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Techno-Economic Aspects of a Wood-to-Ethanol Process: Energy Demand and Possibilities for Integration

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Full-scale ethanol production from spruce has been evaluated, mainly from an energy perspective, using an Aspen Plus-model including all major process steps. The model input was based on data recently obtained on lab scale or in a process development unit. A number of different process configurations are presented in order to demonstrate how heat integration within the ethanol process significantly reduces the energy demand, and thereby the production cost. Co-location and integration with a combined heat and power plant is discussed as a way to further increase the energy efficiency and improve the process economy.

1. Introduction

Ethanol is expected to be one of the main renewable alternatives replacing fossil fuels in the transport sector. Therefore, it plays a crucial part in achieving the goal set by the European Commission to replace 20% of conventional fossil fuels by 2020. Traditional ethanol production is based on materials rich in sugar or starch, e.g. sugarcane, corn or wheat. However, to be able to meet future increasing demands, ethanol also needs to be produced from lignocellulosic feedstock, such as different types of wood and agricultural residues.

A process based on enzymatic hydrolysis and fermentation is today regarded as the most promising alternative in converting the carbohydrates in lignocellulosic materials into ethanol in an energy-efficient way with high yields and low production cost (Galbe and Zacchi, 2002; Wooley et al, 1999). Pilot scale production plants and pre-commercial demonstration facilities have recently been taken into operation in several places world-wide (Abengoa Bioenergy Corp, USA; Iogen Corp, Canada; SEKAB, Sweden). However, the process concept has not yet been demonstrated on industrial scale.

Live steam required in the process is generated in a steam boiler by burning part of the solid residue together with the concentrated liquid from evaporation of the stillage and possibly some biogas generated in wastewater treatment (WWT). The excess solids, which mainly consist of lignin, can be made into pellets or be burnt in order to generate heat and electricity, and thus serve as a valuable co-product. The energy demand of the process affects the amount of solid fuel co-product, and high energy efficiency is of great importance for the process to be economically feasible.

This study is a techno-economical evaluation of ethanol production from spruce. It is intended to form the basis for a forthcoming investigation on the potential for further reductions of the production cost and improvements of the overall energy efficiency by process integration of a wood-to-ethanol process with a combined heat and power plant. The study focuses on the energy demand and efficiency, and one of the aims was to identify and quantify heat losses in the process. The ethanol process was evaluated using a model including all major process steps, since changing the conditions in one process step is likely to affect other parts of the process.

2. Material & Methods

2.1 Raw material

In Sweden spruce is considered the main alternative as feedstock in a wood-to-ethanol process, due to its abundance and relatively high content of carbohydrates that can be hydrolysed to fermentable sugars. The dry raw material consists of 59.3% hexosans (glucan, mannan and galactan), 8.0% pentosans (xylan and arabinan) and 27.5% lignin. The remaining 5.2% is made up of acetyl groups, ash and extractives. The dry matter (DM) content was assumed to be 45%. Theoretically, 426 litres of ethanol can be produced from the hexose sugars per dry metric ton of raw material. An additional 59 litres can be produced if also the pentose sugars are converted to ethanol.

2.2 Process description

The proposed ethanol plant is assumed to be located in Sweden, with the capacity to process 200 000 dry tons of raw material annually. The process design, based on SO_2-catalysed steam pretreatment followed by simultaneous saccharification and fermentation (SSF), has been described in more detail elsewhere (Sassner et al, 2007; Wingren, 2005; Wingren et al, 2006) and only comments on minor modifications will be provided here.

Process data for the pretreatment (205 °C, 1.25% SO_2) and SSF steps were based on results recently obtained in the experimental and analytical work performed on lab scale or in a process development unit at the Department of Chemical Engineering, Lund University, Sweden. The overall ethanol yield, including yeast production and ethanol losses in the process, is 295 litres per dry metric ton, corresponding to 69.3% of the theoretical value, based on the hexosan content in the raw material.

The ethanol concentration obtained after SSF is 4.0% [w/w]. Distillation and molecular sieve adsorption are used to produce pure (>99.8%) ethanol. The distillation step consists of two stripper columns (20 trays each with 50% Murphree efficiency) and a rectification column (40 trays with 75% Murphree efficiency), which are heat-integrated in order to reduce the energy demand (see Fig. 1). The remaining water in the overhead vapour leaving the rectifier is removed in the dehydration columns, which are regenerated with a pure ethanol stream. The regenerate is returned to the rectifier.

The evaporation system consists of five effects with 4-bar steam as heating medium in the first effect (see Fig. 1). Boiling point elevation was accounted for (Larsson et al, 1997) and overall heat transfer coefficients were varied between 700 and 2000 W/m^2 °C depending on the temperature and concentration of the liquid. The pressure in effect 5 is 0.2 bar. The stillage streams leaving the two stripper columns are fed to evaporator

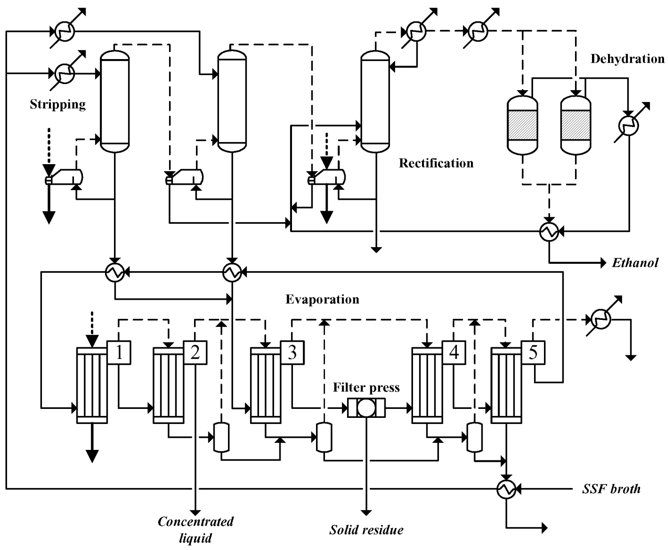

Fig. 1. Flowsheet for the base case distillation and evaporation steps.

effect 3 before the water-insoluble fraction is separated. The temperature is thereby somewhat reduced before the solid-liquid separation takes place. The solid residue (40% DM) is fed to the dryer, while the liquid fraction is returned to evaporator effect 4. The liquid leaving effect 2, with an assumed dry matter content of 60%, is sent to combustion.

Wingren et al. (2006) suggested a number of alternative configurations of the evaporation step, which reduce the energy demand and thus the production cost. Two of them will be considered here; a) the use of eight evaporator effects instead of five, and b) mechanical vapour recompression (MVR) applied to the first effect followed by three conventional effects, which utilise flash vapour from expansion of the condensate leaving effect 1.

Part of the evaporation condensate is recycled to the SSF step. The rest is sent to the WWT facility, where it is treated by anaerobic digestion followed by an aerobic step together with the flash streams mainly originating from the pretreatment step. Experimental data regarding treatment of the process streams in question are scarce, making the performance of this step very uncertain. It was assumed that 50% of the COD is converted to biogas, producing 0.35 m^3 methane per kg COD consumed.

The drying of the solid residue from 40 to 88% DM was modelled as a steam dryer working at 4 bar with superheated steam as the drying medium. A requisite amount of the dried solid residue, set to match the process steam demand, is burnt in a steam boiler together with the concentrated liquid from evaporation to produce live steam for the process. Excess solid residue is made into pellets and sold as a solid fuel co-product.

2.3 Methods

Mass and energy balances were solved using the commercial flowsheeting program Aspen Plus (version 2004.1 from Aspen Technology), and capital costs were estimated either with Icarus Process Evaluator (version 2004.2 from Aspen Technology) or from vendor quotations. The annual capital cost was determined by multiplying the fixed capital investments by an annuity factor of 0.110. All costs have been converted to euros (€) from Swedish kronor (SEK), using an exchange rate of 9 SEK/€. The feedstock cost (14.2 €/MWh) and the income from selling the solid fuel (20.8 €/MWh) are based on current Swedish wood prices. Other costs used in the study are reported elsewhere (Sassner et al, 2007).

3. Results & Discussion

3.1 Energy demand

An energy flow diagram of the base case configuration is presented in Fig. 2, in which the thickness of each arrow represents the energy content (based on heat of combustion) relative a reference state of 10 °C (assumed ambient temperature) and water in liquid phase. Of the 139.2 MW originating from the spruce chips, 48.5 MW ends up as ethanol and 41.5 MW as pellets. The overall process heat duty in the form of boiler-generated steam is 32.7 MW.

Heat losses are represented by the black arrows. A considerable amount of heat (16.9 MW) is lost due to condensation of the vapour leaving the last evaporator effect. The heat losses in SSF and distillation are also due to cooling. The high moisture content (32%) of the fuel used for steam generation results in unutilised heat leaving the combustor in the form of vapour in the flue gases. Also in WWT, a significant amount (11.6 MW, mainly in the form of sludge) is unutilised, but as the process step is associated with great uncertainties it will not be further discussed here.

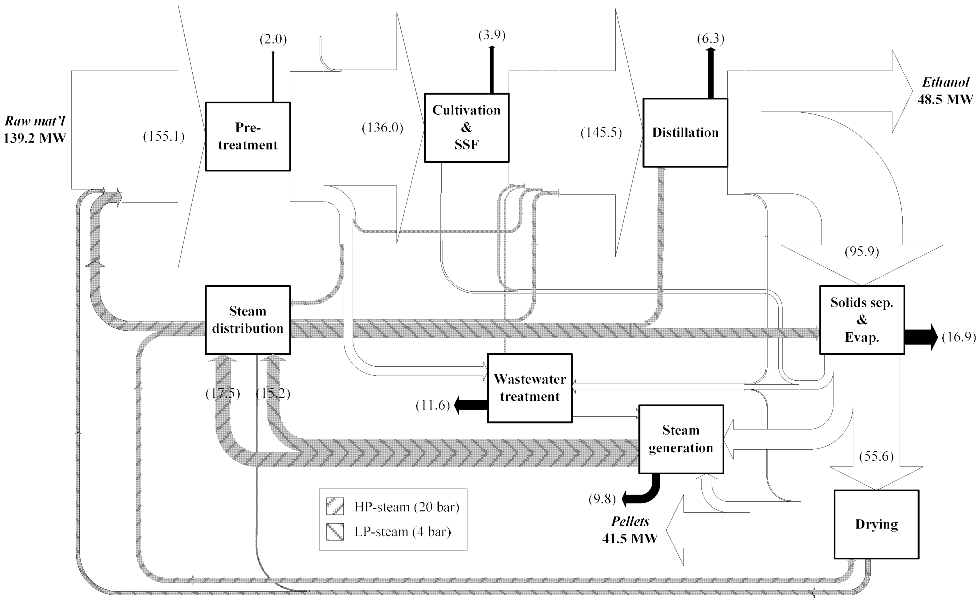

Fig. 2. Energy flows (in MW) in the base case configuration. Bordered arrows represent real process streams, while arrows without borders are heat flows, representing the net flow of energy.

Cost- and energy related process data for the base case and the alternative process configurations are summarised in Table 1. The energy efficiency is defined as the energy output in the products (ethanol and solid fuel), based on the higher heating values, divided by the energy input, comprised of the raw material, electric power requirement (assuming an electricity-to-fuel ratio of 0.3) and a minor contribution from the addition of enzymes and molasses (for yeast cultivation).

In the base case configuration the energy demand of distillation, including preheating of the SSF broth, and evaporation constitutes 76% of the overall process heat duty. The distillation step, as configured in Fig. 1, is already a rather well heat-integrated system. Energy demand reductions mainly rely on future process improvements, such as more efficient carbohydrate-to-ethanol conversion including utilisation of the pentose fraction, and increased substrate concentration in SSF, provided that the ethanol yield is maintained. These improvements would result in higher ethanol concentration in the distillation feed stream. For instance, an increase of the ethanol concentration from 4 to 5 wt-% reduces the energy demand in distillation by approximately 12% on a per litre of ethanol basis.

The low dry matter content (4.4%) of the liquid fraction of the stillage makes evaporation an energy-demanding step. With eight effects instead of five, the overall heat duty is reduced by 14% and the production cost by 2.3%. Applying MVR to evaporation results in 34% lower heat duty and 5.7% lower production cost. The cooling need in the condenser is reduced to 5.7 MW. Although the entire solid residue is pelletised and sold, the MVR configuration results in a surplus of secondary steam corresponding to 1.7 MW, which is condensed by cooling water. The energy efficiency is increased to 63%. It should be noted that improvements in process performance, e.g. as those mentioned above, would make the alternative process configurations less advantageous.

3.2 Co-location and process integration with another plant

Co-production of ethanol, electricity and heat (for district heating), by co-location and process integration of the ethanol plant and a biomass-based combined heat and power (CHP) plant has been proposed as a promising alternative for Swedish conditions. The concept has the potential to drastically increase the energy efficiency and reduce the ethanol production cost. A study on co-production of ethanol and electricity from

Table 1. Energy- and cost-related process data

	Base case	8 effects	MVR
Heat (MW / MJ L^{-1})	32.7 / 15.8	28.1 / 13.6	21.4 / 10.4
Electricity (MW / MJ L^{-1})	4.6 / 2.2	4.6 / 2.2	6.0 / 2.9
Fraction of the dried solid stream used in the steam boiler (%)	23	12	0
Energy efficiency (%)	58	61	63
Production cost (€ L^{-1})	0.473	0.462	0.446
Co-product credit (€ L^{-1})[a]	0.106	0.120	0.136

[a] *included in the production cost*

softwood, based on conditions in California, USA (Kadam et al, 2000), showed that significant capital cost reductions could be obtained, resulting in improved process economy.

Live steam required in the ethanol process is provided by the CHP plant. No separate steam generation system is thus needed in the ethanol process, which significantly reduces the investment cost. The solid residue and the concentrated liquid from the ethanol process are used for steam generation in the CHP plant. The implementation of flue gas condensation for generating heat used in a district heating distribution net greatly improves the boiler efficiency, and also reduces, or even removes, the need for drying the solid residue. If applicable, the evaporation and distillation steps can be configured in such a way that the waste heat is available for district heating, reducing the demand for cooling water. Other benefits with a co-location would be that some buildings and facilities as well as some work force can be shared. Furthermore, shared feedstock handling may guarantee a more consistent quality of the feedstock used for ethanol production (e.g. bark-free) to a higher degree than a stand-alone process, resulting in higher productivity. Finally, the process economy of a stand alone process is very dependent on the ethanol yield. The higher flexibility of the integrated plant concept probably reduces this dependency. This makes co-location economically less risky, which may be of importance for a successful full-scale introduction of ethanol production from lignocellulosic feedstock.

4. Conclusions

For a wood-to-ethanol process, the production cost is highly dependent on the energy demand. Heat integration within the ethanol process is possible to a large extent, and this significantly reduces the energy demand, and thereby the production cost. Co-location with a combined heat and power plant, which currently is investigated, has the potential to increase the energy efficiency and reduce the production cost even further.

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