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DYNAMIC STUDY OF THE INTEGRATED EVAPORATION AND ETHANOL FERMENTATION STAGES OF A SUGARCANE BIOREFINERY USING EMSO SOFTWARE

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Brazil is one of the world leaders in ethanol production, which uses sugarcane as feedstock. The production of second generation ethanol from sugarcane bagasse is still under development, but it is a general consensus that this process must be integrated to the consolidated first generation ethanol production one. Although there is much research on the integrated process, most works in this field are devoted to assess the steady-state process. The knowledge of the process dynamics has an essential role in its efficient operation, economics, variability, safety, and control. In this study two main stages of the ethanol production, namely, continuous multiple-effect evaporation and batch fermentation, were coupled using phenomenological dynamic model. The dynamic model was implemented in EMSO (Environment for Modeling, Simulation, and Optimization), and simulations were performed to analyse the dynamic behaviour of this integrated system. A disturbance was applied on the evaporators feed sugar concentration and its dynamic response was analysed. The last evaporator response stabilized after 32 minutes and the fermentation system after about 7 hours.

Keywords: Dynamic Analysis, Sugarcane biorefinery, Fermentation, Multiple-effect evaporation, EMSO.

Introduction

The dynamic behaviour of an industrial process describes its transient response to different kinds of input disturbances in the system, provided mainly by the environment, the operating conditions, and variability of the feedstock. The recognition of the importance of the dynamic analysis by the industry in the initial stages of the development of a process and how the study of this behaviour in the early steps could result later in economic benefits regarding efficient start-ups, consistent product quality, less-frequent emergency shutdowns, reduced environmental contamination and a safer operation [1].

Brazil is one of the world leaders on sugarcane production, most of it being used as feedstock to the industry of sugar and ethanol, generating large amount of cellulosic biomass as by-product, which is currently being used as fuel to steam and bioelectricity generation. Both ethanol and biothermal electricity have been gaining ground in the Brazilian energy matrix and, with the current research on a substitute for fossil fuels, studies on the development of new technologies and more efficient sugarcane processing are being made [2]. The usage of sugarcane cellulosic biomass as raw material for ethanol production, denominated second-generation ethanol, takes advantage of the available first generation ethanol plants. Therefore a parallel second generation process can be integrated to them, sharing equipment and process facilities [3].

As a process still under research and development, simulations are necessary to evaluate its behaviour and parametric sensibility. In this work the main steps of ethanol production (continuous multiple-effect evaporation and batch fermentation) are dynamically analysed by the integration of their phenomenological models in EMSO (Environment for Modeling, Simulation, and Optimization). The choice of EMSO was motivated by its free availability for academic purposes, the library of models provided and compatibility with thermodynamic and fluid properties plugins. This simulator runs both steady-state and dynamic models using an object-oriented modelling language and block-oriented modelling framework that can be used to build models of equipment and processes diagrams with both text and graphical approaches [4]. The models used were integrated with modified parameters, to be able to run simultaneously as a system. The process dynamic behaviour was evaluated by the application of a disturbance on the concentration of soluble solids in the evaporator input stream, simulating changes originated by feedstock variation, process disturbances, and possible effects of a potential integration of a parallel second-generation ethanol process.

A typical sugarcane processing factory is made for the production of both ethanol and sugar with differences appearing only in the second-half of the process. The process is basically composed of cane reception, cane preparation, juice extraction, juice treatment, juice concentration, fermentation, distillation, and dehydration. As a brief description of the process, feedstock is received and introduced to the factory, for cleaning and impurities removal, and sent to the preparation step that chops the cane to promote an efficient juice extraction. The first-generation ethanol production process receives sugarcane juice from the mills and initiates a physicochemical treatment for removal of impurities. The clarified juice is then concentrated with standard or multiple-effect evaporators and is sent to reactors, where the mixing with yeast occurs and the sugar is then converted to ethanol. The final step is the purification of the product with centrifuges and distillation columns. To produce anhydrous ethanol, an azeotropic distillation step is also necessary [5].

Instead of burning all sugarcane bagasse for electric energy and steam production, part of this biomass is diverted to be converted into ethanol. Briefly, the first two steps of the general process are bagasse pre-treatment, to separate cellulose and hemicellulose of the other components of biomass, and hydrolysis of carbohydrate polymers (cellulose, and possibly hemicellulose) to give rise to a sugar rich stream. The hydrolysis of cellulose generates glucose syrup, which is then mixed with the sugarcane juice (composed mainly by sucrose) in the evaporator input [6].

Experimental

Phenomenological models in EMSO of the two core steps of the ethanol production, evaporation and fermentation, were connected and simulated simultaneously as an integrated process. Since the models were developed separately by [7] and [8] there were differences in the operating condition (mainly flow rates) and in units base (mass, amount of substance, and volume). A buffer tank model was connected in between the two-steps models and changes in the evaporator design and operating parameters were made to make the models represent a system of the same process (*i.e.*, of the same scale).

The evaporator model was based on a Robert evaporator and was used to describe a four-effect evaporation system [7]. Each effect has a liquid input flow, a steam input flow, used as energy source, and two output flows, one liquid representing the juice and the other one the vapour (steam) flow. Liquid and vapour output are then inserted into the next evaporator, which works in the same way. Dimensions were estimated for an industrial scale of 700 m^3/h of clarified juice fed into the evaporator system with 15.0 % in mass of sugar. The value of steam flowrate in the inlet of the first effect was specified based on the amount required for reaching around 19.5 % in mass of soluble solids (denominated Brix degree or °Bx) on the concentrated juice that leaves the last device. The model computes differential equations, regarding material and energy balances, and equations regarding volumes, levels of juice inside the evaporators and operating pressures. In the model, the solution was considered a binary ideal mixture of water and sucrose. Thermodynamics properties and correlations of each component were obtained from VRTherm software.

After leaving the fourth effect, the concentrated juice enters the buffer tank, which is directly connected to the fermentation system. The model of the alcoholic fermentation reactor was based on a fed-batch process and followed equations of global and component mass balance. The fed-batch system was composed of six fermentation reactors. A set of valves controlled the cycle of inoculation, feeding and discharge of the reactor system. The six reactors are scheduled with an offset of one sixth of a full cycle between each other. The flow input to each reactor was discontinuous, but followed a time function, controlled by the valve opening, so that the overall system was continuous. The fermentation by *Saccharomyces cerevisiae* followed a kinetic model that included cell inhibition. The reader is referred to [8] to find model parameter values, as well as details on the fed-batch system and kinetic model equations.

The fermentation model contains a cell recycling system, in which the outlet stream of each fermenter is connected to a tank and a centrifuge. From the latter, two outlet streams are withdrawn, one rich in ethanol and the other one rich in yeast. Part of the yeast rich stream is purged and the remainder is recycled. This recycle stream is mixed with pure water and sent to the fermenters.

Operating variables were based on [2] and [6] data, adapted to the fermentation system requirements. A disturbance was carried on the evaporator input concentration at 600 seconds, increasing its sugar concentration from 15.0 % on mass to 16.0 %, based on variability on sugarcane concentration presented in local industries. The response behaviour was analysed throughout the system.

Results and Discussion

Fig 1 shows the response of the first evaporator to the disturbance applied. The analysis was carried out on sugar mass percentage of the liquid outlet stream. As one can notice, this behaviour is characteristic of a first order system, as the evaporator acts as a tank, taking about 24 minutes for response stabilization.

The remaining evaporator stages presented similar responses of sugar mass concentration in the outlet streams (figures not shown due to space limitation), each one showing a delayed response, since the devices are in series. The second evaporator took around 26 minutes to achieve steady-state, the third took 31 min and the fourth took 32 min with an output sugar concentration of 20.5%.

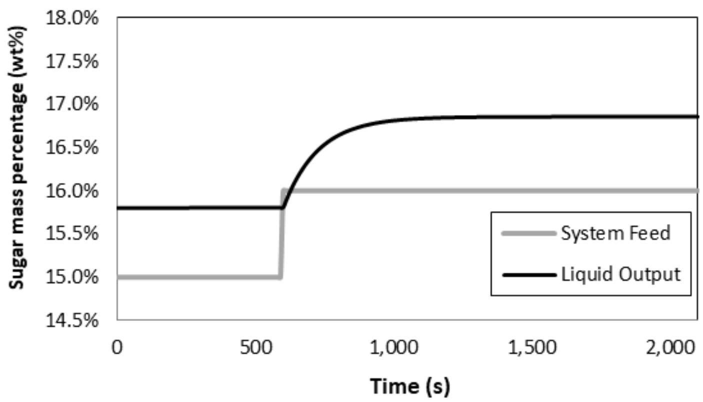

Figure 1 - Response of sugar mass concentration of the first evaporator to feed concentration disturbance from 15.0 % to 16.0 %.

The buffer tank received the fourth evaporator liquid outlet stream and showed a delayed response, since a transfer lag is introduced by the evaporator multicapacitive system and by its own volume. This response behaviour is shown in Fig 2, in which the left axis represents the first evaporator inlet sugar mass percentage and the right axis shows the sugar mass concentration inside the buffer tank in kg/m^3, the unit used to express components content in the fermentation system. It is possible to observe that the tank concentration takes about 7 hours to reach the steady state after being disturbed.

As a fed-batch process, each fermenter operates in distinct phases, receiving a feed stream from the buffer tank at different moments. Therefore there is variation in the response behaviour for each device. Table 1 presents ethanol concentration in each fermenter over time in a 12 hour cycle, making evident its change. Ethanol initial concentration is established by [8]. The first column exhibits a sudden increase in ethanol concentration at the first 6 hours of fermentation. The same fact is noticed in the second column and in the third. The increase represents a response from the disturbance since the three devices are on the filling phase, corresponding to the reception of a more concentrated feed, leading to increased ethanol concentration (inhibition by substrate is not observed under the process conditions). After the filling phase, each device is maintained in batch for 5 hours with a stable behaviour and then the content is discharged, the fermenter is cleaned and the cycle is restarted. The inoculum stream has low ethanol concentration and the beginning of its phase is characterized in Table 1 by the decrease in concentration. Each of the last 3 fermenters received a steady-state feed because they were not in the filling phase when the disturbance occurred. Therefore the disturbance was not evident in the last 3 columns of Table 1.

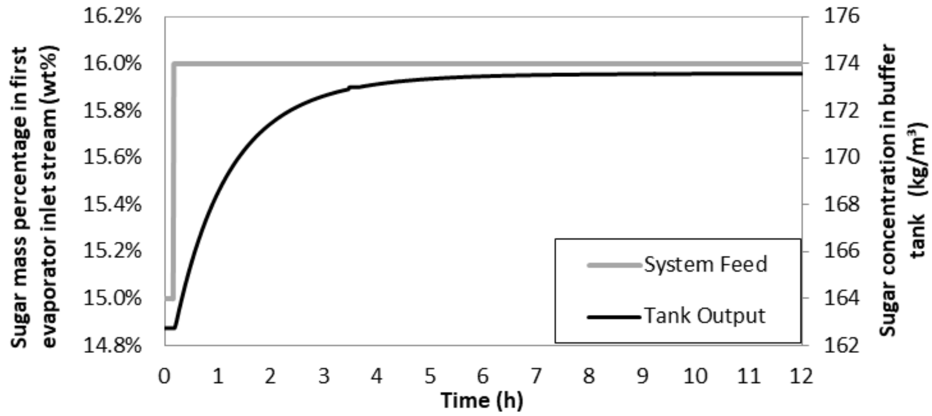

Figure 2 - Response of sugar mass concentration of buffer tank to the disturbance of first evaporator feed concentration from 15.0 % to 16.0 %.

Table 1 - Ethanol concentration in each fermenter at each hour.

	Ethanol concentration (kg/h)					
Time (h)	Ferm 1	Ferm 2	Ferm 3	Ferm 4	Ferm 5	Ferm 6
0	36.20	51.80	63.50	68.20	68.10	68.10
1	38.41	57.15	65.60	68.20	68.10	68.10
2	49.12	61.03	66.61	68.20	68.10	64.24
3	55.75	64.00	66.61	68.20	68.10	39.81
4	60.28	65.30	66.61	68.20	60.01	50.72
5	63.55	65.30	66.61	68.20	39.91	57.27
6	64.93	65.30	66.61	60.37	50.99	61.63
7	64.93	65.30	66.61	41.02	57.56	64.74
8	64.93	65.30	64.36	51.86	61.91	66.06
9	64.93	65.30	44.30	58.27	65.00	66.06
10	64.93	59.99	54.25	62.50	66.30	66.06
11	56.58	57.20	64.04	66.78	66.30	66.06
12	56.58	57.20	64.04	66.78	66.30	66.06

Conclusions

The analysis of the dynamics of the integrated system allowed a better understanding of the system's behaviour when the input concentration is disturbed. The evaporation and fermentation systems showed a consistent behaviour as their responses were propagated in the process. Response time and residence time in this process depended mainly on equipment size, being most buffered in the tank between evaporation and fermentation sub-systems. The process dynamics demonstrated the potential of integration with a parallel second-generation ethanol production process as it showed stable responses to disturbance on concentration, one of the main variables that would be affected by the addition of the second generation ethanol production process.

EMSO showed to be efficient in performing dynamic analysis in industrial processes. As an equation-oriented simulator, it is suitable for integrated systems and demonstrated to be a flexible tool on equipment modelling and process simulation.

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