 48 hours.

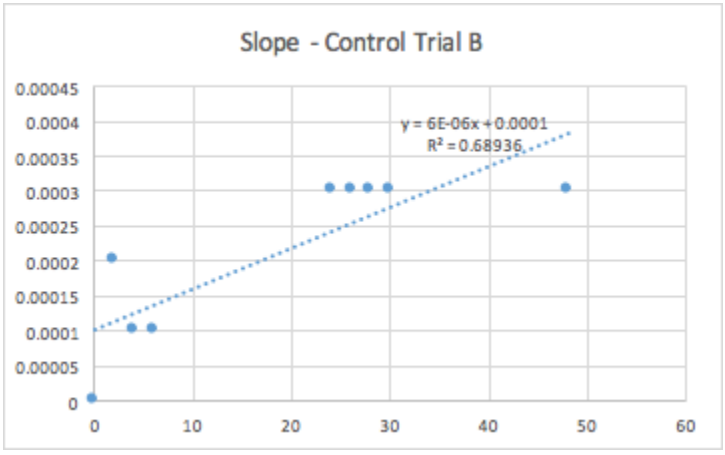

Figure 13: Absorbance slope vs Time for Control Trial B aged over 48 hours.

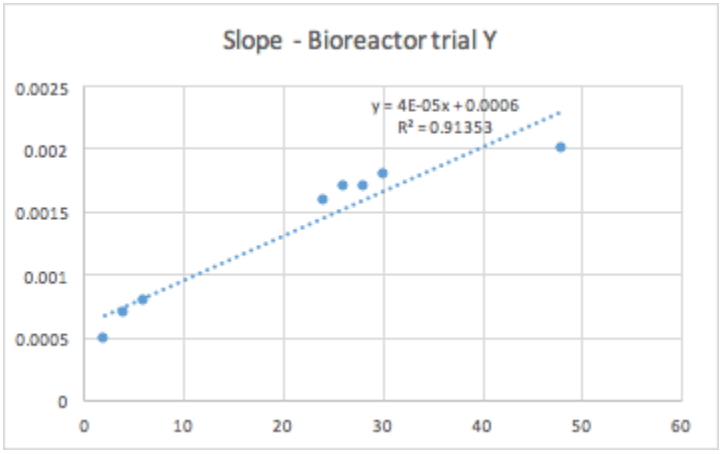

Figure 14: Absorbance slope vs Time for Bioreactor Trial Y aged over 48 hours.

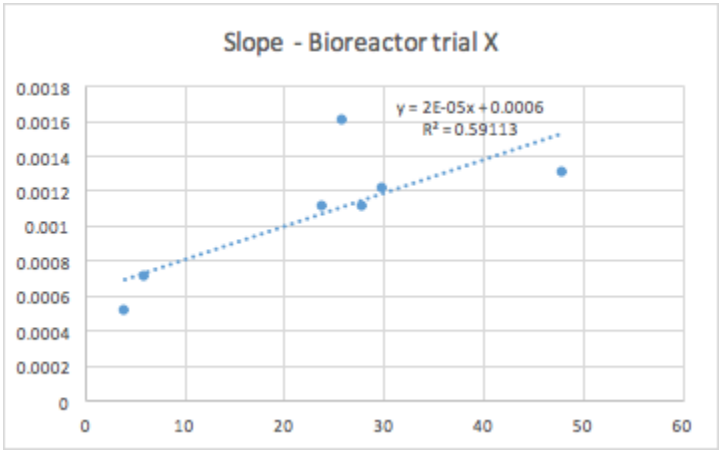

Figure 15: Absorbance slope vs Time for Bioreactor Trial X aged over 48 hours.

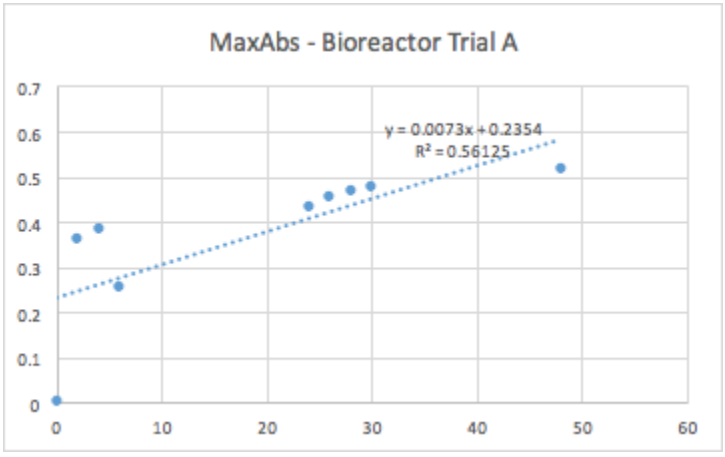

Figure 16: Max Absorbance vs Time for Bioreactor Trial A aged over 48 hours.

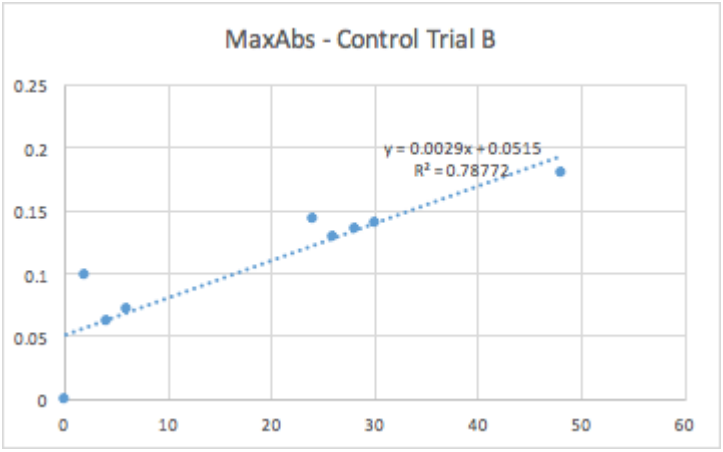

Figure 17: Max Absorbance vs Time for Control Trial B aged over 48 hours.

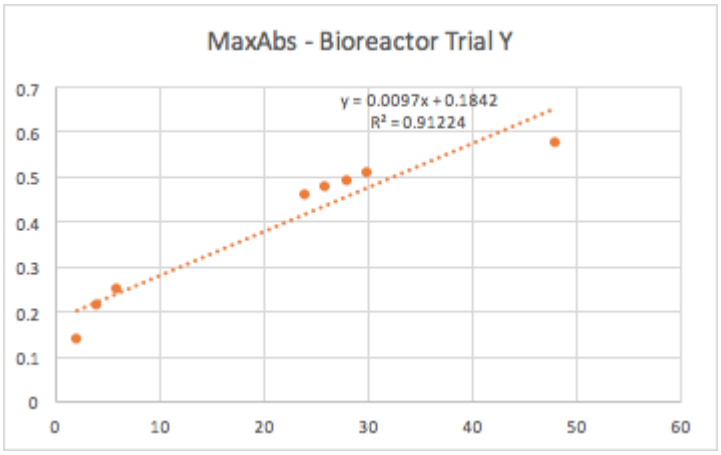

Figure 18: Max Absorbance vs Time for Bioreactor Trial Y aged over 48 hours.

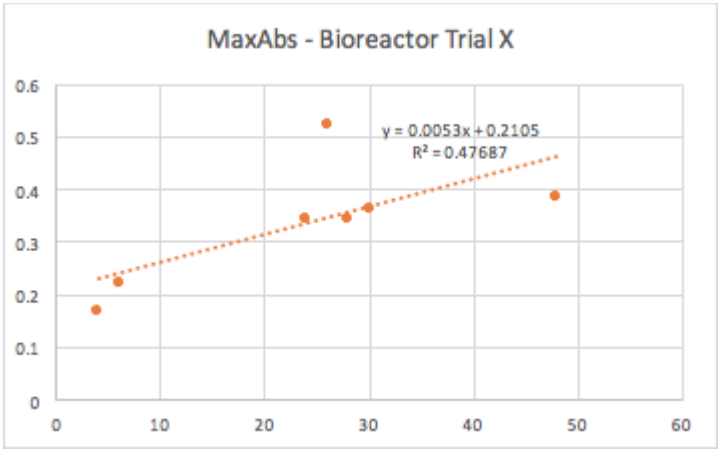

Figure 19: Max Absorbance vs Time for Bioreactor Trial X aged over 48 hours.