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Improvements in fermentation and cogeneration system in the ethanol production process: Hybrid membrane fermentation and heat integration of the overall process through Pinch Analysis

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ABSTRACT

The incorporation of an alternative technology for the fermentation process, and an improved cogeneration system in the first-generation ethanol production process were evaluated; and a heat integration analysis was performed as well. The hybrid membrane fermentation, the alternative technology, was considered as a non-conventional operation, and its impact on the overall energy consumption of the integrated process was estimated. The improved cogeneration system contemplated a supercritical cycle, and the increase in surplus electricity was also evaluated assuming a mixture of bagasse and sugarcane straw as fuel. The heat integration of the process streams was performed applying the Pinch Analysis in order to determine the targets for minimum external heating and cooling. Furthermore, the integration of the multiple-effect evaporator of sugarcane juice, to the process, was optimised based on the heat integration analysis results. Moreover, the results showed a possibility of generating a surplus electricity of 138 MW (275 kWh/t of cane) with the new technologies applied.

1. Introduction

A sustainable future, regarding energy utilisation and resource conservation, depends on the increase of the participation of renewable energy in the global energy matrix, especially in developing countries. Such increased participation can help in extending fossil fuel reserves, besides helping with the process of reducing greenhouse gas emissions, and enable better energy security on a global scale. The use of environmentally sustainable technologies is necessary to achieve these goals; however the biggest challenge of these technologies is that they also need to be economically feasible. Within the economic development scenario, which is part of a sustainable development, the concepts of energy efficiency and process optimisation are fundamental in the processes that use renewable energies [1].

In this context, the sugarcane has been one of the main crops used to produce energy vectors from renewable sources in the last years. In this industry, the alcohol fuel (ethanol), an alternative fuel; and the bioelectricity produced from cogeneration systems, are products with great capacity of expansion. Although this sector used to be low-efficient in terms of energy use, the concern regarding energy efficiency, as well as the treatment and disposal of waste, is growing nowadays [1].

It is a fact that the traditional ethanol production process has many energy deficiencies that result in an excessive energy consumption, mainly, in the integration of reaction and separation areas. These areas are mainly composed of three operations: (i) fermentation, (ii) simple distillation and (iii) dehydration. However, these energy deficiencies can lead to a greater opportunity for optimisation and reduction in energy consumption [2].

In ethanol distillation, the energy consumption depends explicitly on the ethanol concentration in the feed wine. Consequently, there is an effect on the energy consumption due to the way in which fermentation process is conducted. Still, there are several factors that affect the alcoholic fermentation, such as the ethanol produced in the fermentative medium, which has an inhibitory effect on the cell growth of yeast. In this context, one possible solution is to partially change the structure of the

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fermentation and separation areas, in the ethanol production process, so that the ethanol is continuously extracted as it is produced in the fermentation. This can be achieved by implementing pervaporation membrane technology in the conventional fermentation process, which would result in a positive impact on the energy consumption in the process.

Taking into account the sugarcane plantations, in recent years, the sugarcane industry has undergone changes such as a drastic reduction of harvesting burning of sugarcane plantations, and a proportional increase of mechanised harvesting. Before the mechanisation, the sugarcane straw, comprised of sugarcane tops and dried leaves, was burnt in the field to facilitate the cultivation practices of rattoons, however, with the mechanised harvesting increase; these residues remain on the soil surface. Some studies and management technologies indicate that part of the straw should be left in the cane fields with the objective of assisting in soil conservation and water retention. The amount of straw left will depend on the type of soil. Currently, with the research advances and the interest in its energy potential, a part of the straw is recovered from the field and mixed with the bagasse to be used as fuel in the industry.

Since the bioelectricity became another important product of the mill, the evolution of cogeneration systems became a necessity as well, in order to increase the efficiency of electricity generation. In this scenario, the normal way of improving cogeneration systems consists in reducing the steam consumption of the processes by means of adopting more efficient technologies and heat integration; besides raising the pressures and temperatures in the steam generation process, and in the use of condensing-extraction steam turbines, as in the case of the supercritical cycle, which represents the most efficient systems for electricity generation based on the Rankine Cycle. Nowadays, the cogeneration plant Avedøre II located in Denmark, which is already in use, works with a supercritical steam cycle using different fuels, including biomass. This fact shows the possibility of improvement and optimisation of the cogeneration systems in sugar-ethanol plants with the inclusion of supercritical steam cycles [3].

The heat integration of the process, on the other side, allows the improvement of the energy utilisation of the process streams. This analysis can minimise the process steam consumption and, at the same time, minimise the need for cooling water. It is important to note that the use of process integration techniques, even in similar processes, may require different designs to meet the maximum energy recovery (MER). Each process should be studied separately, considering local operating costs, as well as operating conditions.

At present, there are different studies related to the reduction in energy consumption in the ethanol and sugar production process, such as Moncada et al. [4], where the authors studied different conversion paths from the distribution of raw materials in the sugarcane mill, analysing the variation in the production of surplus electricity and by-products. On the other hand, Ensinas et al. [5] analysed the reduction in steam demand, in a sugarcane plant, applying heat integration; and evaluated different configurations of cogeneration systems including a BIGCC (Biomass Integrated Gasification Combined Cycle).

Regarding process integration research and multi-objective optimisation, several studies can be found in the literature. For instance, Ensinas et al. [6] performed a thermoeconomic optimisation in the sugarcane juice evaporation system and heater network in the plant. Morandin et al. [7] applied optimisation techniques to evaluate the potential for energy savings in the sugarcane conversion process and in the on-site electricity production, assuming bagasse as fuel in the cogeneration system. In addition, Ensinas et al. [8] applied a multi-objective optimisation technique using evolutionary algorithms, setting the electricity production and the produced ethanol as objective functions to be maximized in the production process of first- and second-generation ethanol from sugarcane. Pina et al. [9] evaluated the reduction of the process steam demand and the water usage through heat integration. Regarding alternative technologies in the ethanol production process and its integration through Pinch Analysis, the studies of Palacios-Bereche et al. [10], where double-effect distillation is assessed; Palacios-Bereche et al. [11], who evaluated the introduction of cooling fermentation and vacuum extractive fermentation; and Palacios-Bereche et al. [12] who evaluated different extraction systems for sugarcane juice, are worth mentioning.

Furthermore, the literature presents several studies that, even though not related to the ethanol production from sugarcane, are related to the process integration problem assessed in this study.

Regarding the study of heat integration of multiple-effect evaporators and heat pumps, the study of Sharan and Bandyopadhyay [16] presented a methodology to minimise the overall energy consumption of a system, by thermally integrating a multiple-effect evaporator, thermo-vapour compressors, into the background process. The method focused on the optimal location of the thermo-vapour compressor (TVC) suction position. The authors evaluated two cases; the first one being a corn glucose concentration system, while the second one presented a desalination system. In the same research topic, Oluleye and Smith [18] carried out a study where different technologies of heat upgrading, such as mechanical heat pumps, absorption heat pumps, and absorption heat transformers, are integrated to an existing process through a Mixed Integer Linear Program (MILP). This procedure takes into account the interactions of the aforementioned technologies with the associated cogeneration system, temperature of process streams, and quantity of heat sources, as well as process economics and the potential to reduce carbon dioxide emissions.

Furthermore, in the field of Combined Heat and Power, Total Site Integration is presented as a method for the targeting and integration of individual processes with heating and cooling requirements linked by the same utility system. Several studies have been developed in this area, for instance, Ren et al. [14] presented a method for targeting the cogeneration potential of Total Site utility systems from the pressure values and heat loads of the steam mains, using the commercial software Aspen Plus. The simulator supplies temperature values, flow rates, and shaft powers of steam turbines; furthermore, this study presents a procedure to estimate capital cost, GHG emissions, and the water footprint. In another study, Ong et al. [15] developed a method to visualise and solve Total Site Mass, Heat, and Power Integration, using process integration and process graph techniques (P-graph), which is an approach to visualise multi-dimensional network problems using Mathematical Programming Optimisation. These authors applied the method to evaluate the incorporation of alternative processes, such as gasification of black liquor, hydrothermal liquefaction, simultaneous scarification and co-fermentation of biomass, into an existing Kraft Pulp Mill in New Zealand, together with a combined heat and power system on-site. In the same field, Tarighaleslami et al. [17] presented an alternative method for utility selection and optimisation of Total Site Heat Integration, using cost and exergy derivative analysis. This method can optimise both non-isothermal and isothermal utilities in the same procedure, being the main target the minimisation of the total annualised cost. Finally, Walmsley [13] presented a new approach for a Total Site Heat Integration method for the design of integrated evaporation systems including vapour-recompression based on a hybrid Total Site Profile, which can be applied to optimise industrial case studies, minimising the energy use and costs.

The present work aims at evaluating the incorporation of hybrid