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Recent process improvements for the ammonia fiber expansion (AFEX) process and resulting reductions in minimum ethanol selling price

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ABSTRACT

The ammonia fiber expansion (AFEX) process has been shown to be an effective pretreatment for lignocellulosic biomass. Technological advances in AFEX have been made since previous cost estimates were developed for this process. Recent research has enabled lower overall ammonia requirements, reduced ammonia concentrations, and reduced enzyme loadings while still maintaining high conversions of glucan and xylan to monomeric sugars. A new ammonia recovery approach has also been developed. Capital and operating costs for the AFEX process, as part of an overall biorefining system producing fuel ethanol from biomass have been developed based on these new research results. These new cost estimates are presented and compared to previous estimates. Two biological processing options within the overall biorefinery are also compared, namely consolidated bioprocessing (CBP) and enzymatic hydrolysis followed by fermentation. Using updated parameters and ammonia recovery configurations, the cost of ethanol production utilizing AFEX is calculated. These calculations indicate that the minimum ethanol selling price (MESP) has been reduced from \$1.41/gal to \$0.81/gal.

1. Introduction

Present research in the area of lignocellulosic biomass conversion includes a wide variety of pretreatment methods (Mosier et al., 2005). Previous economic estimates of the AFEX pretreatment process were based on then-existing research results for ammonia loading and recycle concentrations, and enzyme loadings for corn stover pretreatment, hydrolysis and fermentation systems (Eggeman and Elander, 2005). However, new laboratory data have demonstrated reduced ammonia loadings, reduced ammonia concentrations and lower enzyme requirements for AFEX processing of biomass. An improved ammonia recovery system has also been conceptualized and its costs estimated.

Previous cost estimates of the AFEX process were embedded in an Aspen Plus model of the overall biorefinery, initially developed at the National Renewable Energy Laboratory (NREL), Golden, Colorado (Eggeman and Elander, 2005). The NREL model has been adapted and altered at Dartmouth College with input from researchers at Michigan State University (Laser et al., in press). Using the Aspen software and the basic modeling approach developed by NREL, it has become possible to remove and re-insert individual pieces of the model, thereby making “upgrades” to allow for possible technology developments. Some model alterations were made that include eliminating feedstock washing, including an innovative ammonia recovery approach, and raising the feedstock feed rate to 5000 tons dry biomass/day.

2. Background

The specific AFEX process changes were to reduce ammonia loading, reduce ammonia recycle concentration (i.e., not requiring that anhydrous ammonia be used in AFEX), improve the ammonia recovery approach, and reduce enzyme loading. Ammonia loading refers to the ratio of ammonia to dry biomass that enters the AFEX reactor, and in the Aspen model simulations ammonia loading was varied from 0.8 to 0.2 g NH_3: g dry biomass. Ammonia recycle concentration refers to the concentration of ammonia by mass in the recycle stream, which is combined with the fresh ammonia make-up stream and then fed to the AFEX reactor. In simulations, this parameter was varied between 70% and 99% by mass (ammonia in water). Enzyme loading refers to the ratio of cellulase enzyme to glucan fed to the AFEX reactor, where glucan fed is calculated as the dry biomass feed rate multiplied by its glucan content, and was modeled at 7, 15, and 60 FPU/g glucan, (FPU is a measure of the enzyme activity). An enzyme loading of 15 FPU was found to be the economic optimum, and was thus fixed at this value for all subsequent simulations (Teymouri et al., 2005).

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NREL's initial economic analysis (Eggeman and Elander, 2005) compared the economic performance of various biomass pretreatments (dilute acid, hot water, ammonia recycle percolation, AFEX and lime) on corn stover. This analysis found that AFEX produced ethanol fuel at a minimum ethanol selling price (MESP) of about \$1.41/gallon, based on data available in late 2003. NREL's economic comparison of pretreatments is summarized in Fig. 1. The minimum ethanol selling price is the lowest price at which the ethanol produced from the biorefinery can be sold to maintain a set internal rate of return (IRR), while accounting for feedstock costs, capital and operating costs, and secondary products sold at market value. Assumptions for calculating MESP vary somewhat between the previous model used by NREL and the current model, but the calculations are performed using the same equations (Eggeman and Elander, 2005; Laser et al., in press). The previous NREL model assumes a feedstock cost for corn stover of \$35/dry ton, an IRR of 10%, and includes additional feedstock costs for cellulase and corn steep liquor (Eggeman and Elander, 2005). The current model assumes a corn stover feedstock cost of \$40/dry ton, an IRR of 12%, and does not require corn steep liquor or cellulase as feedstock. As a result of increased feedstock cost and IRR assumptions, the current results require a higher MESP to meet performance objectives and thus represent a more stringent test of profitability than the previous simulation. An outline of all key financial parameters used in the economic analysis of the simulations for this work can be seen in Table 1. The current model does not use corn steep liquor or cellulase when implemented with CBP, which is described in this work.

It can be seen in Fig. 1 that the feedstock cost is a relatively small fraction of the cost for most corn stover pretreatment options, while the largest costs are associated with processing. This is characteristic of immature processes. Our objective is to reduce these processing costs to make cellulosic ethanol more competitive with petroleum-derived fuels. It is important to note that AFEX and the entire cellulosic ethanol production process are definitely not mature. We define "mature" process technology as characterized by raw material costs equal to approximately 70% of the overall cost to manufacture. By this definition, petroleum refining and corn wet milling industries are both mature (Lynd et al., 2005a).

Continued laboratory and process configuration research, presented here, have led to important advances in the AFEX pretreatment and related parts of the system since NREL's initial economic estimate (Eggeman and Elander, 2005). We discuss and analyze here the economic impacts of these AFEX process advances in the context of simultaneous saccharification and co-fermentation (SSCF) to produce and ferment sugars from AFEX treated corn stover. Furthermore, by pairing this improved AFEX pretreatment system with CBP the MESP of cellulosic ethanol has been greatly reduced.

Table 1
Financial parameters used in simulations shown in Figs. 10–12

Parameter	NREL2004	All other scenarios
Debt/equity ratio	0/100	40/60
Loan rate (APR)	Not applicable	7.5%
IRR[a]	10%	12%
Federal & state tax rate	39%	39%
Economic life	20 years	25 years
Depreciation period	7 years for general plant 20 years for power and steam production	7 years for general plant 20 years for power and steam production
Depreciation method	MACRS[b]	MACRS
Capital charge rate	18%	−17%
Indirect costs	48% of total installed capital	48% of total installed capital

[a] Internal rate of return.
[b] Modified accelerated cost recovery system.

CBP is a biological process that performs all four steps of enzymatic hydrolysis and fermentation in a single vessel. The ideal CBP system produces saccharolytic enzymes that hydrolyze structural carbohydrates (cellulose and hemicellulose) to oligomers. Then these oligomers are further hydrolyzed to monomers and dimers. Finally these five and six carbon simple sugars are fermented to ethanol or other products such as lactic acid (Lynd et al., 2005b). Such a system has not yet been perfected. Implementing CBP requires the development of microorganisms capable of utilizing all the appropriate components of biomass to produce ethanol at high yields and concentrations. Such a development would be a breakthrough that would ultimately reduce the cost of ethanol biorefining well below the current biological processing method, SSCF,

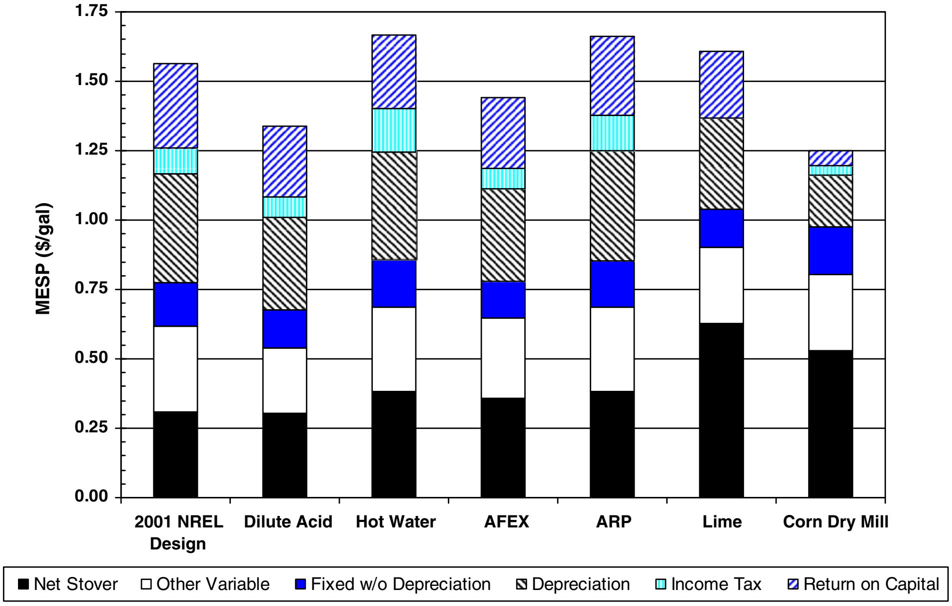

Fig. 1. MESP of various pretreatment options (Eggeman and Elander, 2005).

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(Lynd, 2006). SSCF is a biological processing system that performs the four biologically-mediated events mentioned above in two separate process steps, first enzyme production and then hydrolysis and simultaneous five and six carbon sugar fermentation. For simulations presented here the primary difference in cost between these two biological processing options is the cost of enzyme, which is only required for SSCF.

The ammonia recovery approach for the current model differs from that modeled by NREL in 2003. The previous approach to recover ammonia was distillation and recompression, whereas the current model uses an innovative quench system (Laser et al., in press). Both of these approaches are described in the following section.

3. Model system configuration

An overall diagram showing the major sections of the biorefinery can be seen in Fig. 2. The first two stages, pretreatment and biological processing, are described previously. Ethanol recovery is described later in this document. Water treatment and utilities refers to the cleanup of water to be re-used in the system and its subsequent heating or cooling for use in many biorefinery unit operations. Steam and electricity production refers to the combustion of biomass residues using methane collected during anaerobic wastewater treatment to produce all biorefinery needed steam and the subsequent use of that steam in a Rankine cycle to produce electricity equal to or in excess of the biorefinery needs.

The previous work done at NREL contains crucial differences in many of the stages depicted in Fig. 2 compared with the present work. These differences must be carefully considered to provide appropriate comparisons of the systems modeled. The initial NREL model and the updated model used for the new AFEX process data and ammonia recovery approach presented here differ in the approach for biological conversion, plant size, feedstock handling, product recovery, wastewater treatment, and utilities. The difference in the biological processing step is the change from SSCF in the NREL model to CBP or SSCF in the current model. The major differences between these two biological processing options have already been discussed. It is important to note that when the current model uses CBP, 95% conversion of all sugars to ethanol is assumed. Although the AFEX pretreatment meets this test for glucose with SSCF, it has not yet demonstrated this level of conversion with CBP. These assumptions represent future technology and performance. SSCF uses a separate conversion for five carbon sugars than six carbon sugars. For both types of biological conversion the Aspen simulation follows the same process scheme as Eggeman and Elander.

The biomass feed rate for the current version of the model, developed at Dartmouth (Laser et al., in press), has a default feed rate of 5000 dry ton/day, whereas the original NREL model has a default feed rate of 2205 dry ton/day. In this paper, the flow rate for the Dartmouth model was changed back to the original feed rate of 2205 dry ton/day to better compare results with those from the NREL modeling exercise (Eggeman and Elander, 2005).

Other process changes are as follows. Ethanol recovery was changed in the current model from the NREL approach to reduce energy consumption, but still maintain high ethanol purity. The evaporative concentration of ethanol distillation bottoms liquid was eliminated, and a single distillation column with direct steam injection and an intermediate heat pump with optimal side-stream return followed by molecular sieving were used. The wastewater treatment system was switched from a suspended sludge system in the NREL model to an immobilized film anaerobic digester in the current model. For the current model a chilled water system was added to the utilities section to enable full condensation of recycled ammonia in the new ammonia recovery system.

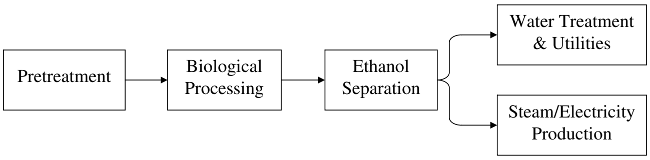

Fig. 2. Overall process diagrams showing major areas of the biorefinery model.

The final major change in the current model is the ammonia recovery approach used with AFEX in the pretreatment stage. In the previous NREL model, the pretreated slurry is flashed and the ammonia vapor compressed and recycled. Ammonia from the flashed solids is removed via evaporation and distillation (Eggeman and Elander, 2005). In the current model, ammonia recovery is achieved by: (1) flashing the pretreated slurry; (2) stripping the pretreated slurry with steam; and then (3) condensing the resulting ammonia vapor (both vapor from the flash and the stripping column) by a combination of direct water quenching and indirect cooling with both cooling and chilled water. Although we are unaware of any existing commercial examples of ammonia recovery via high-solids steam stripping, we envision that the processing equipment will be similar to that used for direct steam drying of solids for which there are an increasing number of commercial examples (Kudra and Mujumdar, 2002; Pronyk and Cenkowski, 2003). The process configurations of the older recompression and the newer quench ammonia recovery approaches are seen in Figs. 3 and 4, respectively.

To use the new quench ammonia recovery approach, the AFEX process must be able to function effectively using ammonium hydroxide rather than pure anhydrous ammonia due to the mixing of water and ammonia in the recycle stream. In contrast, the previous or "classical" approach to AFEX involved adding anhydrous ammonia to biomass containing various moisture levels (Teymouri et al., 2005). Therefore we carried out experiments to determine the effects of the concentration of ammonium hydroxide and how the ammonia (as combinations of concentrated ammonium hydroxide and anhydrous ammonia) and water are added to corn stover on the resulting enzymatic hydrolysis yields. A summary of these experiments can be found in Table 2. In each case, the final ammonia (as anhydrous) to dry biomass loading is 1:1 and the water to dry biomass loading is 0.6:1, AFEX treatment temperature is 90 °C and treatment time is 5 min. These are AFEX treatment conditions identified as optimal for corn stover in our previous research (Teymouri et al., 2005) and are referred to hereafter as "standard conditions".

The first row shows the expected results for the "classical" AFEX treatment, in which all the ammonia is added as anhydrous ammonia and all the water is added to the corn stover prior to adding ammonia, at these standard conditions. Equal or better hydrolysis results compared to classical AFEX (highlighted in Table 2) are achieved under some sets of conditions using concentrated ammonium hydroxide rather than just anhydrous ammonia. The total amount of water present at the end of the treatment (60% dry weight basis) includes about 10% moisture present initially in the dry stover. Thus we have demonstrated that all of the ammonia need not be added as anhydrous ammonia, thereby reducing the capital and operating costs of the AFEX process. The last four lines in Table 2 summarize hydrolysis results obtained when all the ammonia is added as ammonium hydroxide. Under these conditions, sugar yields tend to be lower with lower ammonium hydroxide concentrations. These interesting results are being studied further in our laboratory using a new AFEX equipment approach and reduced ammonia and water to biomass loadings. Results of these investigations will be presented in future publications.

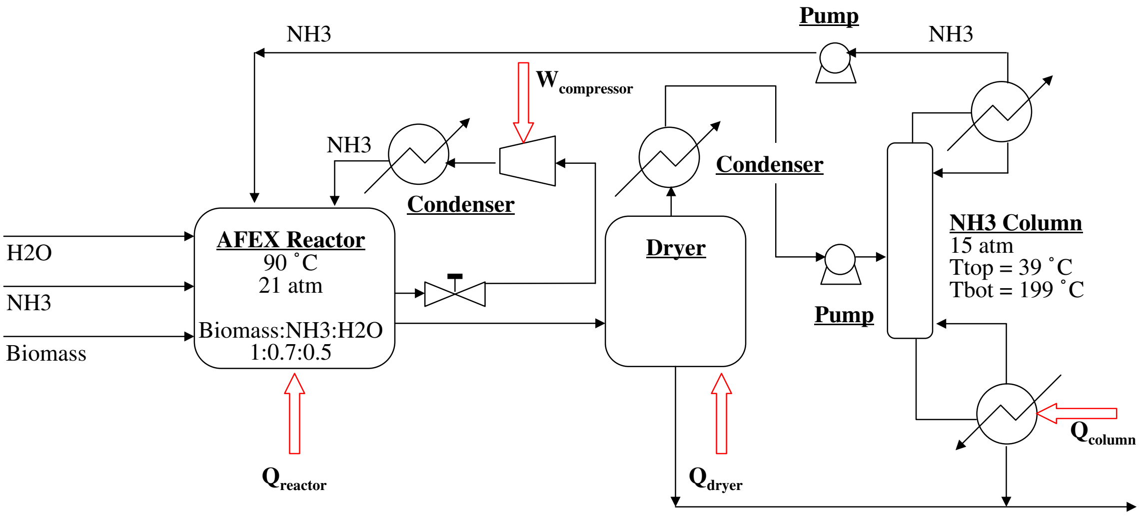

Fig. 3. Process diagram of the pretreatment stage of the biorefinery using previous, recompression ammonia recovery approach; AFEX reactor conditions varied during simulation.

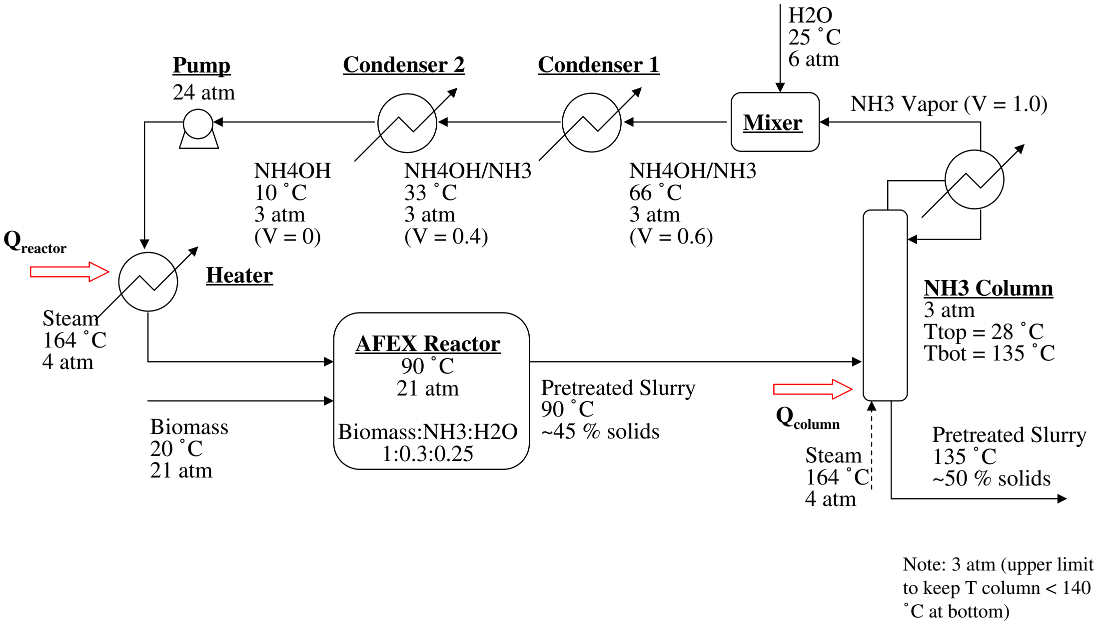

Fig. 4. Process diagram of the pretreatment stage of the biorefinery using new quench ammonia recovery approach; AFEX reactor conditions varied during simulation.

4. Laboratory studies

Another key AFEX techno-economic parameter determined by previous modeling is the ammonia to dry biomass ratio. Ammonia exists in the AFEX reactor as either ammonia gas (in the vapor phase) or as ammonia in contact with the biomass (as ammonia dissolved in water or some other form). Gaseous ammonia can have no effect on biomass chemistry or structure and hence is ineffective in promoting enzymatic hydrolysis. To determine the minimum ammonia loadings required for effective AFEX is therefore to determine effective ammonia loadings when essentially all of the ammonia is confined to the biomass phase by preventing (or minimizing) ammonia evaporation. This was done by pressurizing the AFEX reactor with nitrogen prior to adding ammonia at various loadings and then carrying out AFEX at 90 °C for 5 min. The ratio of ammonia to total system water is kept constant at about 1:0.6. As noted above, AFEX treatment conditions of 90 °C, 5 min, 60% moisture content, and 1:1 ammonia to dry biomass ratio are the "standard conditions" against which results at other treatment conditions are compared in Figs. 5 and 7.

Shown in Fig. 5 is a comparison of the 168 h hydrolysis yields for glucose and xylose under standard conditions with yields obtained at lower ammonia loadings: 0.75 and 0.5 kg of ammonia per kg of dry corn stover ("A" and "B" conditions, respectively). All runs were in duplicate. There is no significant loss in AFEX treatment effectiveness at these lower ammonia loadings. Shown in Fig. 6 are glucose and xylose yields at 72 h of hydrolysis as a function of moisture content at an ammonia loading of 0.5 kg ammonia per kg of dry stover (90 °C and 5 min). Again, there is no significant apparent effect of moisture content on hydrolysis under these conditions. Therefore, the AFEX process is adaptable to both quite dry and quite moist biomass, with little apparent effect on treatment effectiveness. A summary of the time course of hydrolysis for standard conditions and also at the two lower

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Table 2
Glucose and xylose yields after enzymatic hydrolysis for AFEX treated corn stover using different concentrations of ammonium hydroxide (NH_4OH) and different distributions of ammonia and water (NH_3 = anhydrous ammonia, BM = corn stover biomass)

Concentration of NH_3 in NH_4OH (% mass)	Ammonia applied as	Water applied as	% Glucose yield	% Xylose yield
N/A	All NH_3	All in BM	93.0	74.3
50	3/4 NH_3 and 1/4 NH_40H	1/2 in NH_4OH 1/2 in BM	92.2	78.9
33	3/4NH_3 and 1/4NH_4OH	All in NH_4OH	79.9	64.9
41	2/3 NH_3 and 1/3 NH_40H	All in NH_4OH	86.6	70.5
58	2/3NH_3 and 1/3NH_4OH	1/2 in NH_4OH 1/2 in BM	78.2	65.8
50	1/2 NH_3 and 1/2 NH_4OH	All in NH_4OH	57.7	47.9
58	1/2NH_3 and 1/2NH_4OH	3/4 in NH_4OH and 1/4 in BM	85.5	70.4
66	1/2 NH_3 and 1/2 NH_4OH	1/2 in NH_4OH1/2 in BM	97.8	82.0
79	1/2 NH_3 and 1/2 NH_4OH	3/4 in BM and 1/4 in NH_4OH	98.5	78.7
58	1/3 NH_3 and 2/3 NH_4OH	All in NH_4OH	74.5	56.5
73	1/3 NH_3 and 2/3NH4OH	1/2 in NH_4OH 1/2 in BM	81.5	69.7
66	All NH_4OH	All in NH_4OH	71.0	57.0
80	All NH_4OH	1/2 in NH_4OH 1/2 in BM	96.8	79.0
72	All NH_4OH	3/4 in NH_4OH and 1/4 in BM	97.1	79.0
88	All NH_4OH	1/4 in NH_4OH and 3/4 in BM	88.3	75.4
30	All NH_4OH	2.3 g water per g BM	83.6	68.2
15	All NH_4OH	5.6 g water per g BM	70.5	42.5
10	All NH_4OH	9 g water per g 8M	64.9	49.3
5	All NH_4OH	19 g water per g BM	51.3	39.3

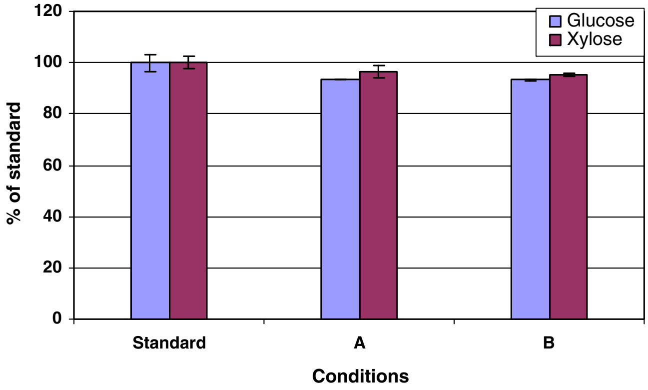

Fig. 5. Glucose and xylose yields after enzymatic hydrolysis at different ammonia loadings compared to yields at standard conditions, 168 h hydrolysis, 60% moisture content at 90 °C, 15 FPU enzyme loading (A conditions 0.75, B conditions 0.5 ammonia loading [kg/kg biomass]).

ammonia loadings is shown in Fig. 7. Initial hydrolysis rates (24 h yields for glucose and xylose) do not diminish at the lowest ammonia loadings compared to standard conditions. Values greater than 100% represent conditions that produce higher yields than standard conditions.

We then tested the effects of various sets of treatment conditions on the 72 h hydrolysis yields of glucose and xylose using ammonia loadings of 0.5 and 0.75 kg ammonia per kg of dry stover, with and without nitrogen pressure. The results plotted in Fig. 8 are the averages of two separate experiments with error bars giving the maximum and minimum experimental values. Clearly, the AFEX treatment is more effective when ammonia evaporation is eliminated or greatly reduced by the nitrogen overpressure.

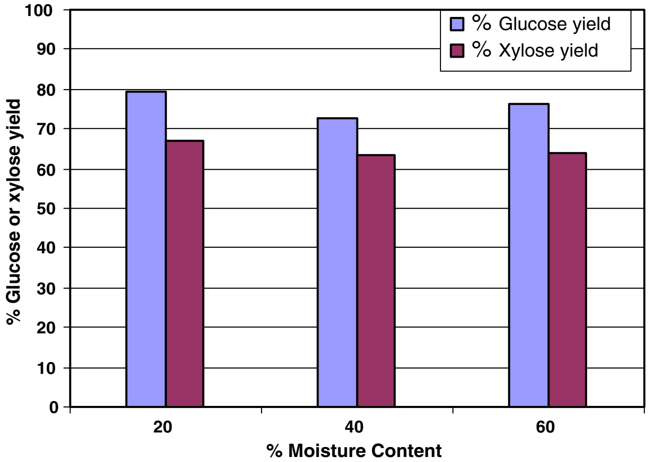

Fig. 6. Glucose and xylose yields after enzymatic hydrolysis at different moisture contents for lower ammonia loading (0.5 kg/kg dry stover at 90 °C, 15 FPU enzyme loading, 72 h hydrolysis).

Finally, we wished to see how much the ammonia loading might be reduced before AFEX treatment effectiveness declined. A summary of these results at 60% moisture, 90 °C treatment conditions, and 16 h hydrolysis can be seen in Fig. 9. The drop off in AFEX treatment effectiveness apparently occurs between about 0.3 and 0.1 kg of ammonia per kg of dry biomass.

Based on these experimental results for ammonia loading and ammonia concentrations required in recycle streams, we assume that an effective AFEX pretreatment for corn stover will result if 0.3 kg of ammonia is used to pretreat 1.0 kg of dry biomass, if the moisture is 0.25 kg per kg dry biomass and if the ammonia is added to the biomass as concentrated ammonium hydroxide at 75% (w/w) ammonia content. These and other conditions are simulated in the process modeling exercise also reported in this work.

5. Results of process modeling

An overall view of the effects on MESP of changing both AFEX process parameters (ammonia loading and concentration of ammonia in the recycle stream) and the configuration of the ammonia recovery process is given in Fig. 10, with these changes addressed individually and in combination. An explanation of the abbreviations used in Fig. 10 is given in Table 3. The new AFEX process parameters show reduced MESP compared to the previous result of $1.41 per gallon (Fig. 1), regardless of the ammonia recovery configuration to which they are applied. The new ammonia recovery approach also shows reduced MESP over the previous recovery approach, regardless of which AFEX process parameters are used. The use of CBP rather than SSCF also provides considerable cost savings. The combination of the new recovery approach with the updated process parameters, in a technology forward context, yields a much improved (lower) MESP.

For the lowest MESP projection at the 2205 dry ton/day scale, feedstock costs are roughly 50% of total manufacturing costs. Thus, even with these considerable process improvements we still fall short of our definition of a "mature" cellulosic ethanol industry, which would have 70% feedstock to 30% processing cost. Increase in plant scale to 5000–10,000 tons per day would increase the ratio of feedstock to processing costs and take us partway toward

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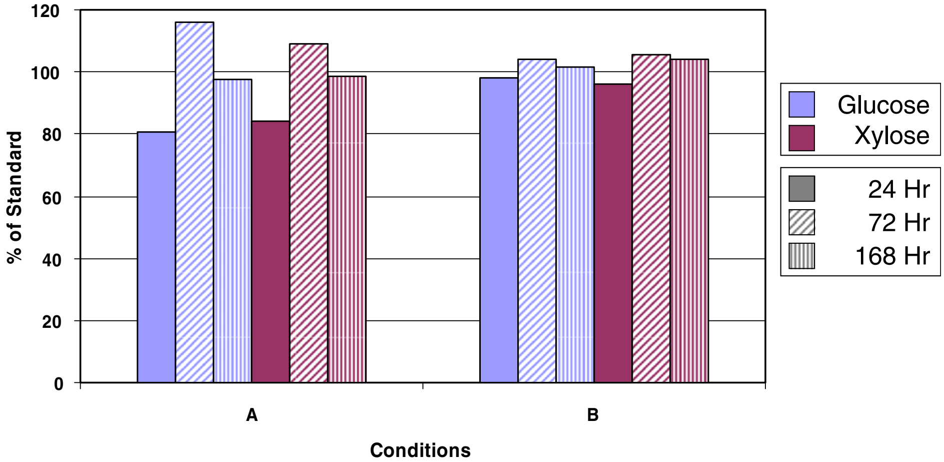

Fig. 7. Glucose and xylose yields after enzymatic hydrolysis at different hydrolysis times as a percent of yield at standard AFEX conditions, 60% moisture content at 90 °C, 15 FPU enzyme loading (A conditions 0.75, B conditions 0.5 ammonia loading [kg/kg biomass]).

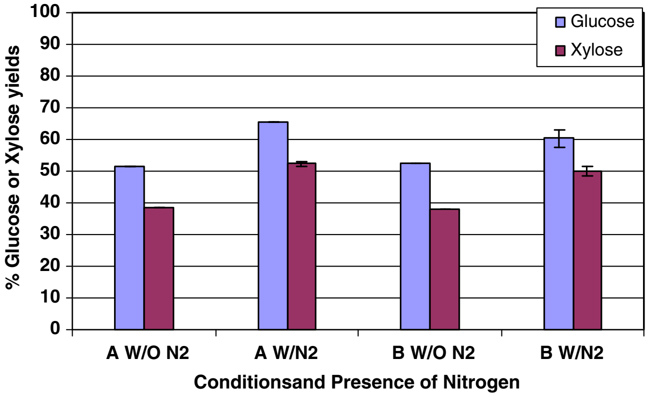

Fig. 8. Glucose and xylose yields after enzymatic hydrolysis of AFEX treated corn stover with and without nitrogen pressure at 15 FPU after 72 h hydrolysis.

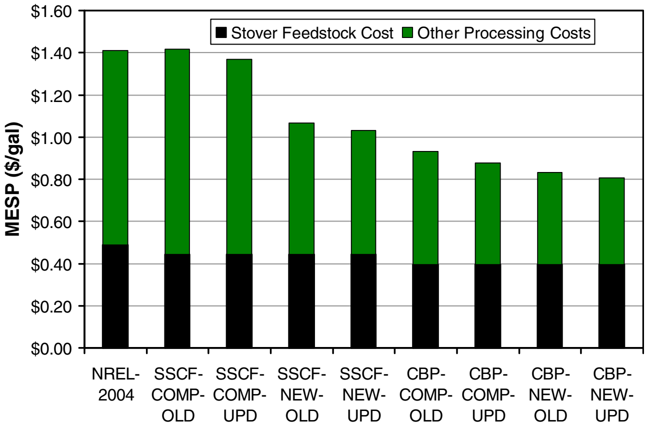

Fig. 10. MESP for the various process simulations listed in Table 3.

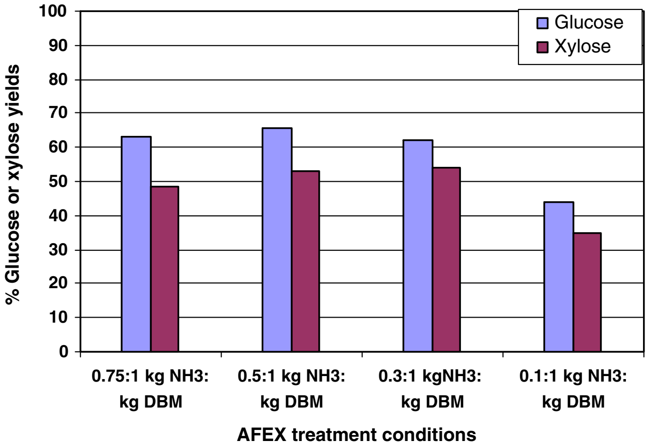

Fig. 9. Glucose and xylose yields after enzymatic hydrolysis of AFEX treated corn stover at different ammonia loadings, 60% moisture content at 90 °C.

Table 3
Abbreviations for simulations tested, producing data shown in Figs. 10–12

Abbreviation	Meaning
SSCF-COMP-OLD	SSCF, NH_3 recompression, old AFEX parameters
SSCF-COMP-UPD	SSCF, NH_3 recompression, updated AFEX parameters
SSCF-NEW-OLD	SSCF, new NH_3 recovery approach, old AFEX parameters
SSCF-NEW-UPD	SSCF, new NH_3 recovery approach, updated AFEX parameters
CBP-COMP-OLD	CBP, NH_3 recompression, old AFEX parameters
CBP-COMP-UPD	CBP, NH_3 recompression, updated AFEX parameters
CBP-NEW-OLD	CBP, new NH_3 recovery approach, old AFEX parameters
CBP-NEW-UPD	CBP, new NH_3 recovery approach, updated AFEX parameters

“maturity” but there still remain further processing cost reductions that can and should be anticipated as these processes mature.

A comparison of the total investment capital (TIC) per annual gallon of ethanol produced for all of the simulations summarized in Table 3 can be seen in Fig. 11. TIC per gallon of annual capacity for the most advanced of these cases is comparable to current TIC per gallon of annual capacity experienced in the corn dry milling industry, which is slightly more than $1.00 per annual gallon for the newest plants. A summary of the operating costs for the simulations listed in Table 3 can be found in Fig. 12. This figure shows the gradual reduction of operating cost as process improvements are made.

The ethanol yields that were assumed for simulation of the biorefinery in all cases are given in Table 4.

6. Discussion

The historical pattern of the processing industries is to reduce processing costs and thus increase the ratio of feedstock cost to

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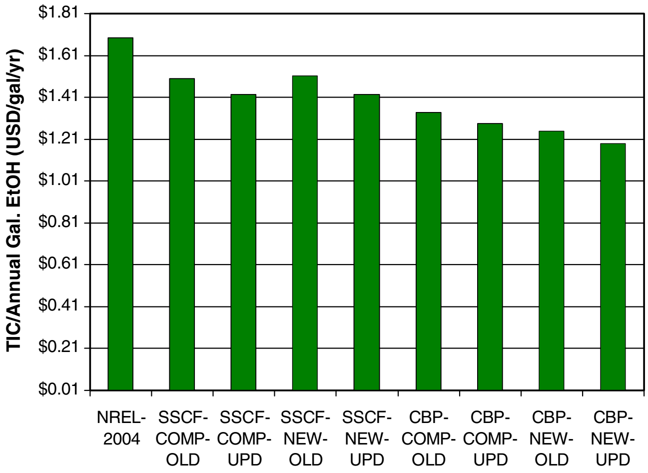

Fig. 11. Total investment capital (TIC) per annual gallon of ethanol produced for simulations described in Table 3 (Eggeman, 2001).

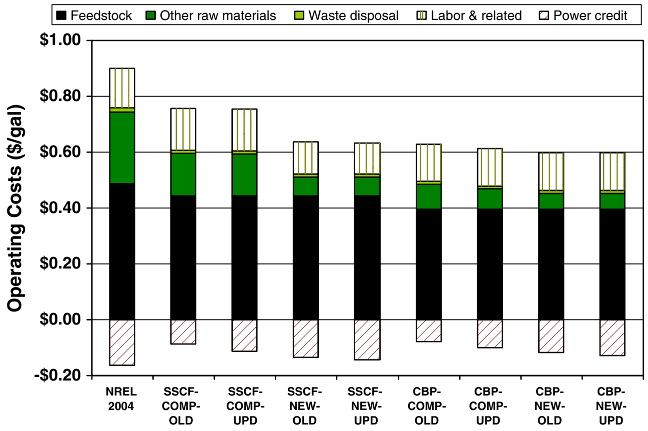

Fig. 12. Break down of operating costs for each simulation listed in Table 3.

Table 4
Ethanol yields for various simulations presented in Figs. 10–12

Scenario	Ethanol yield (gal/dry ton)
NREL 2004	70.5
SSCF-COMP-OLD	69.7
SSCF-COMP-UPD	69.7
SSCF-NEW-OLD	69.6
SSCF-NEW-UPD	69.6
CBP-COMP-OLD	78.1
CBP-COMP-UPD	78.1
CBP-NEW-OLD	78.0
CBP-NEW-UPD	77.9

processing cost. By using the minimum amount of ammonia and water required to carry out AFEX, and recovering and recycling as much of the ammonia as possible in the most efficient manner, processing costs have been greatly reduced compared to estimates which are only two years old. Decreased ammonia loading and lower required ammonia recycle concentrations mean that less total ammonia must be recovered and concentrated per gallon of ethanol produced, reducing both capital and operating costs. The new ammonia recovery process significantly reduces operating costs by using cool water rather than mechanical energy to recover aqueous ammonia. Capital cost for pretreatment, however, is not greatly affected by this new ammonia recovery approach.

As indicated in Fig. 10, SSCF provides attractive ethanol MESP values, but that even better economic performance can be expected if CBP can be realized. In Fig. 10 it is important to note that the feedstock cost/gallon of ethanol in all the cases is approximately equal. The cost reductions in all the simulations studied here result directly from new processing developments. As mentioned previously, using petroleum refining as a model for a mature processing industry, process maturity is achieved when approximately 70% of the cost to manufacture is raw material cost, with about 30% as processing costs. Given the current feedstock cost of $40 per ton, process maturity for cellulosic ethanol would result in a MESP of about $0.56 per gallon. Thus even with these advances reported here, process maturity is still some distance in the future.

7. Conclusion

The results of this study demonstrate the importance of well-grounded techno-economic analysis to identify the most important cost elements in a given processing system. Using the results of the thorough and painstaking NREL study, which are only two years old, we were able to focus our experimental studies on those elements of the AFEX process that contributed most to its cost, namely ammonia loading, ammonia recycle concentration and ammonia recovery approach. With that focus, we were able to significantly reduce the estimated cost of the AFEX process and the MESP of ethanol produced in an integrated biorefinery using AFEX as a pretreatment. Based solely on these improvements in AFEX, the predicted MESP was reduced from about $1.41 per gallon to about $1.03 per gallon using SSF as a bioconversion approach. If CBP can be developed and integrated with AFEX, a further reduction in MESP to about $0.80 per gallon can be anticipated.

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