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Lignocellulosic biorefinery processes energy integration

María González Alriols[1], Araceli García[1], Fathia Chouaibi[2], Nejib Hajji[2], Jalel Labidi[1]*
[1]Chemical and Environmental Engineering Department, University of the Basque Country.Plaza Europa, 1, 20018, Donostia-San Sebastián, Spain
[2]ENIG, Rue Omar Ibn El Khattab, 6029 Gabès, Tunisia
jalel.labidi@ehu.es

Lignocellulosic biomass, particularly agricultural and forestry residues, is becoming a potential renewable energy and products source. Biorefinery technologies include a primary separation of the main constituents of lignocellulosic biomass: cellulose, hemicelluloses and lignin, as well as further treatment and processing. The aim is to obtain energy and different platform chemicals that will be the base of a complete chemical industry. The economic competitiveness of these processes is highly dependent on the separation and purification technologies used and the process energetic efficiency. Process simulation tools are very useful to design a competitive and effective biorefinery scheme. In the present work, the energetic and economical efficiencies of organosolv-ethanol biorefinery process were analyzed using the simulation software Aspen Plus®. Furthermore, Aspen HX Net software was used to design the heat exchange network in order to improve process energy consumptions. The Pinch technology was successfully applied reducing the associated utilities requirements and making the process more competitive.

1. Introduction

A global energy consumption continuously increasing, the limited character of fossil resources and the instability of oil prices are decisive factors for finding alternative technologies to increase the energy efficiency of industrial processes and to search for other ways to produce energy, heat, electricity, fuels, materials and chemicals. Biomass utilisation is generating considerable interest in the last years (Hoogwijk et al., 2003). Lignocellulosic materials constitute an abundant, available, versatile, and economic source of resources to exploit that, sometimes, are generated as a by-product or residue in agricultural, forest and industrial activities (Zhang et al., 2010). Cellulose, hemicelluloses and lignin are the three main fractions that form lignocellulosic biomass. The extraction, separation and purification treatments of these components are the key point in the process profitability (Mosier et al., 2005). The efficiency of biorefinery processes depends on the energy requirements and solvents and reactive consumptions of the selected route. This way, the simulation of biorefinery processes is a useful tool to analyze their energetic efficiency and to improve the process heat exchange design. In this work, Aspen Plus® software was used to simulate the fractionation process of lignocellulosic biomass into cellulose, hemicelluloses and lignin based on experimental

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data. Organosolv-ethanol process was selected for biomass treatment. This system, known as Alcell®, uses only alcohol as reactant without catalyst or alkali compounds, which greatly facilitates solvent recovery process in addition to obtaining more pure products than other systems (Stockburger, 1993). Lignin, cellulose and hemicelluloses were defined by their chemical structure and physical properties which were obtained from the National Renewable Energy Laboratory (NREL) database (NREL/MP-425-20685; task number BF521004), whereas other conventional components were selected from the ASPEN PLUS data bank. NRTL-RK (Non-Random, Two Liquids - Redlich Kwong) model was used to simulate the thermodynamic properties of solutions in the organosolv-ethanol process.

The process simulation allowed the obtaining of mass and energy balances and to design solvents and reactants recovery and recycle. The energetic and economic efficiency of the process was also calculated. Furthermore, Pinch-based process integration methods (Aspen HX Net software) were applied in order to analyze the energy integration possibilities and to calculate the optimised HEN designed related costs.

2. Process description

Organosolv-ethanol biorefinery process consisted of several stages: raw material fractionation (reaction); separation of solid and liquid fractions; solid fraction (SF) washing; liquid fraction (LF) processing for the obtaining of by-products and the recovery of dissolved chemicals and energy. Organosolv-ethanol process flow sheet is presented in Figure 1. The raw material (biomass) was mixed with the solvent (ethanol-water, 60/40 w/w) in a pressurized reactor (T: 160ºC, time: 90 min, liquid/solid ratio: 6/1 w/w). Once reaction time was finished, the pressure reached during the reaction was reduced up to atmospheric value in a flash operation that allows recovering a stream composed by ethanol and water that was condensed and recycled. Furthermore, a wet solid fraction (SF) mainly constituted by cellulose and a liquid fraction (LF) containing dissolved hemicelluloses, lignin and the remaining solvent were obtained. The SF was sent to the washing stage, where a mixture of ethanol-water with the same concentration used in reaction stage was used for cleaning the fibers. The washed SF is filtrated and the resulting washing liquor (WL) is mixed with the LF from the reactor forming the total liquid fraction (TLF), which was treated to recover by-products and solvents. Firstly, lignin content in LF was obtained by precipitation by adding of two volumes of water. Remaining LF after lignin precipitation was sent to the distillation unit, where a mixture of ethanol-water was obtained as distillate and recycled to the reaction unit. The residue, composed by water and co-products, mainly hemicellulosic sugars, was treated by heating in a flash unit to obtain a clean water stream, which was sent back to the lignin precipitation unit, and a concentrated stream with the remaining process by-products for subsequent treatment and use. The simulation scheme was developed using the following inlet streams to the reactor: 1,000 kg/h of dry raw material and 6,000 kg/h of solvent (ethanol-water 60% w/w). Raw material composition was defined as a typical lignocellulosic non-wood material composition: 45 % cellulose, 28 % hemicelluloses, 25 % lignin, 2 % inorganic compounds (% on a dry weight basis).

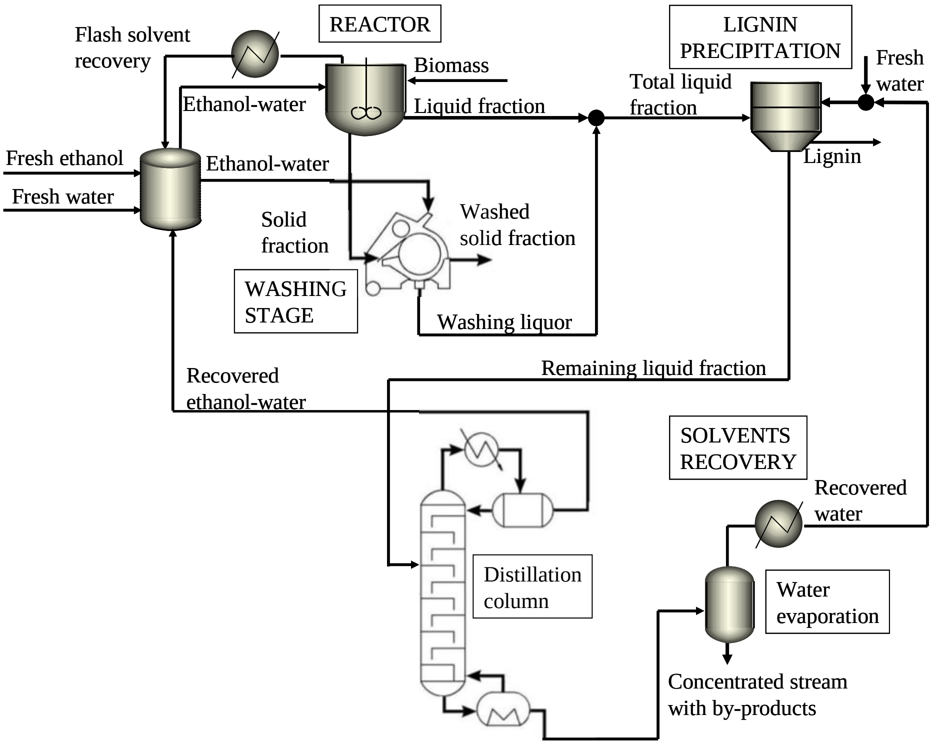

Figure 1: Process diagram of the organosolv-ethanol biorefinery process

3. Results

The utilities consumption associated to the process was calculated and it is presented in Table 1. Low pressure steam (LPS) at 5 bar and medium pressure steam (MPS) at 15 bar were used to heat and water at 20 ºC, which was heated up to 40 ºC, was used for cooling. To determine the corresponding cost of steam and cooling water requirements, a factor of 48 €/kWy (heating) and 4.7 €/kWy (cooling) was applied respectively. As it can be seen, most of the process utilities consumption was associated with the solvents and by-products recovery stages. Thus, in order to improve the costs associated with the utilities requirements, the HEN of the organosolv-ethanol process was analyzed using Aspen HX-Net software.

The grid of the original HEN obtained from the simulation is presented in Figure 2. The hot streams were numbered H1–10 and the cold streams C1–3. The first hot stream, H1, was the stream existing the reactor with the obtained products; H2 corresponded to the by-products (hemicellulosic sugars) stream after solvents recovery; H3 was the recovered water; H4 and H5 were the liquid and vapor streams obtained in the flash stage after the reactor; H6 to H9 corresponded to the obtained lignin fractions by precipitation and H10 was the solid fraction.

Table 1: Utilities requirements and associated costs for the organosolv-ethanol process. MPS: Medium pressure steam; LPS: Low pressure steam; CW: cooling water (20-40 ºC).

	Utility requirements			**Costs**	
PROCESS STAGE	**MPS**	**LPS**	**CW**	**Heating**	**Cooling**
		kg/h		k€/y	
Reaction stage					
Raw material and solvent heating	904	0	0	25.4	0
Products cooling	0	0	10,800	0	12
Post-reaction flash					
Vapor stream condensation	0	0	62,895	0	6.9
Liquid stream cooling	0	0	204	0	5.7
Pulp conditioning					
Pulp washing and cooling	0	0	30	0	0.8
Lignin fractions conditioning					
Lignin fraction cooling	0	0	31	0	0.9
Solvents and by-products recovery					
Liquid fraction heating before distillation	0	332	0	9.33	0
Distillation condenser	0	0	201,130	0	22
Distillation reboiler	0	7,883	0	221	0
Water evaporation	0	4,647	0	130	0
Flash water stream condensation	0	0	4,644	0	130
By-products cooling	0	0	68	0	1.9
Total	**904**	**12,862**	**279,802**	**386**	**180**
Energy (MW)	**0.5**	**8.7**	**9.3**		
GENERATED (kg/h)	**0**	**0**	**0**	**0**	**0**
NET REQUIREMENT	**904**	**12,862**	**279,802**		
TOTAL COST				**566**	

Regarding the cold streams, C1 was the solvent stream; C2 was the distillation unit residue stream and C3 was the remaining liquid fraction that was fed to the distillation column. Utilities were defined as follows: cooling water: CW and medium and low pressure steam MPS and LPS respectively. The analysis gave a minimum hot utility demand of 1.729MW and a minimum cold utility demand of 2.91 MW. The minimum number of heat exchange units was 15 with a total area of 685 m^2. Several improved HEN designs were obtained with HX-net, from which, the one that presented the minimum total cost index was selected. Table 2 presents the actual hot and cold utilities demands for the existing process as well as the ones for the improved calculated design. The grid of the improved HEN design is presented in Figure 3. The improved scheme HEN presented H3 stream divided in two fractions as well as C2 stream. H3 was used to heat a fraction of C2 and C3 streams. Furthermore, H1 was used to heat C1 stream. In this scheme, the heating and cooling demands were reduced in a 30.6% and a 47.3%.

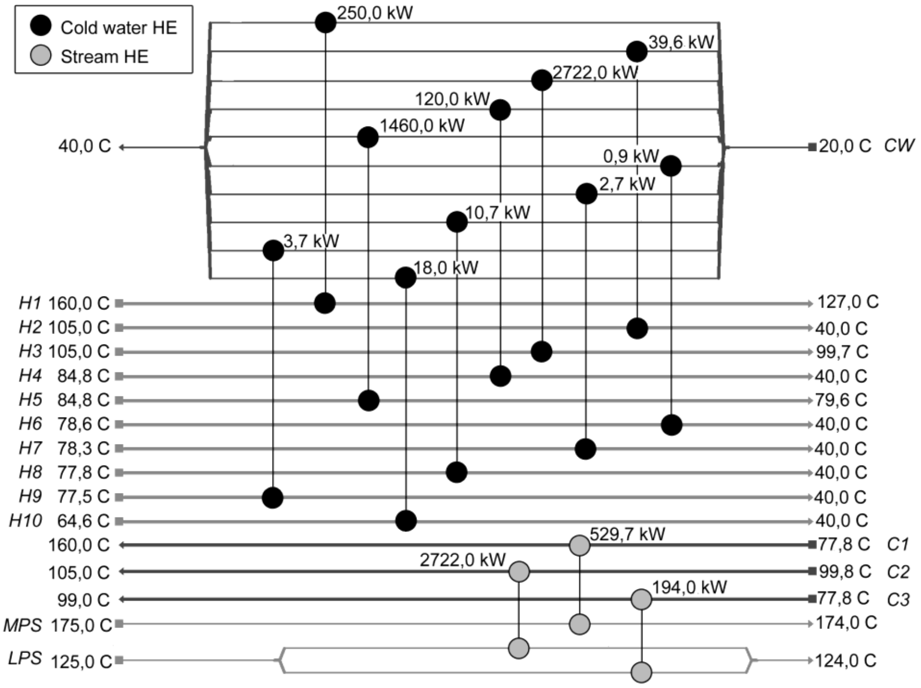

Figure 2: Existing heat exchanger network (base case).

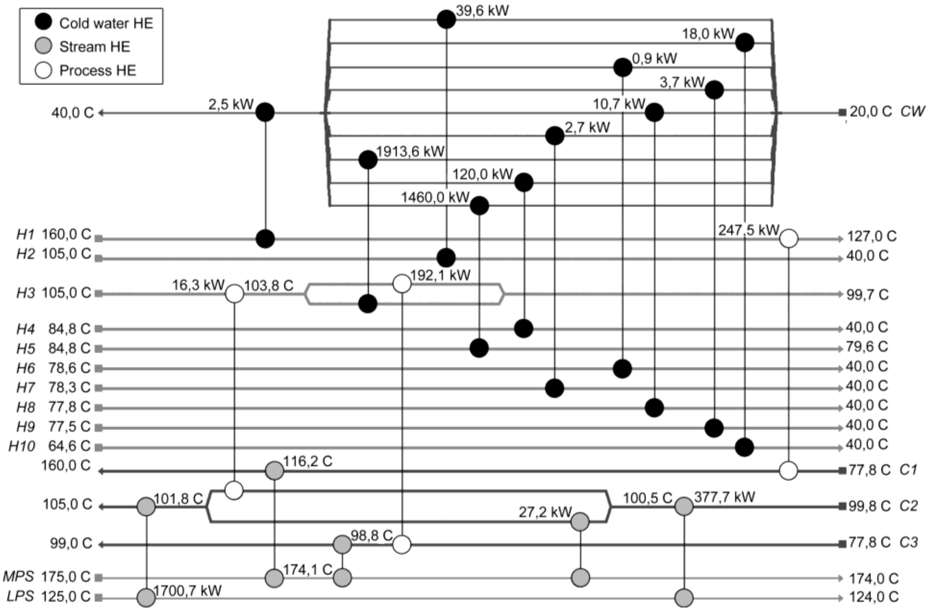

Figure 3: Improved HEN design for minimum total cost scheme.

Table 2: Utilities demand and associated costs of the existing process and the calculated scenarios.

		Existing Process	Minimum Total Cost Design
Heating demand	(MW)	3.446	2.390
Cooling demand	(MW)	6.775	3.572
Number of units		13	18
Total area	(m^2)	231	316
Heating Cost	(Cost)	$2.1\cdot10^5$	$1.46\cdot10^5$
Cooling Cost	(Cost)	$4.5\cdot10^4$	$2.41\cdot10^5$
Operating Cost Index	(Cost)	$2.6\cdot10^5$	$1.75\cdot10^5$
Capital Cost Index	(Cost)	$2.2\cdot10^5$	$2.96\cdot10^5$
Total Cost Index	(Cost)	$3.3\cdot10^5$	$2.62\cdot10^5$

4. Conclusions

Organosolv-ethanol biorefinery process allowed an integral use of the raw material and the obtaining of high added value by-products, as well as the recovery of the solvents. Pinch technology was successfully applied to improve the process heat exchange network reducing the utilities requirements making the process more competitive.

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