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Multi-objective optimization of an industrial ethanol distillation system for vinasse reduction – A case study

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ABSTRACT

The fluctuation in the price of oil and the positive consequences of fuels from renewable sources (compared to fossil fuels) propel the expansion of biofuel global production. In this work, the current distillation operation of an ethanol distillery is simulated and compared to the use of indirect heating, evaluating the environmental and economic impacts associated with vinasse fertirrigation by using an external automated tool. Results show that the replacement proposed decreases approximately 15% of the amount of vinasse. Moreover, as the modifications do not change the outlet flowrates, such revamping might be done without additional operational changes that could affect the productivity. The environmental evaluation presents positive results, showing that the new configuration may decrease all environmental impacts categories assessed. From an economic perspective, the plant could also have higher profits, presenting a payback period of 3.57 years. Finally, the new improved system is treated as a multi-objective optimization problem and it is solved by using the weighted sum method to obtain the Pareto frontier, providing the optimal solutions that trade-off economic and environmental objectives.

1. Introduction

Sugarcane biofuel processing has been one of the most important and strategic sectors in the Brazilian economy, being Brazil the world's largest sugarcane ethanol producer (UNICA and APEX-BRASIL, 2017). However, the success of Brazilian distilleries depends on how they overcome the new scientific challenges faced, mainly about process optimization, energy integration, energy cogeneration, and sustainability (Amorim et al., 2011).

One of the main challenges is regarding the reduction of the sugarcane vinasse. This liquid residue of the distillation process is rich in minerals and is commonly used to irrigate sugarcane crops, known as fertirrigation; nevertheless, if produced in excess, it brings environmental and economic problems. The direct application of vinasse to the soil may cause salinization, leaching of metals present in the soil to groundwater (killing animals and aquatic plants), changes in the soil quality due to unbalance of nutrients (mainly manganese), alkalinity reduction, crop losses, increase of phytotoxicity, and unpleasant odor (Navarro et al., 2000; Santana and Machado, 2008). Moreover, vinasse is an additional source of greenhouse gases emissions to the atmosphere, especially N_2O and CH_4. Emissions might result from aerobic and anaerobic decomposition of the organic matter contained in vinasse that occurs during temporary storage, transportation, or after the application to the soil (Carmo et al., 2012; Moraes et al., 2017; Oliveira et al., 2013). Other potential problems related to vinasse storage in open ponds (which is the current scenario of the distillery studied) are water pollution and insect proliferation (Dunkelberg et al., 2013). In Brazil, fertirrigation frequently becomes an economic problem when the area to apply vinasse is not available. This might happen when the crop belongs to the suppliers or it is located far away from the industrial plant. Besides, Brazilian environmental legislation recently established criteria and procedures for vinasse application to the soil. Such environmental technical standard P4.231 (CETESB, 2015) defines the maximum dosage of vinasse to be used in the fertirrigation, causing problems of surplus of vinasse stored in open ponds.

Although the use of vinasse is a topic widely investigated in literature, most of the researches focuses on energy production, treatment before disposal, and yeast production (Christofoleti et al.,

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2013; España-Gamboa et al., 2011; Leme and Seabra, 2017; Moraes et al., 2014; Pires et al., 2016), but do not study the possibilities to improve economic and environmental aspects by reducing the amount of vinasse produced. In order to achieve this objective, the most promising options are concentration by evaporation and the use of indirect heating in the distillation system. Concentration by evaporation reduces the volume of vinasse considerably; however, the high energy demand, fast incrustation of evaporators, and spontaneous crystallization are important limitations of this alternative (Christofoleti et al., 2013; Gomes et al., 2011).

Thus, the objective of this work is simulate, analyze, and compare economic and environmental aspects of a full-scale industrial system of an alcohol distillery operating with direct and indirect heating using Aspen Hysys process simulator integrated to Matlab. The models mimic the distillery of the *Cooperativa Agrícola de Astorga Ltda* (COCAFE), which is located in the Northwest of Parana State, (South of Brazil), processing around 180 t/h of sugarcane juice and producing approximately 380 m^3/day of hydrous ethanol.

2. Problem statement

The problem addressed in this article can be formally stated as follows. Brazilian distilleries are required to reduce their vinasse production in order comply with the recent environmental technical standard, which in turn will meet RenovaBio purpose. RenovaBio is an initiative of the Brazilian government whose objective is guarantee the expansion of biofuel production in the country, based on environmental, economic, and financial sustainability, in harmony with the Brazilian commitment at COP 21 (MME, 2017). Although many authors have been proposing new design for ethanol plants in order to improve their sustainability (Leme and Seabra, 2017; Macrelli et al., 2012; Moraes et al., 2015; Petersen et al., 2015), usually, the capital costs are not feasible for Brazilian sugarcane industries, reducing the likelihood of putting these improvement projects into practice. Therefore, the objective of this analysis is to propose a low investment cost modification that leads to significant reductions in economic expenses and environmental impacts.

3. Case study

In this work, the Use of Reboiler (UR) and the Direct Steam Injection (DSI) are compared in order to provide heat to the first distillation column of the COCAFE distillery. The UR and the DSI alternatives are analyzed using two criteria to accomplish a fair comparison between them. Firstly, the simulation is developed in Aspen Hysys to measure the production of ethanol, flegma, and vinasse (the whole description of the process is available in Appendix A). Secondly, the information in the simulator is used to perform an economic and environmental evaluation programmed in Matlab.

After the distillation process, which is the first process inside the system boundary analyzed (Fig. A1), the pumping station sends the stored vinasse from open ponds to the lorry, being transported at relatively long distance and then applied to the soil, by broadcaster. The characteristics of this transportation step to perform the economic and environmental analysis are: (i) lorry capacity of 60 m^3; (ii) average distance for the vinasse fertirrigation from the sugarcane processing facility to the sugarcane crop of 90 km; (iii) vinasse dosage of 150 $m^3 \cdot ha^{-1}$ and (iv) cost of fertirrigation per ton of vinasse = \$ 0.75 (Santos et al., 2015; Zorzenoni et al., 2014). It is important to highlight that as the rest of the activities (evaporation and fermentation processes) are common for DSI and UR, all the evaluations are executed only inside the boundary system, which covers the distillation and fertirrigation processes.

Finally, for the best configuration found in the second step, a multi-objective optimization is performed in order to obtain a set of alternative solutions representing the optimal trade-off between the economic and environmental aspects.

3.1. Comparative study of the process alternatives

A comparative study is performed by setting the mass flow of the stream *V1-A* to zero $kg \cdot h^{-1}$ and removing the adjust block *ADJ-1* (Fig. A1). Thus, the variation of vinasse, flegma, and ethanol mass flow are calculated when the direct heating is replaced by indirect heating.

The evaluation tool programmed in Matlab includes independent modules for the economic and environmental impact assessment based on the material and energy balance and the equipment inventory retrieved from Aspen Hysys simulation used to obtain a rigorous model of the plant. The approach uses a dynamic link, known as Component Object Module (COM) technology, to connect and send the results to Matlab. Fig. 1 summarizes the procedure followed. Detailed information about the automated tool can be found in Torres et al. (2011).

3.1.1. Economic module

The following section is a brief description of the economic methodology used in this work taken from Turton et al. (2012). The capital cost estimation is based on the inventory of the equipment and their design parameters directly retrieved from the simulation, which in turn are fixed based on the operational parameters of the COCAFE plant. The direct manufacturing costs include the following material and energy streams: product streams, utilities, emissions, and waste streams. Usually, the fuel used to supply the energy to produce steam in the boiler is one of the major operating expenses; however, as the ethanol distillery uses its own sugarcane bagasse as a fuel, the prices of low (LP), medium (MP) and high-pressure (HP) steam are computed considering the estimated savings avoiding the cost of burning natural gas in the boiler. The waste treatment cost is due to the cost of vinasse discharge based on its transportation and application to the soil. All the sugarcane vinasse produced is considered to be used in the fertirrigation. The operating labor cost is estimated based on the number of operators required per equipment unit per shift. Then the fixed costs and general expenses can be calculated applying factors to the values previously computed to obtain a final manufacturing cost, which are calculated from capital cost investment regarding Brazil conditions: annual interest rate of 12.65% for the capital investment (BCB, 2016), and an equipment life span of 20 years.

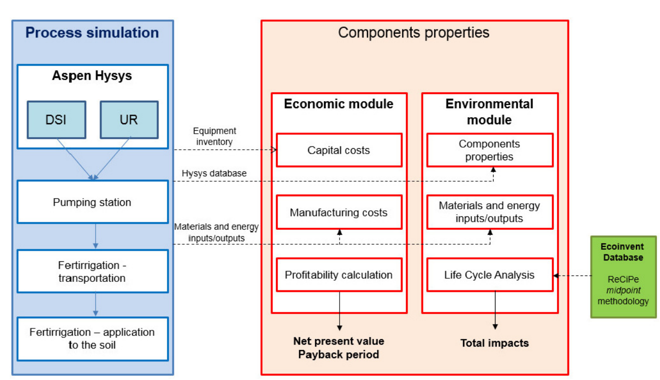

Fig. 1. Flow diagram of the automated procedure for the environmental and economic evaluation based on process modeling.