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High Solids Loading in Ethanol Production – Effects on Heat Integration Opportunities and Economics

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Production of lignocellulosic ethanol still suffers the drawback of high production cost. Methods for making the process more cost efficient are therefore of high importance for commercialising large-scale production. One way of improving the process economics is to ensure efficient heat integration within the process, thereby reducing process energy costs. Another opportunity to improve production costs is to design the process for high solids loading in the bioreactors. By operating the process with higher solids concentrations (so-called high-gravity), water flows through the process will be reduced, which would enable smaller equipment and lower energy demand for downstream separation and purification of the ethanol product. However, problems with pumping and mixing are also likely to occur due to higher viscosities. Furthermore, the yield will be lower due to increased concentration of inhibitors. In addition, the opportunities for heat integration within the process will be affected. In this paper, the effect on heat integration opportunities of the high gravity concept is investigated for ethanol production in a stand-alone process in which fractionation of the softwood raw material is assumed to be achieved with steam explosion. Estimations of how the process economics will be affected are also provided.

1. Introduction

Lignocellulosic raw materials can provide environmental and strategic benefits for the production of ethanol or other biofuels and chemicals (Viikari et al., 2012). One of the main barriers for commercial large-scale production of lignocellulosic ethanol is the high cost of production (Balat, 2011). Methods for making the process more cost efficient are therefore of high importance. One opportunity to improve production costs is to minimise the process energy demand by increasing the process heat integration or by designing the process for high solids loading in the fermentation step. The higher solids loading (also called high-gravity) reduces the water flows through the process and thereby the energy demand, especially in the distillation step (Modenbach and Nokes, 2013).

Bechara et al. (2014) applied a rigorous optimisation methodology to minimise the need for external hot and cold utility in steam explosion lignocellulosic ethanol process. The results show that working at high gravity conditions in the hydrolysis reactor (20 % solid loadings in the optimal case, versus 2 % in the base case) could be advantageous. However, difficulties will arise when operating at high gravity conditions, such as problems with pumping and mixing due to higher viscosities and lower yield due to increased concentration of inhibitors (Koppram et al., 2014).

In previous studies, the effect of high gravity was investigated for an alkaline-based ethanol process integrated with a pulp mill. Heat integration opportunities and energy balances were established for the integrated concepts, both for high gravity process conditions and more conventional solids concentrations and the overall economics of the ethanol production were evaluated (Lundberg, 2015). The conclusion was that the cost of distillation, contrary to what is often claimed, is not the major advantage of high gravity. Instead, the cost of stillage treatment and assumptions about how this is done were of significance. If the stillage was assumed to be evaporated, high gravity brought large energy and cost advantages. Consequently, it seemed to be mainly the evaporation and not the distillation that was most

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affected by high gravity conditions. Not surprisingly, the studies also confirmed the absolute importance of maintaining the yield at a high level also when increasing the dry solids concentration in the process.
In this paper, the effect of high gravity is investigated for ethanol production in a stand-alone process, in which the wood fractionation is assumed to be achieved with steam explosion instead of alkaline pre-treatment.

2. Studied systems

Figure 1 shows a simplified process layout of the steam explosion to ethanol production process set up in the simulation program WinGEMS. The incoming wood (Win) is softwood containing about 62 % fermentable C6 sugars and 28 % lignin, while the rest is C5 sugars and extractives. The ethanol production process begins with a steam pretreatment procedure which is considered to be efficient on woody biomass (Wingren, 2005). In the pretreatment step, sulphur dioxide (SO_2) and steam (HP, LP) are used to modify the incoming raw material to facilitate the subsequent enzymatic reaction (Sassner, 2007). Before entering the pre-hydrolysis and SSF (Simultaneous Saccharification and Fermentation) procedure the slurry from the pretreatment is flash-cooled in two steps (F1, F2) and diluted to a concentration of about 13 % WIS (water-insoluble solids) for the conventional case or to 30 % WIS for the high gravity case followed by cooling to about 37 ºC. The higher solid loading represents an upper limit of what it possible to achieve today with agricultural residues in experimental settings and in a pilot plant scale and has recently been used as an input to a process model of a lignocellulosic based ethanol process (García et al., 2013). Data for the hydrolysis and fermentation processes in this study are based on experimental studies; see Wingren (2005) for conventional and Xiros and Olsson (2014) for high-gravity data. The unfiltered broth from the SSF consisting of ethanol, water and solids such as lignin and yeast, is first preheated and then transported to a distillation plant for concentration of ethanol and separation of water and solids. The stillage from the distillation contains both suspended solids (mixture of lignin and carbohydrates) and dissolved solids (pentosans, glucose, extractives etc.) that are separated from the thin stillage by a pressure filter. The thin stillage is evaporated and then burned in a power boiler to produce steam. Part of the separated solid residue is burned in the power boiler to balance the steam demand and the rest is dried and pelletised and sold as a fuel.

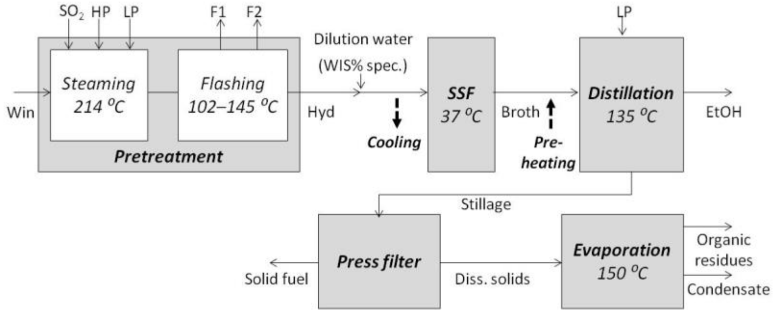

Figure 1: Simplified process layout of the steam explosion pre-treatment process.

The same simulation model and process specifications were used for the conventional and high gravity model with the exception of the amount of dilution water (which leads to different WIS%) and the ethanol yield, as shown in Table 1. The steam demand of the Conventional and High Gravity cases varies significantly. According to the results from the process simulation, the total steam demand of the High gravity (reduced yield) case is nearly 50 MW smaller than the conventional case. This is explained by the different water flowrates after SSF, which affects all the downstream operations. Accordingly, the largest differences are seen in the evaporation plant (26 MW) and in the preheating of the feed to the distillation plant (16 MW). Since the reduction in yield due to the higher solids loading is highly uncertain, the effect of assuming different yields is illustrated by having two high gravity cases – one with reduced yield and one with the same ethanol yield as the conventional process, called High Gravity (maintained yield). However, no process model has been built for this case, and the numbers for the steam demand are therefore estimations based on the results from the two other cases.

Table 1: *Key data for the ethanol process before heat integration retrofits.*

		Conventional	High Gravity (reduced yield)	High Gravity (maintained yield)
Win: wood input	BDt/h (bone-dried t/h)	75.0	75.0	75.0
HP: high pressure steam	°C	214	214	214
LP: high pressure steam	°C	150	150	150
F1: flash 1	°C	145	145	145
F1: flash 2	°C	102	102	102
Hyd: Hydrolysate	WIS% (water-insoluble solids)	13	30	30
EtOH: Ethanol production	t/h	16.1	13.0	16.1
Ethanol yield on wood	% w/w	21	17	21
Total steam demand	MW	122.2	72.8	73.9
Specific steam demand	MJ/lEtOH	21.8	13.0	13.2

3. Methodology

The analysis will focus on the changes in pellets and bark exports, electricity production, investment costs for distillation of different configurations (including the investment cost of the retrofits involved in the integration scheme) as well as on the effect of the yield. The methodology for heat integration, as well as for investment costs estimation is described in Lundberg (2015).

A performance indicator called profit opportunity was defined to compare the high gravity case with the conventional solids loading. This profit opportunity represents the known (calculated) economic benefits of high gravity compared to conventional process conditions and is defined as:

$$\text{Profit opportunity} = \Delta\text{Revenues}_{\text{EtOH}} + \Delta\text{Revenues}_{\text{Elec}} + \Delta\text{Revenues}_{\text{Bark+Pellets}} - a\Delta\text{Inv}_{\text{Dist+Retrofit}} \tag{1}$$

where $\Delta Revenues_x$ is the difference between revenues of x (Ethanol, electricity produced or bark and pellets exports) in the High Gravity concept compared to the conventional case, a is the annuity factor, which is set to 0.1 and $\Delta Inv_{Dist+Retrofit}$ is the difference in distillation plant and heat integration investment costs for the two concepts.

High gravity conditions are first introduced just before the SSF reactor, therefore the process operations upstream SSF are the same for the conventional and high gravity cases. Accordingly, many of the contributions to the total production cost (e.g. raw material costs or investment costs for the pretreatment step) are the same for the high gravity and the conventional cases, and cancel each other out in the calculation of the profit opportunity. Other costs are unknown or associated with large uncertainties and are therefore left out of the calculation e.g. the electricity consumption or investment costs for other equipment than those related to the distillation plant and heat integration retrofits (such as the SSF reactor, boiler, turbines and pelletizing equipment, see Section 4.3). Therefore, the profit opportunity can be interpreted as the maximum allowed value of the uncertain cost differences for high gravity to be more economical than a conventional process. This means that high gravity can become feasible even if the profit opportunity is negative, provided that the unknown costs for high gravity are lower than their corresponding costs for the conventional case.

4. Results and discussion

4.1 Effects of heat integration for conventional and high gravity process conditions

By conducting retrofits for heat integration, it is possible to reduce the steam demand at both conventional and high gravity conditions, as shown in Table 2. For example, the feed to the distillation plant could be preheated with excess heat available in other process streams e.g. stillage from distillation towers, the surface condenser of the evaporation plant, or the broth to the SSF reactor. Moreover, the steam demand for preheating the wood chips before pretreatment can be significantly reduced if the pretreated material is flashed at a higher temperature than that proposed in the simulation model. In this way, flash steam at a higher temperature can be used to preheat the raw material to a larger extent. To do this, the flashing should be done at 165 °C instead of 145 °C in the first step (F1) and 110 °C instead of 102 °C in the second step (F2). Nevertheless, experiments need to be carried out to ensure that the modified flashing does not affect negatively the properties of the pretreated material.

By retrofitting the processes in the previously described way, it is possible to achieve important steam savings for both the conventional (47 MW of steam savings) and the high gravity processes (34 MW of steam savings). Since the excess heat available is different, larger steam savings are in fact possible for the conventional process than for the high gravity process. Still, the large differences in steam demand for evaporation and distillation make the high gravity process much more favorable in terms of total steam consumption. This advantage is maintained even when calculating the specific steam demand per liter of ethanol produced.

Table 2: Key data for the ethanol process after heat integration retrofits.

		Conventional	High Gravity (reduced yield)	High Gravity (maintained yield)
Win: wood input	BDt/h (bone-dried t/h)	75.0	75.0	75.0
HP: high pressure steam		** Replaced by flashed steam, F1 **		
LP: high pressure steam		** Replaced by flashed steam, F2 **		
F1: flash 1	°C	165	165	165
F2: flash 2	°C	110	110	110
Hyd: Hydrolysate	WIS% (water-insoluble solids)	13	30	30
EtOH: Ethanol production	t/h	16.1	13.0	16.1
Ethanol yield on wood	% w/w	21	17	21
Total steam demand	MW	75.4	38.5	39.7
Specific steam demand	MJ/lEtOH	13.5	8.5	7.1

4.2 By-products exports and distillation costs

The differences in steam demand affect the potential for by-products production. With conventional solids loading, the stillage from the distillation plant is not sufficient to cover the heat demand of the processes. Therefore, in addition to the stillage, all of the bark and some of the pellets are also combusted to provide process heat. For the high gravity case with reduced yield, more stillage and pellets are generated due to the lower ethanol yield, at the same time as less process heat is needed due to the higher concentrations in the process. Therefore, in this case, neither bark nor pellets are needed internally at the ethanol plant and all of it can be sold. In addition, a heat surplus is generated from the combustion of stillage, which enables electricity production in a condensing turbine. For the high gravity case with maintained yield, the heat production from stillage almost exactly covers the heat demand of the process.

Table 3 shows the amounts of bark and pellets that can be exported from the ethanol plant for the different cases, the electricity production (i.e. the total production, not the net export), and the corresponding economic value of these by-products. Note that Table 3 only shows the electricity production. Differences in electricity consumption between the conventional and the high gravity cases are also highly likely to occur, but are not accounted for here (see Section 4.3).

Table 3: Exports of bark and pellets, and production of electricity.

	Conventional	High Gravity (reduced yield)	High Gravity (maintained yield)
Pellets	20.1 t/h	25.9 t/h	24.1 t/h
Bark	0.0 t/h	7.0 t/h	6.7 t/h
Electricity production	18.7 MW	16.3 MW	9.1 MW
Value of pellets (25 EUR/MWh) and bark (20 EUR/MWh)	153 EUR/m^3_{EtOH}	284 EUR/m^3_{EtOH}	214 EUR/m^3_{EtOH}
Value of produced electricity (60 EUR/MWh)	56 EUR/m^3_{EtOH}	60 EUR/m^3_{EtOH}	27 EUR/m^3_{EtOH}
Investment cost for distillation	4.3 EUR/m^3_{EtOH}	4.1 EUR/m^3_{EtOH}	3.7 EUR/m^3_{EtOH}

Although the by-products revenues clearly increase with increased solids loading (calculated as per cubic meter of ethanol), this must be seen in the light of the decreased revenues from ethanol production if the process yield is reduced. Considering the assumed price of ethanol to be 500–650 EUR/m^3_{EtOH} (see Section 4.4), it can be seen that the by-product revenues have a significant importance for the profitability of the process concept. Nevertheless, if high gravity can be accomplished with maintained yield, this is clearly advantageous in terms of by-products exports.

In addition to differences in the potential for by-product production, a clear effect of high gravity is the reduced water flows to the distillation plant. Table 3 also shows the specific investment costs for the distillation plant assuming a configuration with three distillation columns for both conventional and high feed concentrations. As can be seen, there is an advantage for high gravity with respect to the investment cost for distillation.

4.3 Other effects of high gravity

Increasing the solids loading of the SSF process might be a way to reduce the size and thereby the investment costs of the reactors thanks to smaller water volumes. However, several factors are likely to counteract this cost reduction. The main problems of the high gravity process are the increased viscosity and the higher concentration of inhibitors (Koppram et al., 2014). Both these factors have an influence on the process productivity (i.e. on yields and/or residence time). For example, the increased viscosity might require longer residence times to achieve good mixing. If the mixing is not satisfactory, it will not be possible to reach the same yields as for conventional process conditions. Higher concentration of inhibitors will also negatively affect the yield. To diminish the yield reduction, the loading of enzymes and yeast can be increased or chemicals can be added (Xiros and Olsson, 2014), in all cases, the operating costs will increase. The cost of the SSF reactors depends on residence times, volumes and mixing arrangements. There is not sufficient data available to estimate the influence of high gravity on these costs.

Another cost that might be reduced when introducing the high gravity concept is the cost of electricity consumption. With smaller water flows, the need for pumping will decrease. However, the increased concentration will, at the same time, lead to higher viscosities, and thereby greater pressure drops, which risks cancelling out the benefit of the smaller volume flows.

A few costs are the same for the conventional and the high gravity process concept. For example, with the modelled process concept, the pretreatment step will be unchanged when changing the solids loading in the SSF. However, if the yield is assumed to be lower for the high gravity case, these costs will always be higher for the high gravity case expressed in EUR/m^3 ethanol. Nevertheless, in the studied stand-alone steam explosion concept, most parts of the process will be downstream of the SSF reactors and hence subject to higher concentrations, or correspondingly to lower water flows.

4.4 Profit opportunity for high gravity

The profit opportunity is estimated to 5.3 millions EUR/y when the yield for the high gravity process is maintained at the same level as for the conventional case. This is equivalent to an investment of 53 MEUR. Hence, there is substantial room for allowing higher costs in parts of the ethanol plant when going to the high gravity-process – provided the yield is maintained at levels within about 1.5–2.5 percent units from that of conventional process designs. Figure 2 shows that the profit opportunity is significantly below zero for the reduced yield assumed for the high gravity process. Two levels of ethanol selling prices have been assumed for the calculations shown in Figure 2. The price of 650 EUR/m^3 represents an estimated European biofuels selling price including policy support in 2020 as given by the scenario tool ENPAC (Axelsson and Pettersson, 2014). The lower price of 500 EUR/t could, for example, represent a situation with significantly lower policy support levels.

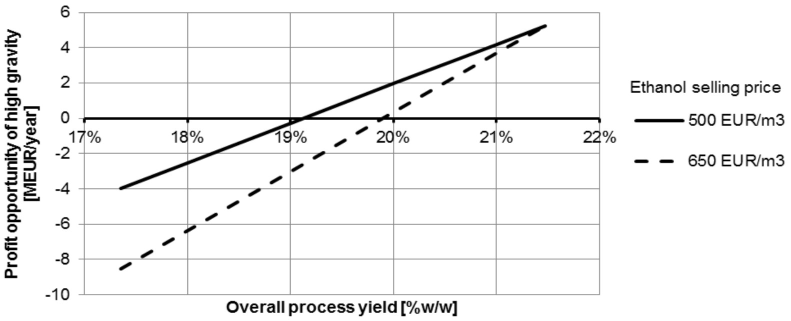

Figure 2: Profit opportunity of operating the ethanol process at high gravity conditions.

There is, however, a potential for high gravity even at negative values of the profit opportunity. In particular, if the productivity is not significantly reduced due to the high gravity process, the costs of bio-reactors might be decreased thanks to the smaller water volumes. On the other hand, the profit opportunity should cover increased costs due to longer residence times, increased chemicals loading, higher electricity consumption and more advanced reactor equipment to handle the more difficult mixing conditions.

Implementing the high gravity concept in the steam explosion process presented in this paper seem more advantageous than in an alkaline-based ethanol process integrated to a pulp mill (Lundberg 2015) This is, at least partially, due to the fact that large steam consumers (in particular the evaporation of stillage) are unaffected by high gravity in the alkaline process (since stillage is sent to effluent treatment or potentially recirculated as process water), whereas in the steam explosion process, a large reduction in the steam demand for evaporation of the stillage is observed.

5. Conclusions

The results from this study suggest that operating at high gravity conditions could be an interesting strategy to decrease the ethanol production cost in a stand-alone steam explosion process. The advantages of the high gravity process are related mainly to a significant decrease in steam demand and a resulting increase of by-products production. However, the benefits of high gravity with respect to by-product production must be compared to the disadvantages of a lower overall yield.

It has been demonstrated that in a high gravity process, there may be room for substantial investments, provided that the yield is maintained at a high level. It was shown that if the yield is maintained at the same level as in a conventional process design, additional annual capital and operating costs for the high gravity process can be up to approximately 5.3 million EUR if the high gravity process should be attractive compared to a conventional plant. These additional costs should be sufficient to purchase most of the extra costs for equipment needed in the high gravity ethanol plant, which includes, but is not limited to, the pre-treatment vessel, the SSF reactor with advanced mixing equipment and the pelletising plant. The available capital should also compensate for the potentially higher costs for mixing and pumping. The results also indicate that the room for investments and higher operating costs decreases rapidly as the overall yield decreases. Accordingly, maintaining a high yield is of critical importance to achieve a good economic performance.

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