Techno-Economic Study for Lignocellulosic Biomass Processing and Ethanol Fermentation Refinery Design

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Abstract

Among the major obstacles being faced in the 21st century, two of the most prominent are those of energy security and environmental sustainability. Rising oil prices, decreasing oil reserves, and the threat of global warming as a result of the combustion of fossil fuels all allude to the potentially devastating consequences we may face if a sustainable fuel economy is not realized. One of the initiatives being undertaken is a mandate that automotive fuel must contain at least 10% vol. ethanol. As such, ethanol demand is expected to observe rapid growth in the short term. The challenge that this paper confronts is to safely, reliably, and efficiently produce a high capacity output of quality ethanol. It is proposed a refinery which converts a low-value cellulosic biomass into high-value ethanol and other value-added co-products is designed in an environmentally sustainable fashion while maintaining economic competitiveness. The proposed refinery framework is to include biomass pretreatment, parallel mixed sugar fermentation and simultaneous saccharification and fermentations, distillation processes and several solid-liquid separation systems. This paper provides simulations and economic analysis of a biorefinery consisting of parallel mixed sugar fermentation and simultaneous saccharification and fermentation which gives a distinct advantage over a simpler single simultaneous saccharification and fermentation (SSF) approach.

Keywords
Lignocellulosic Biomass, Biomass-based Ethanol, Simultaneous Saccharification and Fermentation.

1. Introduction
One of the major obstacles that will have to be faced in the 21st century is that of energy security. Oil resources will inevitably be exhausted, and a replacement to fossil fuel will be absolutely necessary. Now is the time that to capitalize on other fuels and technologies, and put ourselves in a competitive position for the coming decades. One of the fuels already becoming an integral component of the energy economy is ethanol. This is in part due to the need for fuel substitutes, as well as for environmental benefits. The government of Canada plans to reduce green house gas emissions by 260 million tonnes by 2012, as required by the Kyoto Accord. In order to meet this target, one of the initiatives has been to mandate that at least 35% automotive fuel sold in Canada must contain at least 10% vol. ethanol by the year 2010. Considering that in Ontario alone, gasoline consumption for the year 2004 exceeded 15.7 billion barrels, the demand for ethanol will be observing exponential growth in the short term. Canada does not have the capacity to provide this volume currently, and significant capital investment will be required to satisfy demands and reduce foreign dependency on ethanol. This provides an excellent opportunity to invest in a known, reliable, and demanded fuel technology.

Ethanol application in gasoline is as an oxygenate additive to replace Methyl T-Butyl Ether (MTBE). MTBE is proved to be responsible for considerable groundwater and soil contamination that have a very long half life compared to ethanol which is very biodegradable. Ethanol when combusted, produce carbon dioxide and water, considerable cleaner than conventional gasoline combustion emissions. Ethanol can also be used to power fuel cells. Along with the environmental benefits, there are major economical benefits of producing ethanol as well. An increased use of ethanol in gasoline reduces the overall volume of pure gasoline required and thereby reducing the

dependency on non-renewable resources such as oil which in primarily located in politically unstable areas of the world. According to a report published in the January 27th, 2006 edition of the journal Science by University of California-Berkeley's Energy and Resources Group and the Goldman School of Public Policy, ethanol fuel produced from corn reduces petroleum use by about 95%, while also reducing greenhouses gases by about 13%. The article also state that if ethanol is produced from grasses and other lignocelluloses biomass, there will be a slightly decreased energy benefit, but the environmental benefits would be greatly enhanced. According to US department of Energy studies, there is an 18% ~ 29% reduction in net greenhouse gas emissions for sugar fermented ethanol compared to an 85% reduction for lignocellulosic ethanol over gasoline. In addition to this, the cost for ethanol feedstock from sugar and starch (grains and fruits) is much higher than cellulose feedstock that cannot be digested by humans as food. Furthermore, as a plant is composed primarily of cellulose, a larger portion of the plant can be used in the production of ethanol rather than just the grains and fruits. In this paper, a comprehensive biomass refinery framework that will utilize promising novel technology to convert low-value raw materials into a high value, quality ethanol product, feasibly and economically, resulting in net positive environmental impacts.

2. The Process Overview

The proposed refinery framework includes pretreatment, SSF, and distillation processes, along with several solid-liquid separation systems. In order to operate efficiently, certain processes must be designed around a specific feed stream. There are several pretreatment techniques which are suitable for certain feedstock, and there are several orientations which hydrolysis and fermentation may be orchestrated. With the intention of utilizing various feeds, several pre-treatment processes will be incorporated into the refinery. Also, a novel process which combines hydrolysis and fermentation, called simultaneous saccharification and fermentation (SSF), will be incorporated, with the intention of reducing capital costs and increasing the rate of ethanol production. The final operation is the purification of ethanol to a fuels grade quality through distillation and subsequent purification. The diagram below outlines the general process for converting the feedstock used into high-purity ethanol. Our target design production for the refinery will be 200,000 Liter per day (1,300 barrels per day) of 99.5% fuel-grade ethanol.

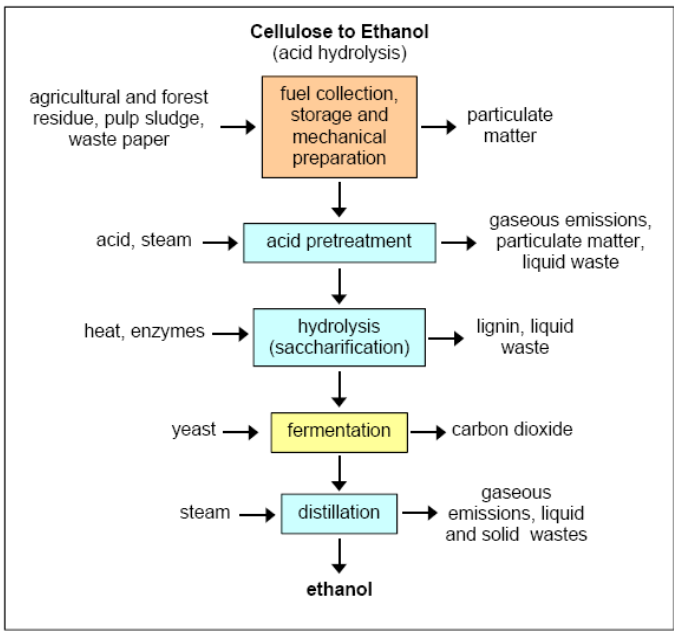

Figure 1: Process overview for conversion of cellulose into ethanol

3. Feed

Lignocellulosic (biomass) materials are products such as paper, wood, and other fibrous plant material. Biomass resources are in general abundant and are typically not in the human food chain making these materials relatively inexpensive feedstocks for ethanol production. The term lignocellulose is derived from the three major organic fractions that comprise biomass materials - cellulose, hemicellulose, and lignin. The typical range of dry-weight compositions of these materials are 35%–50% cellulose, 20%–35% hemicellulose, and 12%–20% lignin. The biomass materials also contain small amounts of ash and extractives (Wyman, 1999).

Cellulose is made up of long chains of glucose sugars. Hydrogen bonds hold the long cellulose chains tightly together in a crystalline structure rendering the cellulose insoluble to hydrolysis. The crystalline cellulose must be subjected to some preliminary chemical or mechanical degradation before it can be broken down into glucose [1]. Hemicellulose consists of short, highly branched chains of sugars. It contains pentoses, five-carbon sugars such as xylose and arabinose, hexoses, six-carbon sugars such as glucose, galactose, and mannose, and small amounts of other chemicals. Hemicellulose chains are more easily broken down to form their simple monomeric sugars than is cellulose because of their highly amorphous and branched structure. Since pentose sugars comprise a high percentage of the available sugars in plants, the ability to recover and ferment them into ethanol is important for the efficiency and economics of the process. The exact sugar composition of hemicellulose can vary depending on the type of plant. Lignin is not a sugar-based structure but is instead a phenylpropylene polymer. Lignin is the permanent bonding agent among plant cells and is always associated with hemicellulose in the cell wall. Lignin provides structural support for plants, thus trees have higher lignin contents than grasses (Wyman, 1999).

Two biomass materials were chosen as feedstock for the biomass refinery – Cave-in-rock species of switchgrass and Monterey pine species of softwood. Switchgrass is a perennial plant that is native to the prairies. Switchgrass grows south of latitude 55° N. from Saskatchewan to Nova Scotia, and south throughout most of the United States east of the Rocky Mountains. It is most abundant in the Great Plains and eastern states. Switchgrass grows on a variety of soils if soil moisture is adequate. Switchgrass is tolerant of moderate soil salinity and acidity, growing in soil pH ranging from 4.5 to 7.6. Monterey pine is the most widely planted pine in the world. For the purposes of this paper, the composition of the entire tree will represent the composition of this feed. In reality, the feed may be composed of wood chips and foliage from only certain parts of the tree where compositions may vary. The composition of switchgrass and softwood are given in the figure below (Silzer, 2000).

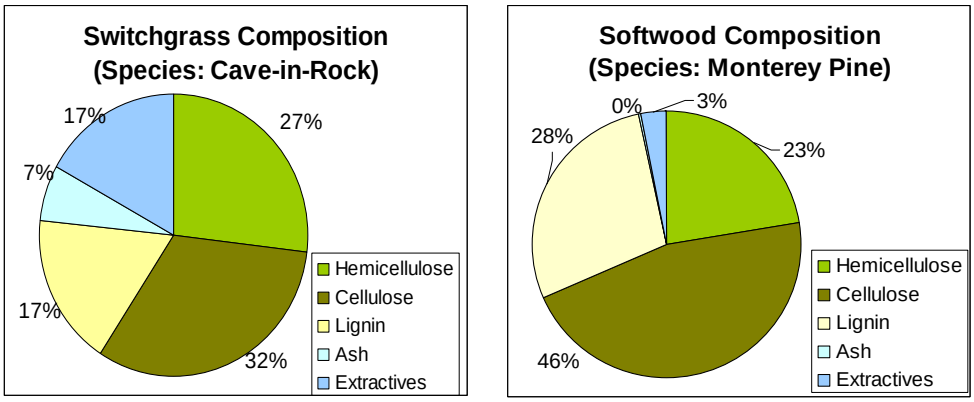

Figure 2: Composition of switchgrass and Softwood

The benefit of using feedstocks such as these is the potential for material cost reductions. The figure below compares the cost of corn which is traditionally used for producing ethanol in Canada to the two biomass materials used in this project (USDE, 2005).

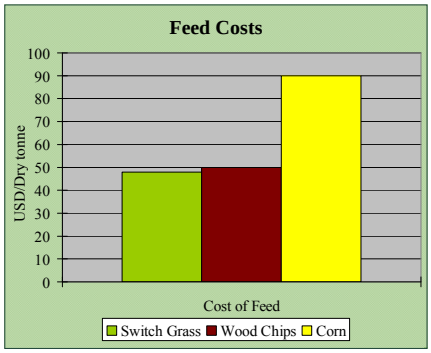

Figure 3: Feed Costs of Switchgrass, wood chips, and corn

4. Pre-treatment Process

There are several factors that influence the yield of sugars from lignocellulosic materials. Some of these factors include the crystallinity of cellulose, lignin content and the porosity of the biomass material. The pretreatment process alters the structure of the biomass feed allowing greater accessibility to the cellulose that comprises it. Without pretreatment, sugar yields from the hydrolysis step that follows are low. The pretreatment stage allows greater access by disrupting the lignin that binds the cellulose and by removing hemicellulose as well. The pretreatment stage also decreases the crystallinity of the cellulose and increase the pore size of the cellulose thereby increasing the accessible surface area for hydrolysis. The function of pretreatment is represented in the schematic diagram shown below (Mosier, et al. 2005).

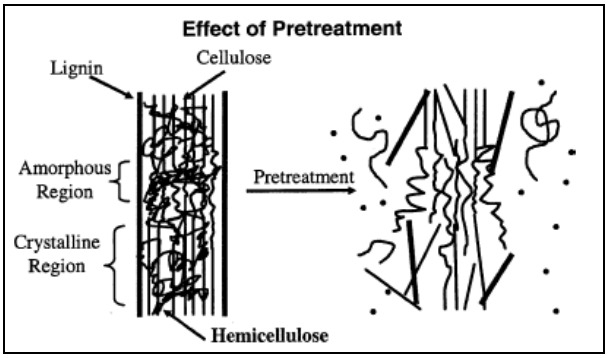

Figure 4: Goals of pretreatment on lignocellulosic material

There are several techniques that can be utilized for the pretreatment of lignocellulosic feedstock. These include liquid hot water, ammonia fiber explosion (AFEX), ammonia recycle percolation (ARP), lime, and dilute acid. Dilute acid pre-treatment is utilized in this project. This pre-treatment method utilizes dilute sulphuric acid at high temperatures to effectively dissolve the hemicelluloses and disrupt the lignin-hemicellulose-cellulose interactions thereby increasing the digestibility of cellulose. This method achieves high reaction rates with low acid consumption of low cost sulphuric acid. The concentration of acid is 1.0% w/w and therefore will not require an acid-recovery system. The pre-treatment is operated at a temperature of 180°C.

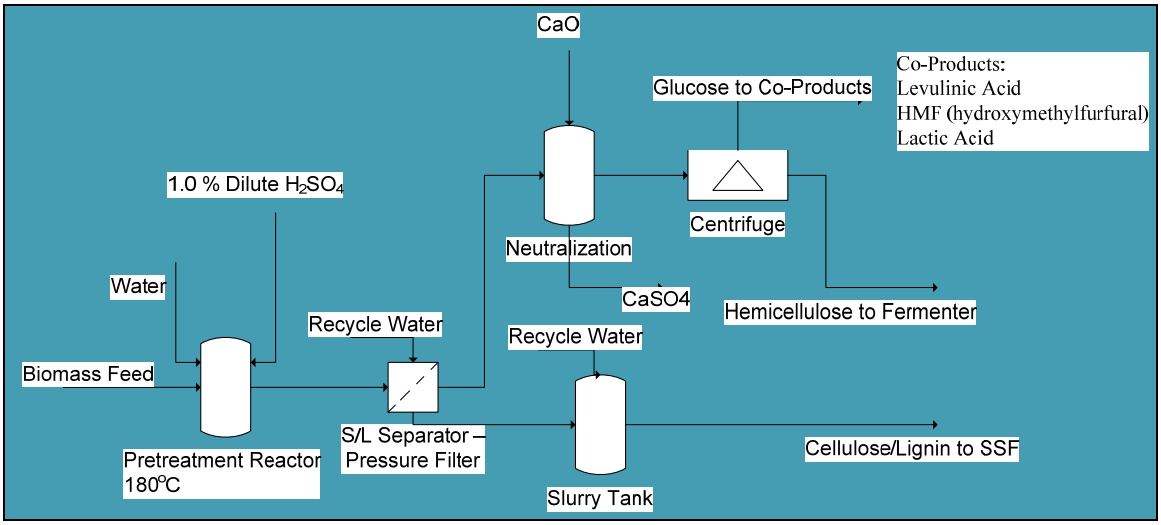

Figure 6: Process diagram for pretreatment and processing prior to hydrolysis and fermentation

The effluent from the pre-treatment stage is separated to a solids stream containing primarily cellulose and lignin and a liquid, prehydrolysate stream consisting primarily of hemicellulose with some glucose and solubilised lignin content. The conditions used in this paper will be representative of a general case for the biomass feed. The percentage of the original composition of the biomass in each stream will vary with the type of material used. Therefore, specific conditions have to be established based on the composition of the incoming feed. A

representative composition consisting of 80% of the hemicellulose, 10% of the glucose, and 20% of the lignin from the original biomass feed will make up the prehydrolysate stream. This is determined based on the experimental conversions. The figure below displays the recovery of xylose sugars from the dilute acid pretreatment of switchgrass (Esteghlalian 1996 and Schell 2002). The solids stream contains the balance of the composition that has not been solubilised during pre-treatment. This is to account for the varying yields by dilute pre-treatment for different feed compositions.

The prehydrolysate stream is neutralized using CaO and then sent to a centrifugal separator. The centrifugal separator allows glucose and/or xylose to be extracted from the process for further refinement to other co-value products. The balance of the prehydrolysate stream is sent to a fermenter where the sugars are converted into ethanol. The solids stream is contacted with water to condition the stream to the appropriate level for processing in the simultaneous saccrification fermentor (SSF). The figure below is a process diagram of the pre-treatment stage and post processing prior to fermentation and SSF.

5. Hydrolysis and Fermentation

In this paper, a parallel process of mixed sugar fermentation and simultaneous saccharification and fermentation (SSF) is employed. During saccharification (hydrolysis), sugar polymers are broken down to their simpler monomer subunits. This is required in order for the sugar to be accessible for subsequent fermentation, either by microbial or yeast. Fermentation is simply the conversion of sugar for the production of energy (ATP) and other byproducts including ethanol. The advantages of utilizing two separate streams and fermentation units will be forthcoming.

There are currently several process options for hydrolysis. These include enzymatic hydrolysis, catalytic hydrolysis (using diluted acid or concentrated acid) and SSF which ultimately combines the enzymatic hydrolysis step with the subsequent fermentation reducing the number of steps and unique reactors required. During hydrolysis cellulose and hemi-cellulose are enzymatically digested into their simple hexose and/or pentose sugar subunits (Saga et al. 2005)

5.1. Substrate Structure and Degradation

Cellulose is a structural polysaccharide composed of glucose monomers linked via β-1,4 bonds. This differs from starch, which is an important glucose polysaccharide used for carbon and energy storage in plants, but linked via α-1,4 bonds. The α-1,4 linkage is easily hydrolyzed by α-amylase, a ubiquitous enzyme produced by many animals and microorganisms. Due to the nature of its linkage, starch is highly amorphous and readily susceptible to hydrolysis. The β-1,4 linkage however, characteristic of cellulose, is broken by a group of enzymes called cellulases which are predominant in only select fungi, bacteria, and protozoans. Cellulose is composed of highly ordered linear chains stabilized by hydrogen bonding, creating a very rigid structure complementing its purpose and inhibiting enzymatic hydrolysis. The kinetics of this reaction is not as favorable as that of the hydrolysis of starch (Glick and Pasternak 2003)

Hemicellulose is a short chain highly branched polymer of several sugar subunits. The main constituent in hemicellulose is the pentose xylose. Hemicellulose is also composed of the pentose arabinose, as well as the hexoses glucose, galactose, and mannose. Due to its highly branched nature, hemicellulose is amorphous and easily hydrolyzed by dilute acid treatment, as is the case in the pre-treatment process. Thus after dilute acid pretreatment, hemicellulose in the feed stream will be hydrolyzed, in the aqueous supernatant, and available for direct mixed sugar fermentation. Sugars in this phase do not require supplemental treatment after exiting the pretreatment stage. The pretreated cellulose however is still highly structured and requires hydrolysis prior to fermentation (Howard et al. 2003, Saga et al. 2005, and Chandrakant and Bisaria 1998). This necessitates the incorporation of a second unit to handle the cellulose stream.

To this end, simultaneous saccharification and fermentation is employed. SSF has several distinct advantages over separate hydrolysis and fermentation. Combining two processes into a single unit reduces the number of reactors involved. But, perhaps more importantly, SSF avoids problems associated with product inhibition of the cellulose enzymes (Dien et al. 2003). In the presence of glucose, the main product of hydrolysis, ß-glucosidase is inhibited from hydrolyzing cellobiose. The buildup of cellobiose, in turn, shuts down cellulose degradation (Thatipamala et al. 1992). During SSF, cellulase enzymes and fermenting microbes are combined and as sugars are produced by the enzymes, the fermentative organisms convert them to ethanol (Chandrakant and Bisaria 1998).

5.2. Fermenting Organism Categorization

An integral part of the fermentation process is the choice of organism. Indeed the lack of an industrially suitable microorganism has often been cited as the major restraint in the commercialization of cellulosic ethanol (Chandrakant and Bisaria 1998). In the past several decades much research has been directed at developing an ideal bacterial strain for the purpose of ethanol production from cellulosic biomass (Glick and Pasternak 2003). Bacterial strains are preferred to yeast strains due to generally higher production rates and to their ease of genetic manipulation. The most promising bacteria identified thus far have been recombinant forms of Escherichia coli, Klebsiella oxytoca, and Zymomonas mobilis.

E. coli and K. oxytoca are both of interest because they are naturally capable of fermenting a wide range of sugars. E. coli is of particular interest because its genome and metabolism are very well studied. However, both of these organisms are capable of limited ethanol production because they do not selectively produce ethanol. Much cellular energy and resources are invested into the production of unwanted products such as acetate, succinate and lactate. Furthermore, E. coli has a particularly narrow pH growth range (ca. pH 6.0–8.0) which makes its use in an industrial setting cumbersome at best. Research and development of these organisms has been directed at minimizing production of these unwanted products, increasing ethanol yields and improving pH tolerances (Chandrakant and Bisaria 1998).

5.2.1. Escherichia coli

Ethanol is naturally produced by E. coli via a pyruvate formate lyase (PFL) pathway (Figure 7-A). Each pyruvate molecule (made from sugars) yields a single NADH+ / H+. However two NADH+ / H+ molecules are required for the conversion of pyruvate to ethanol by E. coli. The organism balances this deficit with the production of acetic and succinic acids. Yeasts (ie. Saccharomyces cerevisae) and the aforementioned Z. mobilis strain are both capable of producing ethanol via a pathway utilizing pyruvate decarboxylase (PDC) which consumes a single NADH+ / H+ for each ethanol molecule yielded (Figure 7-B). These organisms are so called "homo-ethanol fermenters". It was thus reasoned that expressing the PDC gene in E. coli would increase the ethanol yield at the cost of unwanted products and a wide array of E. coli hosts were subsequently screened (Chandrakant and Bisaria 1998).

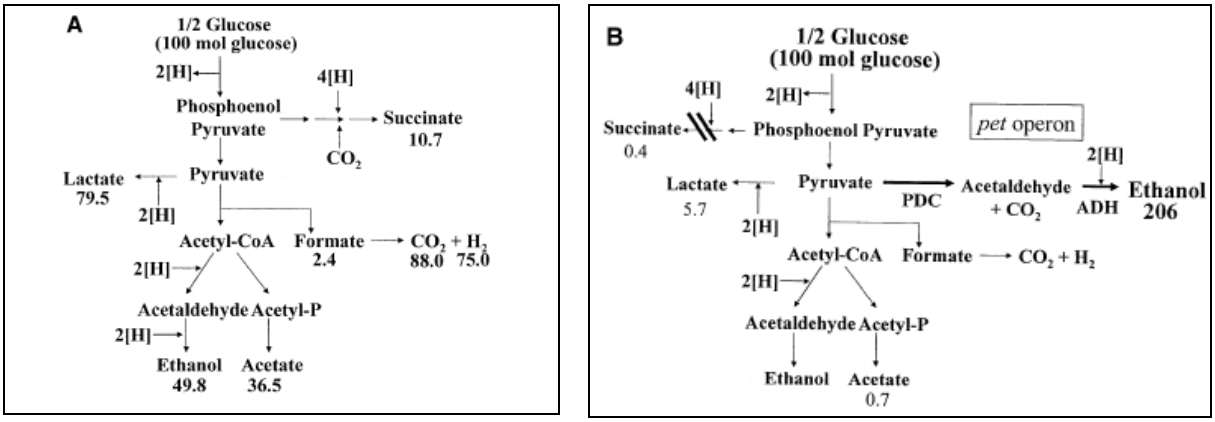

Figure 7: Pyruvate Formate Lyase (A) and Pyruvate Decarboxylase (B) glucose fermentation pathway and relative ethanol yields (Chandrakant and Bisaria 1998)

The creation of an E. coli strain capable of utilizing the PDC pathway proved to be difficult. The genes encoding the PDC enzyme and a Z. mobilis alcohol dehydrogenase enzyme were placed on a plasmid (subsequently called the PET operon) under the control of the lac promoter and used to transform a number of potential E. coli host strains. This operon was however found to be too unstable for industrial uses. Further attempts to stabilize the plasmid (integrating the genes into the PFL gene within the host chromosome) resulted in a construct with a significantly reduced ethanol yield compared to the plasmid bearing strains as a result of depressed gene dosage. After further screening (strains were screened for chloramphenicol resistance, as it was thought to correlate with increased gene expression) an E. coli strain named KO11 was isolated and found to have exceptional ethanol yields nearing the theoretical maximum. Although promising, KO11 was still found to exhibit stability issues and was found to have a

higher than optimal pH growth range for use in SSF (cellulase enzymes function ideally at pH 4.6; KO11 grows ideally at pH 6.5) (Chandrakant and Bisaria 1998).

5.2.2. Klebsiella oxytoca

Klebsiella oxytoca is a gram negative bacteria related to E. coli. Ethanol is naturally produced at relatively low yields in K. oxytoca via the PFL pathway. After transformation with the PET plasmid however, and similar screening procedures as performed in E. coli, yields are raised substantially. Yet overall ethanol yield is still less favorable than that of E. coli (Chandrakant and Bisaria 1998).

5.2.3. Zymomonas Mobilis

Z. mobilis is naturally of great interest because it can ferment glucose (and fructose) at high yields and high rates of production(Thatipamala et al. 1992). It's 2.06 Mb genome has also recently been entirely characterized, enabling us to genetically engineer new mobilis strains to further increase ethanol production rates and yields. Z. mobilis has not however traditionally been considered as a replacement for S. cerevisae in the beverage ethanol industry because it has been known to spoil fermentations with sulfurous flavours and rotten odours. In contrast to the food industry, taste and smell are not critical factors in fuel ethanol production, which naturally makes Z. mobilis a highly promising organism for fuel ethanol fermentation(Thatipamala et al. 1992). Wild type Z. mobilis cannot however grow and utilize other substrates such as xylose and arabinose, main components of hemicellulose. Thus much focus on Z. mobilis has been placed on increasing its range of substrate utilization to enable it to convert hemicellulose into ethanol (Chandrakant and Bisaria 1998).

In order to be useful for SSF processes for cellulosic ethanol production Z. mobilis must be capable of growth on substrates such as xylose and arabinose. To this end, seven genes from E. coli have been successfully integrated into the Z. mobilis genome, giving the strain (named AX101) the capacity of fermentation of both substrates as well as glucose. The xylose fermentation pathway, incorporating the ED pathway, is shown in Figure 8. Importantly, it was shown that these genes were stable in the strain during growth solely on glucose for 160 generations. When grown on all three substrates, total ethanol yield was found to be as high as 0.46 g/g or approximately 90% of the theoretical maximum. This strain was also shown to be capable of growth on inexpensive substrate requiring minimal additional nutrients. The optimal pH of this strain is 5.5 (Chandrakant and Bisaria 1998), making its usage in SSF feasible.

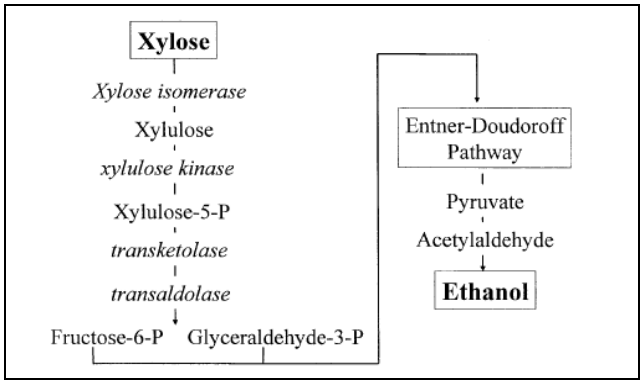

Figure 8: Xylose fermentation pathway of Z. mobilis strain AX101

5.3. Fermenting Organism Selection

The dual fermentation approach of the current process gives us a distinct advantage over a simpler single SSF approach in that it enables us to tailor a unique recombinant microorganism to the distinct constituency and conditions of the different streams exiting pretreatment, namely the supernatent hydrolyzate of hemicellulose (a mixture of pentose and hexose sugars) and the cellulosic slurry. Thus an organism suited towards a high yield of ethanol is selected for the SSF unit, while a robust organism capable of growing on both hexose and pentose substrates is selected for the distinct fermentation unit. Thus a screened strain of Z. mobilis is proposed for the SSF unit, and the xylose and arabinose fermenting Z. mobilis strain AX101 be used for the multiple sugar fermentation unit due to its proven high ethanol yields on three major substrates and very respectable growth rates.

6. Distillation & Purification

The water-rich feed stream of the distillation & purification unit (DPU), which is passed from the micro-filtration unit of the SSFU and containing approximately 5% ethanol, is the fundamental constituent to produce fuel grade ethanol of 99.5%vol. Separation of water is the single most important objective in the DPU, and hence, the unit contains process operations that seeks to achieve water-ethanol separation effectively, while minimizing costs of operations and capital investment. As expected, separation performance of this unit is heavily dependent on the quality of feed that it receives from the SSFU.

The DPU consists of 3 process operations: liquid pressurization via pump, binary distillation, and adsorption via molecular sieve. Desired separation specification of 99.5%vol ethanol cannot be achieved by distillation alone because of the non-ideal solution behavior of the water-ethanol mixture. An azeotrope is observed when the mixture reaches 95.5%mole purity of ethanol. This is a common phenomenon that occurs when one attempts to separate a polar substance from an alcohol group utilizing relative volatilities, because in high alcohol concentrations, the attractive forces of the alcohol group tend to overpower phase change mechanisms of the mixed polar molecule that is governed by entropy. Equilibrium stage operations are no longer effective after it meets an azeotrope, and hence sets a limit on the purity achievable using phase change mechanisms. Obtaining high purity alcohols using fractional distillation methods become more difficult if the molecule is electron rich (i.e. propanol, butanol, etc.).

Since distillation can only offer up to 95.5%mole purity, another unit operation is required to further purify the mixture to 99.5%mole ethanol. Despite the obvious limitation of the azeotrope in the water-ethanol mixture, there are a variety of options to achieve the target specification of 99.5%mole ethanol. Purification methods that are more widely used than others are the addition of benzene/toluene in the distillation environment to break the azeotrope, eliminating water molecules via reaction by adding lime, and selective adsorption of water using molecular sieves. All three methods are capable of achieving 99.5%mole ethanol purity, but has its advantages and drawbacks.

Purification process selected for the DPU is the adsorption process using molecular sieves. The selection was based upon a few facts that related to the process environment of the biomass refinery, and cost. The addition of benzene/toluene in the distillation tower will eliminate the need for a separate purification unit. However, unlike most petroleum refineries that utilize this method to produce high purity ethanol (i.e. Suncor, Sarnia refinery), a biomass refinery does not produce benzene/toluene as a byproduct, hence, must be bought externally. Beside the fact that the refinery cannot produce the additives (Benzene/Toluene) internally, this operation will eliminate the possibility of the finished product being sold for human consumption. This is undesirable in a flexibility stand point, in an attempt to maximize profits.

Lime addition will selectively react with water to form calcium hydroxide. Preliminary calculations to predict how much lime is required for 200,000 L/Day ethanol of 99.5% ethanol show that approximately 12 metric tons are required for successful purification. With the price of lime in 2006 being roughly $70/tonne, the operating cost of purification should be in the range of $1000/day. This additional operating cost was not a significant determining factor because the numbers turned out to be relatively small compared to other operating costs such as steam and furnace fuels. However, the lime addition method creates a great amount of waste sludge, while attempting to coagulate and remove the suspended solids, after the water removal reaction. The sludge produced from this operation is considered to be a non-reusable waste. Lime addition is not suitable because it produced a substantial amount of unfriendly waste that cannot be reprocessed to a useful product.

The 3-Å molecular sieve is a cube zeolite complex made of aluminosilicate. The aluminosilicate complex makes the zeolite negatively charged, which is balanced by positive ions. The positive ions can be changed or replaced to control the pore size, and hence control the adsorption molecule. In the case of the 3-Å molecular sieve, potassium ions fill the voids within the zeolite to reduce the pore size to 3-Å. Water molecules are small enough to pass through the 3-Å openings, while ethanol cannot. The water that passes through the pore openings of the 3-Å molecular sieve will remain trapped inside the zeolite due to the zeolites inner ionic attractive forces. The distillate product from the distillation tower is routed to the absorber column filled with 3-Å molecular sieves. Remaining water from the tower distillate is reduced down to 0.05%mole and is directed to tank as finished product.
The fundamental basis, upon designing the process flow is to produce an optimal environment for the adsorption molecular sieves to function. The 3-Å molecular sieves operate most efficiently when the adsorbent feed is in

vapour phase. To satisfy the operating condition, the overhead distillate is fed into a train of heat exchangers for pre-flash.

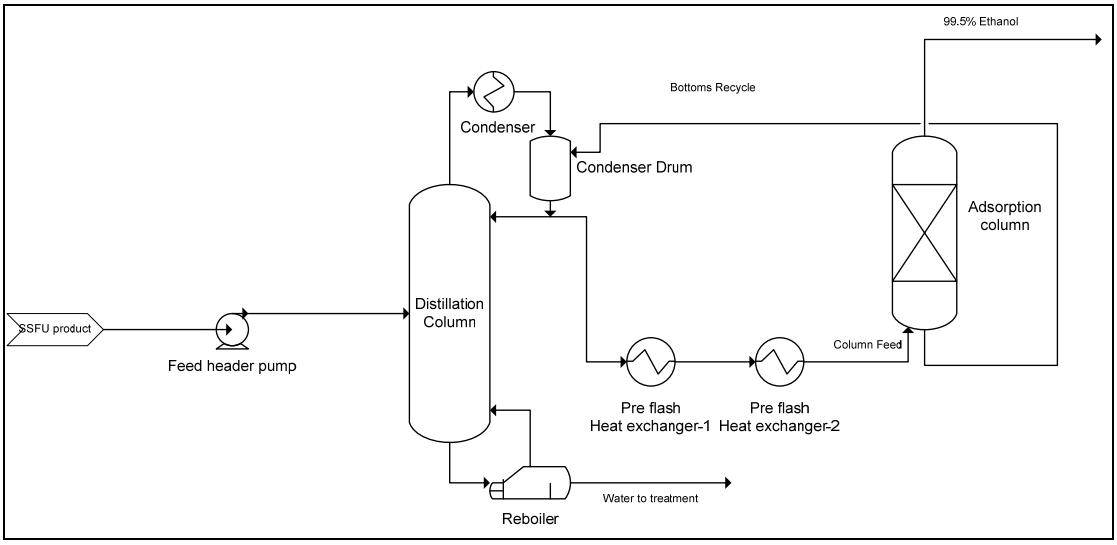

Figure 9: Process Flow Diagram of Distillation and Purification Unit

The flashed vapour is fed into the adsorption column for ethanol purification. Overhead vapour is purified ethanol of 99.5% purity. Possible bottoms liquid is recycled to the condenser drum. Hot liquid stream for the heat exchanger trains are subject to heat integration, if such stream is available in other units. Otherwise, the hot liquid stream is saturated steam at approximately 300psig. The steam operation may require an alteration of the heat exchanger configuration, where a regular shell-tube maybe not appropriate, due to fluid mechanics of the shell side fluid. A Flash drum is recommended in situations where steam must be used as a heat source. Saturated adsorbents are regenerated by applying heat to the absorption column to 300-400°C for approximately 4 hours. An auxiliary absorber tower will be installed and placed in operation, while the absorbents regenerate.

7. Overall Plant Economics

The annual revenue was calculated using current trade value of ethanol listed as a commodity on CBOT (Chicago Board of Trade). The projected cost per liter ethanol produced was compiled using various data from literature. The cost per ethanol value includes predicted feed costs, enzymes and pretreatment chemicals costs, and energy. The result is as follows. All calculations were based on an optimistic point of view.

Proposed production rate	200000 L/day
Estimated production cost per liter	$0.85 per liter
Estimated annual cost	$62.05mm USD
Price of Ethanol as of July/06	$3.80 per US Gallon (USD)
Estimated annual revenue	$73.28mm USD
Projected profit	$11.23mm USD
Payback period	10+ years

This estimate is subject to approximately 40% variance due to uncertainties in price of feed streams (wood, switch grass, etc), and volatile nature of ethanol prices over the past 3 years. These figures should be used as guidelines only and should not be used for closing decisions.

8. Conclusions

Lignocellulosic biomass feeds are a highly available, cheaper alternative to corn for use as feedstock for the production of ethanol. These feeds are reliable and sustainable and provide a source for fuel to meet the needs of society and contribute to energy security in an increasingly environmentally sound manner. Parallel mixed sugar fermentation and simultaneous saccharification and fermentation gives a distinct advantage over other possible process designs. A screened strain of Z. mobilis is to be used for SSF as it is capable of high ethanol yields and high

rates of growth. The xylose and arabinose fermenting Z. mobilis strain AX101 is to be used for the mixed sugar fermentation due to its proven high ethanol yields and growth rates when grown on three major substrates.

The distillation/purification unit is able to produce 99.5% ethanol while satisfying the core values of this project. Molecular sieving is a cheap, efficient method of separation in terms of capital input and maintenance. It is also relatively environmentally friendly compared to other purification methods due to a waste free process. The long expected operating life (approximately 10years) of the molecular sieve purification unit will further enhance the economical analysis in time, and will maximize profits.

It is shown that the cellulosic ethanol production via parallel mixed sugar fermentation and simultaneous saccharification and fermentation is a viable option in the sustainable and profitable production of a high-quality ethanol fuel and can be a valuable contribution to future energy demands.

References

Chandrakant, P., Bisaria, V.S. (1998). Simultaneous Bioconversion of Cellulose and Hemicellulose to Ethanol, 18(4), 295-331.

Dien, B.S., Cotta, M.A., Jeffries, T.W. (2003). Bacteria engineered for fuel ethanol production: current status. Applied Microbiology Technology, 63, 258-266.

Esteghlalian, A, Hashimoto, A, Fenske, J, & Penner, M (1996). Modeling and Optimization of the Dilute-Sulfuric-Acid Pretreatment of Corn Stover, Poplar and Switchgrass. Biosource Technology, 59, 129-136.

Glick, B.R., Pasternak, J.J. Molecular Biotechnology: Principles and Applications of Recombinant DNA. 3rd Ed. American Society for Microbiology. 2003.

Howard, R.L., Abotsi, E., Jansen van Rensburg, E.L., Howard, S. (2003). Lignocellulose biotechnology: issues of bioconversion and enzyme production. African Journal of Biotechnology, 2, 602-619.

Mosier, N, Wyman, C, Dale, B, Elander, R, Lee, Y, & Holtzapple, M (2005). Features of promising technologies for pretreatment. 96, 673-686.

Saga, B.C., Iten, L.B., Cotta, M.A., Wu, Y.V. (2005). Dilute acid pretreatment, enzymatic saccharification and fementation of wheat straw to ethanol. Process Biochemistry, 40, 3693-3700.

Schell, D.J., Farmer, J., Newman, N., McMillan, J.D. (2002). "Dilute Sulfuric Acid Pretreatment of Corn Stover in a Pilot-Scale Reactor: Investigation of Yields, Kinetics, and Solids Enzymatic Digestibilities."

Silzer, T (2000). Panicum virgatum L.. Retrieved January 17, 2007, from Rangeland Ecosystems & Plants Web site: http://www.usask.ca/agriculture/plantsci/classes/range/panicum.html

Thatipamala, R., Rohani, S., Hill, G.A. (1992). Biotechnology and Bioengineering, 40, 289-297.

US Department of Energy, (2005, October 13). Energy Efficiency and Renewable Energy. Retrieved April 17, 2007, from Biomass Program: Pretreatment Technology Evaluation Web site: http://www1.eere.energy.gov/biomass/technology_evaluation.html

Wyman, C. E. (1999).BIOMASS ETHANOL: Technical Progress. Annu. Rev. Energy Environ.. 24, 189-226.

Biography

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