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Ethanol from lignocellulosic biomass: a comparison between conversion technologies

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Abstract

The conversion of biomass into biofuels can increase fuel flexibility and reduce the related strategic vulnerability of petroleum based transportation fuel systems. Bioethanol has received considerable attention over the last years as a fuel extender or even neat liquid fuel. Lignocellulosic materials are very attractive substrates for the production of bioethanol because of their low cost and their huge potential availability. In this paper two different process alternatives for the production of fuel ethanol from lignocellulosic feedstock are considered through a first-principle model of the process. The main objective is the analysis of the energy balance of the different production processes.

Keywords: Bioethanol, process modelling, lignocellulosic feedstock, fermentation, gasification.

1. Introduction

Ethanol produced from lignocellulosic materials has the potential to be a valuable substitute for, or complement to, gasoline. A wide variety of processes for the production of ethanol from cellulosic materials have been studied and are currently under development: lignocellulosic biomass can be converted to ethanol by hydrolysis and subsequent fermentation (in the following denoted as the HF process) or by a thermochemical-biological process, i.e. biomass gasification followed by fermentation (in the following, the TF process) .

In the literature, several flowsheets for the production of fuel ethanol from biomass by hydrolysis and fermentation have been reported. For instance, Wooley et al. [1] describe the global process for ethanol production from wood chips. More recently, Cardona and Sanchez [2] use a process simulator to assess the energy consumption for several process configurations.

On the other hand, although biomass gasification has long been studied [3], its integration with a fermentation process has just started being analysed [4].

The aim of this work is to compare both the HF and TF processes in terms of yield and energy consumption for different flowsheet configurations.

The Aspen Plus™ process simulator is used. Physical property data for many of the key components are not available in the standard Aspen Plus™ and are derived from literature sources [5]. Phase equilibria in the distillation processes, are described by the NRTL model; an ideal Henry law model is adopted to describe the solubility of gases. The reaction units are described by simply fixing the conversions of the specific reactions (as from literature data).

2. The enzymatic process

In the literature, several flowsheets for the HF process are reported. The PFD proposed has been derived from the information collected in previous works [1,2]. As illustrated in Figure 1, the process comprises the following sections:

- biomass pretreatment: hemicellulose and cellulose are freed from the lignin and hemicellulose is converted to C5 sugars;
- cellulose enzymatic hydrolysis: cellulose is broken into fermentable glucose;
- sugar fermentation: C5 and C6 sugars are converted to ethanol;
- ethanol recovery: distillation is used to obtain azeotropic ethanol that is eventually dehydrated by means of molecular sieves;
- wastewater treatment and heat & power generation: the combustion of the lignin and the biogas produced in the wastewater treatment unit is exploited to produce electric energy and steam;

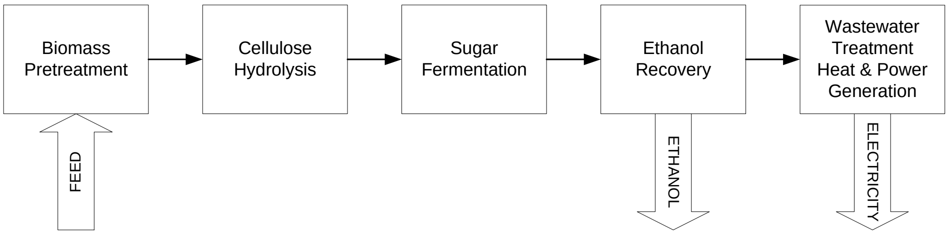

Figure 1. Process block diagram for the HF process.

The hydrolysis and fermentation sections can be designed according to several approaches. The most important ones are the *sequential hydrolysis and fermentation*, SHF (C5 and C6 are fermented into different reactors), the *simultaneous saccharification and fermentation*, SSF (cellulose hydrolysis and C6 fermentation are carried out in the same reactor), and the *simultaneous saccharification and co-fermentation*, SSCF (cellulose hydrolysis and C5 & C6 fermentation are simultaneously carried out in one reactor) [6]. Different process configurations are implemented to take into account the above designs for the hydrolysis and fermentation steps.

Particular emphasis is devoted to the design of a recovery section. The separation is achieved by conventional distillation with schemes patterned after those used in the existing corn ethanol industry [5].

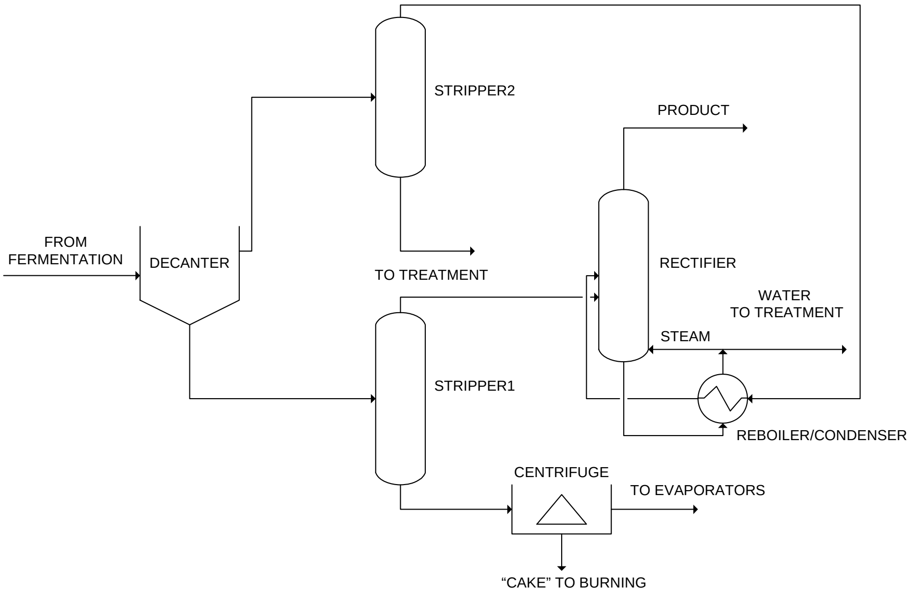

Figure 2. Process flowsheet of the ethanol recovery section in the FT process.

The flowsheet is illustrated in Figure 2. A decanter splits the input stream into two substreams: *i*) a fraction rich in solids, which is fed to an atmospheric column (first stripper) recovering 99% of the product in the distillate (composition: 40% ethanol by weight); *ii*) a second fraction with no solids, which is sent to a pressurised column (second stripper): the distillate (50% ethanol by weight) is used to deliver some of the duty required by the reboiler in the final rectifying column. This last unit is designed to obtain at least a 92% purity in the distillate stream so that molecular sieves can be used to dehydrate the ethanol. The bottoms of the first stripper are fed to a centrifuge to separate the solids from the liquid solution, which is further concentrated through a train of evaporators. The stillage streams from the second stripper and the rectifier are sent to the wastewater treatment section.

The three fermentation alternatives (SHF, SSF, SSCF) are integrated with the recovery section and assessed in terms of ethanol productivity and energy consumption. Results are summarised in Table 1: the SSCF design, i.e. the whole integration of the fermentation process, appears to be the best solution with respect to both ethanol yield and energy costs.

Simulation results also show that by burning the biogas obtained in the waste treatment section and the residual lignin it is possible to generate all the steam required by the process and to produce an electric energy surplus: a plant processing 1000 kton/year of biomass can deliver about 16.9 MW of electric energy to the grid.

Table 1. Comparison of different integration options for the HF process.

Configuration	EtOH yield [L/dry wood ton]	Unit energy costs for distillation step [MJ/L EtOH]	Unit energy costs for evaporation step [MJ/L EtOH]
SHF	270.23	6.39	7.29
SSF	283.73	5.94	6.72
SSCF	310.91	4.41	3.91

Some potential future scenarios are also implemented [6]. Assuming that the yield in the conversion reactor will increase over the years (mainly because of biotech advancement), a short (5 years), middle (10-15 years) and long term scenarios (20 years or more) are simulated and analysed. Results are reported in Table 2 in terms of ethanol yield and energy requirements for the distillation units; there are no significant variation in the energy requirement for the evaporation step.

Table 2. Comparison of different scenarios' performances

Scenario	EtOH yield [L/dry wood ton]	Unit energy costs for distillation step [MJ/L EtOH]
Present	310.83	4.42
Mid-term	360.78	4.07
Long-term	408.45	3.89

3. The thermochemical process

The TF process comprises the following sections (Figure 3):

- Gasification: this is the core of the process where biomass is thermally cracked into a mixture of H_2, CO (syngas), CO_2 and other byproducts;
- gas clean-up and heat recovery: it should be noted that one crucial benefit of this process is that a rather mild purification step is needed and a nearly “crude” gas can be insufflated to the reactor; most of the

steam required by the process is generated here by cooling the gas down to 39 °C.

- fermentation: some bacteria (in particular, the *clostridium ljumgdahlii*) are capable of digesting CO, H_2 and CO_2 to produce ethanol and acetic acid (whose production can be inhibited); the fermentation releases some CO_2, too (in fact, the CO_2 balance is positive, i.e. the fermentation step produces more CO_2 than it consumes);
- ethanol recovery;
- heat & power generation: the unfermented syngas is burnt to produce steam and electricity.

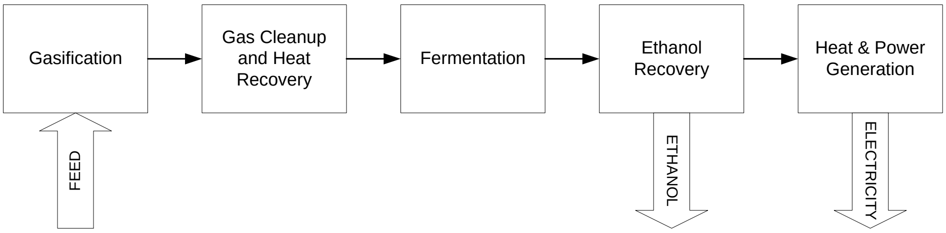

Figure 3. Process block diagram for the TF process.

An equilibrium model of the gasification process is developed and validated by comparison with experimental data [7]. In this case, the most important gasification product is the carbon monoxide, which is more efficiently converted to ethanol. After comparing steam and oxygen gasification, it is found that the best operation is to use pure oxygen for the gasification step (air is not recommended since it excessively dilutes the product stream). A value of 0.35 is chosen for oxygen/biomass ratio (by weight). The simulated mole composition on a dry basis for the gasification output stream is: CO 47.8%, CO_2 15.1%, H_2 37.1%. The gasification model is incorporated within the plant model: the gas stream is cooled down (steam is produced) and then fed to the fermentation tank. It is assumed that a 80% conversion for CO and a 40% conversion for H_2 are obtained.

Several process configuration are compared. In particular, it was verified that ethanol conversion can be boosted by recycling the unfermented syngas. Additionally, since ethanol concentration in the fermentation broth is very low (2.4% weight fraction), the distillation step is rather energy demanding. However, by allowing some ethanol (0.1% by weight) in the bottoms of the rectifying column, which are then recycled back to the fermenter, it is possible to significantly reduce the energy requirement without losing any significant amount of ethanol.

The energy consumption for the ethanol recovery step is about 10.5 MJ per liter of ethanol produced. This is much more that the energy required by the distillation units in the HF process. However, this energy is also generated internally without the need for any external input: steam is produced by cooling down the output gasification stream and by burning the unfermented gas stream (containing unreacted H_2 and CO). Besides, the steam can also be used to produce electric energy. Beyond the electricity needed by the plant, it is estimated that by processing 1000 kton of biomass per year it is possible to deliver about 15.8 MW of electric energy to the grid.

The overall process yield is about 418 L per ton of dry wood (sensibly higher than the yield in the HF process). If in this case, too, we assume a future potential increase in the conversion step (90% and 70% conversions are assumed for CO and H_2, respectively [8]), the total yield could be increased up to 500 L per ton of dry wood. In this work, no improvement is taken into account as far as the inhibition of ethanol in the fermentation broth. Therefore, the increase in the yield does not determine corresponding significant savings in the distillation section.

4. Final remarks

The enzymatic and thermochemical routes to ethanol have been modelled and compared to each other in term of product yield and energy consumption.

Both processes showed a great potential for fuel ethanol production and related costs reduction. In particular, the thermochemical process appears to be a very interesting alternative to produce ethanol because of the higher yield. Nonetheless, some future work is required to analyse the operational and fixed costs for the two technologies in order to assess the resulting price for the ethanol being produced and the return on investment.

References

1. R. Wooley, M. Ruth, J. Sheehan, K. Ibsen, H. Majdeski and A. Galvez. Report No. NREL/TP-508-26157, National Renewable Energy Laboratory, Golden, CO (U.S.A.), 1999.
2. C.A. Cardona and O. J. Sànchez, Energy, 31 (2006) 2447.
3. C. Higma and M. Van der Burgt, Gasification, Elsevier Science, Burlington (USA), 2003.
4. J.M.N. Van Kasteren, D. Dizdarevic, W. R. van der Waall, J. Guo and R. Verberne, Bio-ethanol from syngas, Technical Report, Technische Universiteit Eindhoven & Ingenia Consultants & Engineers, 2005.
5. R. Wooley and V. Putsche, Report No. NREL/MP-425-20685. National Renewable Energy Laboratory, Golden, CO (U.S.A.), 1996.
6. C.N., Hamelinck, G. van Hooijdonk and A. Faaij, Biomass and Bioenergy, 28 (2005) 384.
7. D.L. Klass, Biomass for Renewable Energy, Fuels, and Chemicals, Academic Press, 1998.
8. P.L. Spath and D.C. Dayton, NREL/TP-510-34929, National Renewable Energy Laboratory, Golden, CO (U.S.A.), 2003.