EMPIRICAL AND SIMPLIFIED MODELS FOR AN INDUSTRIAL BATCH PROCESS

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ABSTRACT
In this paper, a dynamic model of the first stage of the crystallization section of a sugar factory is developed In the model is assumed that the sugar room has continuous and batch units. Therefore, it comprehends variables and phenomena relevant to the process and combines the global mass balance; as partial mass balances of solids and sucrose in continuous units, the melter and mulling equip; with empirical and simplified event models for discrete units (such as the batch crystallizer and centrifuges).

Keywords: Empirical models, simplified hybrid models, industrial process.

1. INTRODUCTION

In this work is developed a dynamic model of the first stage of the crystallization section of a sugar factory. The model will be used to make dynamic data reconciliation and to run simulation scenarios in an optimization software tool to manage the process efficiently.

In the sugar industry is used a well-known modelling tool Sugars™ (Weisser 2010), other significant tool is SIMFAD (ICIDCA, 2010). But both of them are based on stationary models and they are not suitable for our purpose. The Center of Sugar Technology of the University of Valladolid (CTA) has developed complex dynamic models of the main process units of the sugar production process (Mazaeda et al. 2010). However, their complexity implies that are difficult to parameterize and its execution has a large computational load. So, neither they are appropriate to our purpose

Nowadays, it is possible to implement dynamic mathematical models in an easy way using a tool of the family of the object oriented modelling and simulation language (OOMSL). Modelica represents an effort to standardize them (Modelica 2010). In our case we use EcosimPro (EcosimPro 2010), because though it does not implement Modelica, it has a complete and simple language for describing hybrid models, a suitable environment for the definition of libraries and models, a good DAE solvers and it allows to use the simulation code as a C++ class.

We propose to develop a hybrid model of the first stage of the sugar room. This model is based on a continuous and dynamic first principles models for the elements responsible for the accumulation of product (melter and mulling unit) and an empirical and event based model for the batch elements (batch vacuum pans and centrifuges), that slow the simulation execution.

Due to the lack of real data, we have used the realistic simulators of the sugar process units of the crystallization section developed by the CTA to obtain a set data to adjust the empirical models.

The paper is organized in this way. In the first section the problem is introduced. In the second the crystallization section of a sugar factory is described. The third part is dedicated to the empirical mathematical model of the batch process units. In the fourth section the validation of the model is outlined. Finally some conclusions and further research is given

2. CRYSTALLIZATION SECTION

The crystallization section is the last department of the sugar factory, in which the sugar is obtained by a crystallization process using the concentrate juice that arrives from the evaporation section.

In modern factories the crystallization section is divided in three stages. The first stage, called stage A, produce commercial sugar and a by-product to fed the second stage. The second stage (B) is a stage of exhaustion, in which sugar B, to feedback to stage A, and a by-product, to feed the third stage, are obtained. Finally, in the stage C, that is other phase of exhaustion, sugar C is obtained and recycled to stage A. Besides the stage C produce a by-product called molasses (Mazaeda 2010, Sarabia 2007).

As the crystallization section, that is also called “sugar room”, contains a great amount of process units, the stage A has been selected as study case (see Figure 1). It can be observed that the melter receives sugar juice from the evaporation section and high purity syrup from the A centrifuges. The melter feeds three batch vacuum crystallizers. The molasses produced by the vacuum pans, each time that a batch has finished, are added to a mulling tank. This tank feds to the batch centrifuges that produce commercial sugar, high purity syrup and low purity syrup that is used to fed the stage B of the crystallization section.

The basic physical principles of the process are the next ones. The syrup from the evaporation stage is sent to the melter, and it dissolves the higher purity syrup from the centrifuges, obtaining a solution that is called *standard syrup*, after a filtering process, it is sent to the vacuum crystallizers. When a vacuum crystallizer is full, it contains a product called massecuite or cooked mass that is a high concentrate water solution formed by crystallized sucrose, sucrose and impurities dissolved. Using steam, as heating way, the massecuite reaches the super-saturation conditions, then small sugar crystals are added and they begin to grow. New syrup must be added to maintain the super-saturation condition. When a suitable size of the crystals has been reached and the vacuum pan is completely full of a product called *mother honey*, vacuum crystallizer is discharge and cleaned. The mother honey is stored in a mulling equipment to feed the batch centrifuges.

Finally, the battery of batch centrifuges are used to separate the sugar crystals from the mother honey. The centrifuges discharged three products: first, the lower purity syrup, second, the higher purity syrup, and, third, the commercial sugar.

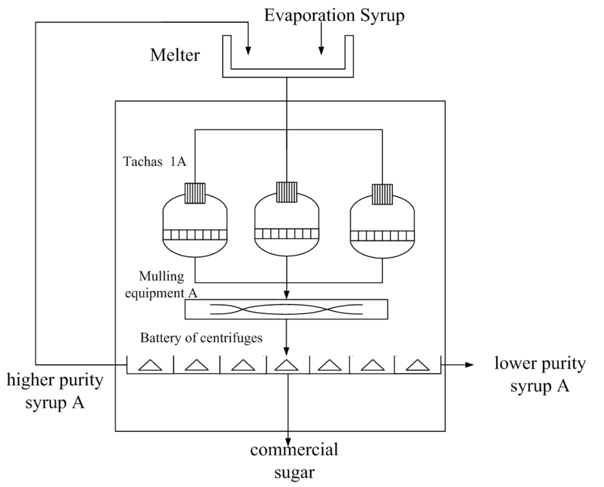

Figure 1. Diagram of stage A of the crystallization section.

The optimal management of the sugar room depends on many criteria that actually must be managed by the operators. Some of them are:

- The steam demand of the sugar room must be homogeneous to not disturb the operation of the steam producer (the evaporation section). Because, the flow rate and sucrose concentration of the syrup that arrives to the crystallization section depends on the operation of the evaporating section. So, each vacuum crystallizer must be turn on in a suitable time to avoid peaks in the steam demand.
- Besides, each sugar crystallizer only must be turn on if there is enough syrup in the melter.
- The discharge of each crystallizer must happen when there is enough space in the mulling equipment. If it is not possible to unload the crystallizer, this one waits until the mulling equipment has enough space to store the mother honey contained in the crystallizer.
- The amount of rich and poor honey separated in the centrifuges affects the quantity of sucrose that must be re-processed with the consequent power consumption and problems of storage. It is possible decide the time in which the centrifugals switch from producing rich honey to poor honey.

3. MATHEMATIC MODELS

It is necessary to develop a mathematical model to simulate the behaviour of the sugar room to calculate the steam demands, the level of the storage units and the properties of the obtained products. As a function of the boundary conditions of the syrup that goes into the crystallization, the pressure of the supplied steam, the start time of production of each crystallizer, the number of batch centrifugals operating and the time to switch from produce the two types of honeys in the batch centrifugals.

For process units in charge of store products (melter and mulling equipment) we use dynamic first principle models based on mass balances of global product, sucrose, sugar crystals and impurities.

As it was shown in the introduction, it is possible for batch crystallizers and centrifugals to develop complete dynamic models based on first principles (Mazaeda 2010), several reasons discourage their use in our case:

- They are too complex to parameterize.
- They are hybrid models, with a lot of events related to state variables. It implies a high computational cost in their resolution. So they are not suitable to decision making based on optimization techniques, because in this case the simulation program must be run a lot of times.

For this reason we propose to develop empirical and simple models of the batch units suitable to our purpose. In particular the model of the batch crystallizer will be detailed and the next assumptions were made:

- There is no interest in the thermodynamic aspects.
- As it can be seen in Figure 2, the flow profiles of steam demand, syrup consumption, and obtained mother honey are always the same ones. Only change the magnitude of the flows in each stage and theirs time events that both of them are calculated using empiric tables.
- As it was impossible to make experiments in the real process, the values to fill the tables were obtained using the realistic vacuum pan simulator developed in the CTA.
- The experiments consist on simulate a complete batch maintaining some boundary conditions.
- The empiric flow profiles must satisfy the mass balances in each batch.

The method used to calculate the flow profiles is the next one:

- First, the supply steam pressure and the properties of standard liquor syrup (brix and purity) are selected as boundary conditions and theirs ranges are specified.

- Second, the execution of each model is made varying only one boundary condition. Thus, the variation of the response can be attributed to the change factor, and therefore it reveals the effect of that factor. The procedure is repeated using next boundary condition. The results of each model execution are the loading and cooking mass, the unloading mass and its properties, the global steam consumption and the loading, cooking and unloading stage times. The Tables 2, 3, and 4 shows some results taken from a more detailed table.

Table 1. Mass of the standard liquor in the load stage and the cooking stage

Pressure 0.9 bar				
Purity\Brix	Mass standard liquor in the load stage .[kg] ($Mass_{load\ stage}$)			
	70	72	74	76
90	58645	58730	58868	58969
92	58655	58736	58871	58971
94	58653	58736	58872	58970
96	58659	58772	58872	58970
Pressure 0.9 bar				
Purity\Brix	Mass Standard liquor in the cooking stage.[kg] ($Masa_{stage\ cooking}$)			
	70	72	74	76
90	626	626	626	636
92	636	636	636	653
94	653	653	653	681
96	681	681	681	523

Table 2. Mass of the mother honey in the discharge stage**.**

Pressure 0.9 bar				
Pureza\Brix	Mass cooking in the unloading stage.[kg] ($Mass_{unloading}$)			
	70	72	74	76
90	7500	6625	5783	5003
92	9065	8078	7135	6248
94	8264	7344	6457	5620
96	7543	6673	5838	5051

Table 3. Time events of the loading, cooking and unloading stage.

Pressure 0.9 bar				
Purity\Brix	Duration of the loading stage [s] ($time_{loading}$)			
	70	72	74	76
90	91	90	92	92
92	92	91	92	93
94	92	92	92	93
96	92	92	92	93
Pressure 0.9 bar				
Purity\Brix	Duration of the cooking stage ($time_{cooking}$)			
	70	72	74	76
90	9907	8839	7841	6895
92	9047	8047	7107	6216
94	8250	7329	6440	5607
96	7500	6625	5783	5004
Presseure 0.9 bar				
Purity\Brix	($time_{unloading}$)			
	70	72	74	76
90	686	686	686	686
92	696	696	697	696
94	713	713	713	713
96	742	741	742	741

- Then, linear adjustments are made of the table experiment values for incorporate into the model. The linear fit is given by equations 1 to 6 and it depends on the boundary conditions.

$$Mass_{loading} = f_n(Brix, Purity, \Pr essure) \quad (1)$$

$$Mass_{cooking} = f_n(Brix, Purity, \Pr essure) \quad (2)$$

$$Mass_{unloading} = f_n(Brix, Purity, \Pr essure) \quad (3)$$

$$time_{loading} = f_n(Brix, Purity, \Pr essure) \quad (4)$$

$$time_{coking} = f_n(Brix, Purity, \Pr essure) \quad (5)$$

$$time_{unloading} = f_n(Brix, Purity, \Pr essure) \quad (6)$$

- Finally, profiles (Figure 2) are estimated using the equations 7, 8 and 9, which satisfy the mass balances and allow interaction with the melter and mulling equip.

$$Win\_loading = \frac{Mass_{loading}}{time_{loading}} \quad (7)$$

$$Win\_cooking = \frac{Mass_{cooking}}{time_{cooking}} \quad (8)$$

$$Woutput = \frac{Mass_{unloading}}{time_{unloading}} \quad (9)$$

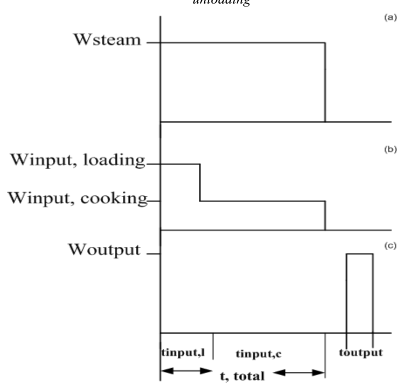

Figure 2. Flow profiles. a) Supply steam. b) Supply syrup. c) Output mother honey.

The batch centrifugal was modelled using the same procedure that for the vacuum crystallizer.

The model of each process unit has been implemented in an object oriented modelling language for hybrid systems named EcosimPro. Later, the model of the first stage of the sugar room has been made selecting, parametrizing and connecting each of the process units that contains.

5. VALIDATION

A qualitative analysis is carried out to validate the resulting model of each process unit in an independent way.

For the vacuum crystallizer, the qualitative analysis consisted in varying some of the boundary conditions such as brix and steam pressure. As an example in the figures 3 and 4 are illustrated the effect of increased and decreased steam pressure supply. An increase in supply pressure causes a decrease in time at the cooking stage, while a decrease of supply pressure causes the opposite effect, due to the fact that the steam pressure falls on the rate of evaporation water contained in the mass within vacuum crystallizer.

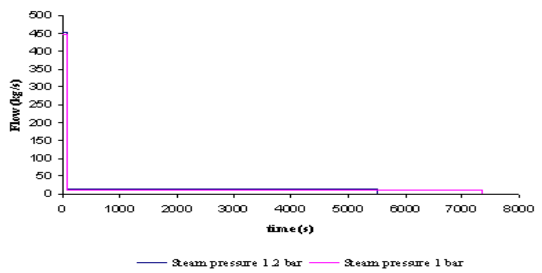

Figure 3. Increased of the steam supply pressure.

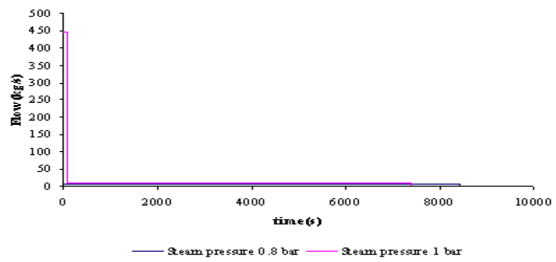

Figure 4. Decrease of the steam supply pressure.

On the other hand, the qualitative analysis in the centrifuge consisted in modifying the time of commutation of honey and varying brix, leaving a fixed value of 12 kg/s of standard syrup received at the melter, with a purity value of 93% size of the crystals 45%. The effect of modifying the time of commutation of honey in the centrifuges is showed next.

The separation between lower purity syrup and the higher purity syrup can be established freely by the operator within certain limits. Must occur at a time after the introduction of water, but can not establish a "best" time for change fits-all operating situations of the plant. If the switching is delayed produce a higher purity of both honeys, which increases the amount of sucrose that is sent to the stages of exhaustion, a change instead of honey in advance will ensure the purity of the honey less poor, but also harm the purity of the rich increased the amount of impurities is recycled to the first stage.

Figures 5 and 6 show the implications of the change of honey. In Figures 5.a and b are plotted the purity and brix of lower purity syrup and higher purity honey, for a switching time of 28 seconds, while in Figure 6.a and b, equivalent information is provided for the case a switching time of 12 seconds. It is noted that an increase of switching time of honey causes increased both the purity of honey, while in the brix this effect is less significant because it does not influence much on the operational level.

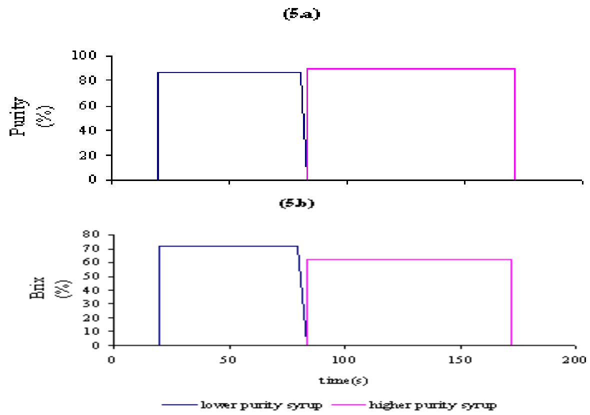

Figure 5. Purity and brix of lower purity syrup and higher purity honey, for a switching time of 28 seconds.

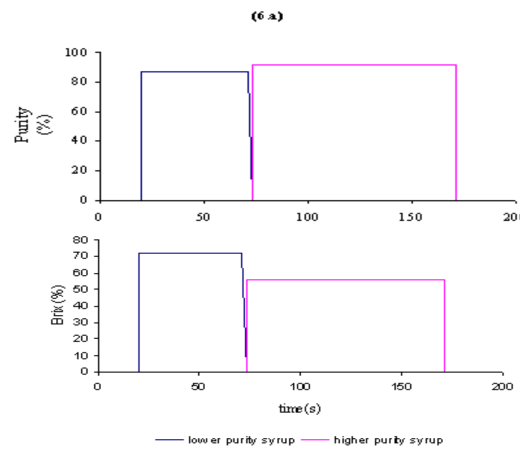

Figure 6. Purity and brix of lower purity syrup and higher purity honey, for a switching time of 12 seconds.

The objectives in this project were to simulate each process unit as an independent element. Further work could be focused in model validation of the whole stage A of the crystallization section. However, this would be a challenge that will require real process data and a full simulation of the process as a whole.

4. CONCLUSION

In this work, a dynamic model of the first stage of the crystallization section of a sugar factory has been developed. The model has hybrid formulation, because use ODEs and events and besides it is a mixture between first principles and empiric formulations.

The next step is to validate the model and complete with the second and third stage of the sugar room. Later, the global model must be used to manage the sugar room in an efficient way.

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