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Research paper

Improving second generation bioethanol production in sugarcane biorefineries through energy integration

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HIGHLIGHTS

- Energy integration of sugarcane biorefinery was performed using Pinch analysis.
- Biorefinery produces bioelectricity, first and second generation ethanol.
- Six different scenarios were evaluated.
- A reduction in energy consumption of more than 50% was observed.
- Energy integrated processes allow second generation ethanol production increase.

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ABSTRACT

New technologies for producing ethanol from sugarcane bagasse and other raw materials have been developed as an answer for the world claim for renewable energy. Second generation ethanol is an alternative to increase the production of the renewable fuel ethanol in Brazil. In this context, in this work energy integration of sugarcane biorefineries was performed, using Pinch analysis. Biorefineries consist in processes for first and second generation (1G/2G) ethanol and bioelectricity production, using hydrothermal, dilute acid and steam explosion pretreatments of sugarcane bagasse. For each process with a different pre-treatment, two different options were considered, to know, to include or not pentoses fermentation step. For the six evaluated scenarios the application of energy integration demonstrated a reduction in energy consumption of more than 50% when compared to the corresponding cases without any energy integration and of more than 30% when compared to processes with project integration, as commonly found in Brazilian industrial plants. Besides the economical advantage, due to the decrease in costs of hot and cold utilities, energy integrated processes allow increase the amount of bagasse that can be diverted for production of second generation ethanol.

1. Introduction

In recent decades studies have demonstrated the use of sugarcane bagasse to produce second generation ethanol (2G) [1–14]. Brazil is the second largest producer and consumer of ethanol in the world behind the United States of America, producing 405,000 bbl/d of ethanol in 2012 [15] and the consolidation of second generation ethanol technology will contribute to make Brazilian ethanol even more sustainable [16].

Process integration techniques provide important advantages for the industrial processes in terms of process improvement, increased productivity, energy resources management and conservation, pollution prevention, and reductions in the capital and operating costs of chemical plants [17]. Energy integration in a sugarcane biorefinery can provide economical advantage, environmental benefits and increased ethanol production. The last factor is related to lower steam consumption in the plant due to energy integration and, consequently, less bagasse need to be burnt in the cogeneration system and its surplus can be made available for the production of second generation ethanol.

Pinch Analysis is one of the most important methods for energy integration. It consists of a set of techniques for the systematic application of thermodynamic concepts and allows that process

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engineers obtain intuition needed in thermal interactions among chemical processes and utility systems [18]. In recent years several studies have shown the application of Pinch Analysis in processes to produce biodiesel [19], biomethane [20], first generation ethanol [21] and ethanol from lignocellulosic biomass [22,23], demonstrating the importance of the technique in processes of biofuels production. Other techniques more robust for energy integration may be cited as methods of mathematical programming for solving mixed-integer nonlinear programming (MINLP) problems [24–30]. However, Pinch Analysis is a method simple, easy to apply and achieves successful results, which justifies the use of this technique. In this context, this work performed energy integration in sugarcane biorefineries using Pinch Analysis, in order to evaluate energy savings and contribute to enable integrated processes for cellulosic biofuel production.

2. Process description

The biorefinery used in this work is the process for first and second generation (1G/2G) ethanol and bioelectricity production by computer simulation (virtual biorefinery) performed on free software EMSO (Environment for Modelling, Simulation, and Optimization). EMSO is a tool for modeling, simulation and optimization of general process dynamic systems. It has an object-oriented modeling language and a graphical user interface, in which the user can manipulate multiple models along with results and graphical illustrations [31,32]. Six different scenarios were considered in these biorefineries, since three different types of pretreatment for bagasse (hydrothermal, dilute acid and steam explosion) and inclusion or not of pentoses fermentation step were considered.

The simulated process for 1G ethanol production uses the typical process configuration of Brazilian plants. The processing of sugarcane begins with cleaning stage, followed by milling, which produces sugarcane juice and bagasse. The juice is chemically and physically treated to remove impurities and it is concentrated. After that, the concentrated juice is fed to bioreactor for reduced sugars (glucose, fructose and sucrose) fermentation by *Saccharomyces cerevisiae*, which produces ethanol, CO_2, and other compounds in lesser amounts. The wine produced in fermentation is driven to the distillation unit, where hydrated ethanol fuel is produced.

In order to produce 2G ethanol, bagasse from the mills is divided into two fractions, one is diverted to cogeneration system and the other is pretreated in order to be hydrolyzed. The cogeneration system is responsible for steam and bioelectricity production. The pretreatment alters the structure of biomass, making cellulose more accessible to the enzymes that convert the carbohydrate into fermentable sugars [33]. Many studies with different types of pretreatment of lignocellulosic materials can be found in the literature, such as steam explosion [34–36], organosolv [37–39], dilute acid [40–42] or alkali [43–45] and hydrothermal [46–48]. In this work three different types of pretreatment for bagasse were used: hydrothermal, dilute acid and steam explosion.

Hydrothermal pretreatment consists in contact of lignocellulosic biomass with water in a liquid state at high temperatures (160–240 °C) and pressure. It is an attractive approach because it does not require the addition of chemicals such as acid or alkali [47]. Hemicelluloses are depolymerized, in certain operating conditions, to oligosaccharides and monomers, and high xylose recovery from biomass can be obtained. The advantages of this pretreatment are due to the use of water, component present in green biomass. Hydrothermal pretreatment is non-toxic, environmentally benign and inexpensive medium [49].

Dilute acid pretreatment is one of the most commonly used methods. It solubilizes hemicellulose and exposes cellulose, making it more accessible for enzymatic hydrolysis. It can be performed in two conditions: during a short residence time at a high temperature (above 160 °C) or a long residence time at a lower temperature [40]. Often sulfuric acid [50] and phosphoric acid [51] are used. Dilute acid pretreatment solubilizes not only the hemicellulose fraction, but also converts the solubilized hemicellulose to fermentable sugars [52]. For a biorefinery this is an important advantage because, commonly, hemicellulose sugars represent a third of carbohydrate total in lignocellulosic biomass materials. However, depending on the pretreatment severity, dilute acid pretreatment may produce inhibitory products for fermentation, such as furfural and 5-hydroxymethylfurfural (HMF) [41].

Steam explosion pretreatment consists in contact of biomass with saturated steam at high pressure, followed by a sudden decompression [53]. In steam explosion pretreatment hemicellulose is partially hydrolyzed to monomers and oligomers soluble in water. Crystallinity and degree of polymerization of cellulose is partially modified, improving enzymatic hydrolysis [54]. Furthermore, steam explosion requires little or no chemical in pretreatment, making it environmentally benign relative to other technologies, such as acid hydrolysis [36].

After the pretreatment two fractions are obtained, one enriched with sugars from hemicellulose (liquid fraction) and other enriched with cellulose and lignin (solid fraction). Hydrolysis of solid fraction is performed by enzymes. The glucose liquor produced in this step is concentrated with the sugarcane juice obtained in first generation ethanol sector. Lignin and cellulose that was not hydrolyzed in hydrolysis reactor are available for the cogeneration system. When considering pentose fermentation in the biorefinery process, the hemicellulose fraction converted into fermentable sugars (mainly xylose) is sent to pentose fermentation process (catalyzed by yeast *Pichia stipitis*). Wine produced by this fermentation process is then returned to first generation ethanol sector to be mixed with wine produced by the fermentation with *S. cerevisiae*. Fig. 1 shows a simplified diagram of processes for 1G/2G ethanol and bioelectricity production. More details on process specifications can be found on Furlan et al. [55].

Brazilian sugarcane biorefineries often present some degree of energy integration, which depends on the design of each plant. The simulated biorefinery has energy integration between streams of wine and vinasse and between the juice stream coming out of sugarcane mills and the concentrated juice stream that comes out of evaporator (see Fig. 1). This degree of energy integration is commonly found in Brazilian plants and is named in this work biorefinery “with project integration”. When no energy integration is present, every heating and cooling of streams is provided by hot and cold utilities and the biorefinery process is then named in this work “without energy integration”.

3. Methodology

Initially, a study of the six different scenarios of biorefinery was conducted to identify possible streams for energy integration, considering restrictions of process. Pinch Analysis requires streams data such as initial and final temperature, mass flow and definition of stream type (hot or cold). Information was obtained from simulations in the free software EMSO. For each identified possible stream heat capacity and heat duty were calculated. Heat capacity was assumed constant.

The choice of the minimum temperature difference between hot and cold streams depends on the characteristic of a process [56]. In this work, a minimum temperature difference (ΔTmin) equal to 10 °C was defined. The ΔTmin value influences consumption of utilities in the process. It could be optimized in order to obtain more accurate values of energy savings, but, as it will be