



MODELING, SIMULATION AND CONTROL IN PROCESS INDUSTRY AND ITS RELEVANT IMPORTANCE

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Modeling is an important tool to study and evaluate the behavior of the chemical process. Combination of simulation and control, it exhibits various characteristics of the process and provides the right direction to obtain the desired results from the chemical reactors. This paper discusses the various technical aspects of modeling, simulation and control in the process industries. The utilization and the relationship among the three techniques, modeling, simulation and control have been discussed. A case study is then presented for a batch reactor (in a sugar manufacturing plant) to use the modern techniques for modeling, simulation and instrumentation control. Presenting various scenarios on the above discussed techniques, the task has been dealt with comprehensively.

Keywords: Modeling, Simulation, Process, Sugar, Mass balance

1. Introduction

Mathematical modeling covers the basic aspect of chemical engineering and defining the behavior of a chemical process. By understanding the chemical behavior we can simulate to obtain different results, study the dynamics of a process and optimize or control it.

Mathematical modeling and simulation reduce the cost of running experiments physically by developing an understanding of the process and helps in the decision making processes. Engineers and scientists can easily find useful and meaningful results from modeling and simulations. Also in the decision making criteria, process can be simulated and depict the behavior of a real system under various circumstances. Studying the dynamics of the process is relatively easy to reduce the production costs and to save the time.

Process Industry from the day of its inception has transformed through many changes. Decreasing the cost of production and increasing the profit is the main target of different industries. Modeling and simulation techniques have been found to increase productivity from the plant thus increase profits. Decreasing the total cost of production has also been found by optimization.

Optimization is the technique employed after modeling and simulation to achieve the desired targets. Control in process industries also improves the specification of the products which ultimately increase the profit and quality of product. Also the instrumentation control will help to achieve the steady state operation in case of disturbances.

The combined effect of modeling, simulation and control techniques improve the process understanding, studying various dynamics, increasing throughput and quality. In a nut shell, these techniques are vital for the excellent understanding and operation of a modern chemical processes.

“Advancements in computing power, availability of PC-based modeling and simulation and efficient computational methodology are allowing leading edge of prescriptive simulation modeling such as optimization to pursue investigations in systems analysis, design and control processes that were previously beyond reach of the modelers and decision makers” [1].

2. Process Modeling and Simulation

This paper discusses the process modeling and simulation of a sugar industry. So first we shall

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discuss the sugar manufacturing process in brief in order to develop an understanding of the physical and chemical phenomena's that govern the system.

2.1. Sugar manufacturing process

Broadly speaking, the following unit operations and unit processes are undertaken to accomplish this process for converting sugar cane into refined (white) sugar.

2.2. Cane preparation:

Raw material, Sugar cane, is passed through a heavy duty shredder to obtain finely crushed cane. No liquid separation from solid content takes place and juice is retained in the solids as with other components (mainly water and organic impurities).

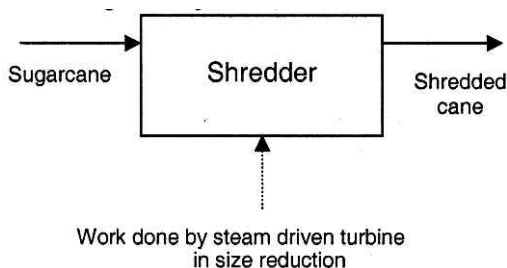


Figure 1. Shredding in Operation.

2.3. Juice extraction

The next grinding stage occurs in milling, where juice extraction takes place from shredded sugar cane. Solids, which are called bagasse, are separated from the liquid and subsequently, the liquid is sent for clarification. Some water is also used for efficient extraction of sucrose (sugar) from solids.

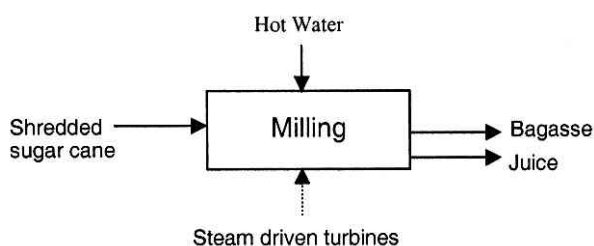


Figure 2. Mass balance in Milling.

2.4. Juice clarification

First the liquid is heated to a temperature of 75 °C; after which lime is added to remove organic impurities. No separation takes place as the lime is added alongwith the incoming juice and sent for

Secondary heating, where its temperature is raised to 105 °C. Separation of the mixture occurs only in the Clarification unit where the mixture is given some retention time. A few ppm of polyelectrolyte are also added at this stage.

Impurities are separated as filter cake while clear juice is sent for Evaporation.

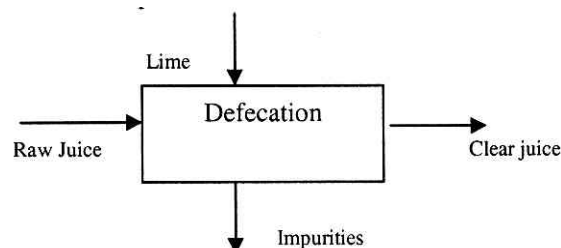


Figure 3. Process of Defecation

2.5. Juice concentration

Clear juice is concentrated by evaporating over 75 % of the water content in quadruple effect evaporators, to achieve what is called "syrup".

2.6. Crystallization

This step constitutes boiling to convert syrup into massecuite, which is a mixture of "sugar crystals" and molasses. Molasses is similar to sugar crystals but with a lower sucrose content.

2.7. Curing and purging

Curing and Purging are unit operations which are carried out to separate sugar crystals from molasses in centrifugal machines. In other words, we are separating a higher purity product from a lower purity content.

2.8. Grading and packing

In this section Sugar is dried, graded and packed in 50 Kg polypropylene bags.

2.9. Modeling of the process: Building the basics

In this grinding section of sugar manufacture, four types of mass balance approaches were tried.

1. Using only Base Plus Delta Model
2. Using Bond Equation for Crushing
3. Open Cells and Sucrose relationship
4. Considering Crusher Efficiency

Crushing

The Base Plus delta model describes the behavior of an output to an input. When the steam flow rate or pressure changes; the rpm of the turbine shaft change which causes crushing of the shredder to vary. Thus more steam pressure implies more crushing, which means more sucrose is extractable in milling.

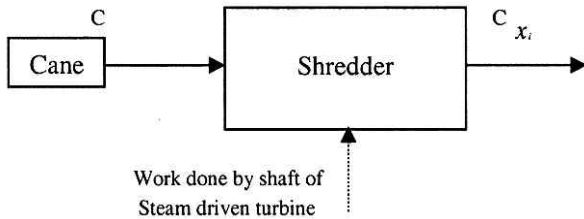


Figure 4. 1st approach to mass balance at shredder.

Assumptions of the model

Increasing steam pressure means more extraction, which means more sugar is extractable in the later stages. However, there is a design restriction of $\pm 5\%$ of the base case value. This restriction was imposed when assigning the pressure of the steam in the process entity. It was not allowed to go beyond $\pm 5\%$. The base case value of steam pressure of the industry studied was 16kg/cm^2 (designed), thus upper bound of 16.8 and lower bound of 15.2 of steam pressure were imposed in all specifications.

The following Model was developed:

$$x_i = x_i^{\text{base}} + \sum_j c_{1,ij}(u_j - u_j^{\text{base}}) \quad (1)$$

$$15.2 \leq u_j \leq 16.8 \quad (2)$$

Where x_i is Composition of individual specie in sugar cane namely sucrose, water, organic impurities and bagasse.

x_i^{base} is base case value of sugar cane composition of individual specie i . These values are fixed and assigned by the user.

$c_{1,ij}$ is the coefficient relating to output change of specie i , to input variation of utility j . This is a parameter and set a value. It can later be estimated through parameter estimation.

u_j is the utility j , (steam, water property etc).

u_j^{base} is the base value of utility j . It is also a parameter.

i = Sucrose, water, organics, bagasse*

j = Steam, Exhaust Steam•

The utility considered in this case is only “live steam”. However, provision is left for more utilities which become vital in later stages of the process, such as exhaust steam, which has different properties as live steam introduced here.

The relationship shows how the composition of the outlet of crusher (the shredded sugar cane) varies with input condition, which is steam pressure.

Milling

In the milling operation, more sugar cane is crushed. Steam is used in this process, as well as water as a utility. Water is added in the last mill (of a milling cycle of 6 mills) to increase extraction of sucrose. Again it was found that steam consumption was related with product quality (sucrose in product). So the base plus delta model was a combination of effect of steam and water on sucrose recovery as shown below.

$$x_{in,i-1} = x_i + \sum_j c_{2,ij}(u_j - u_j^{\text{base}}) + c_{w,i} \times (W - W_b) \quad (3)$$

Where x_i is composition of individual specie in shredded sugar cane exiting out of shredder,

$x_{in,i-1}$ is the outlet mass fraction of the specie(i) in Juice.

$i-1$ indicates that there is no solids (bagasse) in juice.

$c_{2,ij}$ is the coefficient relating to output change to input variation of steam.

u_j is the utility (steam, water etc. property).

* Note that $i=1$ for sucrose, 2 for water, 3 for organic impurities, 4 for bagasse.

• Similarly for utility, $j=1$ for live steam and $j=2$ for exhaust steam (provision made here).

Since the properties of the steam are the same as in the Shredding operation, they are not defined different variables.

$C_{w,i}$ is the coefficient relating to the effect of water flow rate when it changes from its base flow rate, on the product quality.

i = Sucrose (1), water (2), organics (3), bagasse (4); (in this order).

j = Steam (1), Exhaust Steam (2)

W is the flow rate of water, and

W_b is the base case water flow rate (assigned in the process to be 8.1). Note that this specification is according to simple engineering relationship,

$$W_b = 0.2 \times \text{Sugar Cane} \quad (4)$$

However, any arbitrary value can be specified.

Simulation result

The simulation of the above yielded negative value for x bagasse (composition of bagasse in shredded sugar cane), perhaps due to the values of coefficient assigned in $C_{2,j}$. The upper and lower bounds for mass fraction of species were put between 1 and 0 respectively. After arbitrary adjustment of the parameters, still no conclusion was reached as x bagasse remained outside the declared bounds.

The mass balance equation was then altered according to the following diagram:

Steam driven turbines

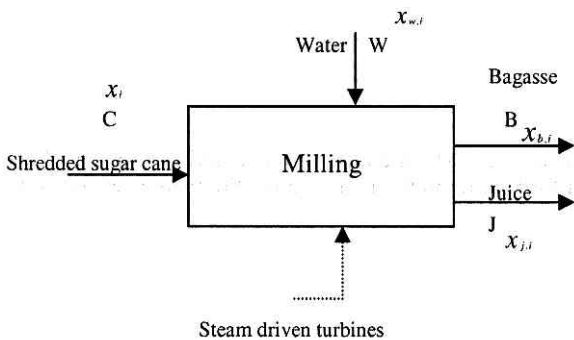


Figure 5. Mass balances in Milling

As seen from the figure that some solids are produced which are sent to boiler for steam generation purposes, while the product is separated and used for further downstream operation. After this stage, juice contains only sucrose, water, and organic impurities; the fourth component (bagasse) disappears.

Mass balance

$$\text{Sugar cane} + \text{Water} = \text{Juice} + \text{Bagasse}$$

$$\text{SugarCane} \cdot x_i + \text{Water} \cdot x_{w,i} = \text{Juice} \cdot x_{j,i} + \text{Bagasse} \cdot x_{b,i}$$

$$\sum_{i=1}^n x_i = 1 \quad (5)$$

$$\sum_{i=1}^n x_{b,i} = 1 \quad (6)$$

$$\sum_{i=1}^n x_{j,i} = 1 \quad (7)$$

The recovery equations were also specified:

$$R_{i-1} = \frac{x_{j,i-1} \cdot J}{x_{i-1} \cdot C} \quad \dots (8)$$

for $i-1$ = sucrose, water and organics.

$$R_i = \frac{x_{b,i} \cdot J}{x_i \cdot B} \quad \dots (9)$$

for i = bagasse only.

Simulation result

After repetitive simulations by altering the values of assigned variable (the water content in bagasse = 0.50), no convergence of solution was obtained within the bounds specified for variables. The values of some variables were found to lie outside the bounds. This might be the result of sensitive process parameters or specification.

For example, the composition of sucrose, water, organics and bagasse in outlet bagasse flow rate came in the following respect.

Table 1. Composition of various species.

| Sucrose | Water | Organics | Bagasse |
|---------|-------|----------|------------|
| 0.0 | 0.5 | 1.0 | 0.58949625 |

The juice flow rate composition was as shown in the following order.

Table 2. Juice Flow rate Composition

| Sucrose | Water | Organics | Bagasse |
|---------|-----------|----------|---------|
| 1.0 | 0.7731761 | 0.0 | 0.0 |

Thus the simulation failed to reach a solution for the variables within the bounds specified in the problem, consequently, another approach was needed. This was found by how much increase in opening the cells of sugar cane fibre is achieved by crushing. If the crushing would disintegrate sugar cane in to very fine pieces so that its cells are ruptured and sucrose is easily recoverable; then there could be a way to relate it to steam consumption. This is true since, this is the actual representation of the process that is carried out on the sugar shredder.

3. Using the Bond Equation for Crushing

The Bond Equation for crushing is used for size reduction techniques. Since the crushing (work index, according to Bond's equation) is essential for sucrose recovery. In other words, it is related to the amount of work which is essential to carry out sufficient release of sucrose.

3.1. Bond Equation* for Crushing

$$W = 10 \times W_i \left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}} \right) \quad (10)$$

where, W_i is the Work Index

P is the Product size in microns

F is the Feed size in microns

and W is Work (work input by steam driven turbine).

It was assumed that since steam input is directly related to turbine rpm, it is convenient to replace turbine rpm with steam pressure.

By calculating the work index (W_i) for some value of Steam pressure (W), Product size (P) and Feed size (F); different values of Steam pressure (W) were calculated as shown in the following table.

Table 3. Values of steam pressure

| W_i in kW | P in micron meter | F in micron meter | W in kW |
|-------------|---------------------|---------------------|-----------|
| 3600 | 100 | 400 | 1800 |
| 3600 | 83 | 400 | 2160 |
| 3600 | 123 | 400 | 1440 |

Note that the W_i is fixed, and also Feed size (F), which means that there is no change in physical properties of the raw material. The different values of W are calculated, which shows the direct relationship between product size and Work input. This means that, as the steam pressure varies from its base value, considered here to be $\pm 20\%$, an effect is observed in the output quality. Increased value of steam pressure from the base case increases the size reduction of outlet product and vice versa.

It was assumed that crushing at Shredder represented a size reduction of the product to 1/4th of the feed size. Also, the crushing or comminution in grinding is 1/5th of the Feed size. Resultantly, this gave an expression:

$$\text{Product size in Milling} = 0.8 \times \text{Product size in Shredding}$$

The inverse relationship shows that the Product size decreases after Milling.

Table 4. Product size after different operations

| Product size in Shredding(micron meter) | Product size in Milling(micron meter) |
|---|---------------------------------------|
| 100 | 80 |
| 83 | 66.4 |
| 123 | 98.4 |

In order to relate the product size to sucrose recovery; it was assumed to have a linear relationship. This was purely based upon abstract engineering knowledge, which means that if more size reduction is achieved; it is easier to extract sucrose. In other words, the lesser the size of the product, the recovery of end product is easier. This is represented in the following graph.

* [3] <http://www.elorantaassoc.com/eob97.htm>

The next task is to study the effect of steam pressure in milling operation; it was related again in the form of a base plus delta model, similar to the base plus delta model equations described above.



Figure 6. Product Size and Sucrose Relation

$$x_i = x_{i,i}^{base} + \sum_j c_{3,ij}(u_j - u_j^{base}) \quad (11)$$

x_i , is the mass fraction of sucrose considered here; i.e. x_i , because this is the component in which we are interested. The value of composition of sucrose is found from the graph shown above.

$c_{3,11}$ is the coefficient relating steam versus sucrose %.

The typical values of the above variables are shown in the table below.

Table 3. Values of Different Variables

| x_1 | x_1^{base} | $c_{3,11}$ | u_1 (kg/cm ²) | u_1^{base} (kg/cm ²) |
|-------|--------------|------------|-----------------------------|------------------------------------|
| 0.2 | 0.16 | 1.33E-04 | 16.8 | 16 |

The values of coefficient $c_{3,11}$, is calculated against defined values of other variables, which is then used for subsequent calculations for finding the values of x_1 against different pressure changes. However this technique was found to be less useful than “number of open cells against sucrose extraction” technique employed in the next step, due to a number of linear relationships and coefficients.

4. Open Cells and Sucrose Relationship

Since number of open cells is increased due to crushing, this facilitates the optimum extraction of sucrose from sugarcane.

A linear relationship was developed where the base case value of open cells is a fixed quantity. It varies as the steam pressure varies. An increment in steam pressure results in an increment of open cells that are produced and decline in steam pressure from base value results in decreased number of open cells.

$$a_i = a_i^{base} + \sum_j c_{ij}(u_j - u_j^{base}) \quad (12)$$

Where, a_i^{base} is the base case value of open cells; assigned to be ≈ 0.875 .

a_i = Open cells due to steam variation.

c_{ij} is the coefficient relating to open cells with steam pressure

u_j is the utility steam pressure

u_j^{base} is the base value of steam utility (16 kg/cm² \approx bar)

The coefficients for number of open cells produced are quite similar to each other of sucrose and organic impurities; but they are different for water and bagasse. This is due to the reason that steam does not affect bagasse content and water is also merely affected. So a lower value of coefficient was assigned to water and bagasse.

The next task is to relate open cells to composition of shredded sugarcane which becomes the inlet of the mills; which necessitates another relationship. For this purpose, the following relationship between open cells produced after shredding, and sucrose extraction in milling was developed.

$$a_{i-1} = m_{x_{i-1}} + c$$

Where a_{i-1} is the number of open cells in specie i-1; sucrose, water and organics;

m is the slope of the straight line

x_{i-1} is the composition of specie i ; sucrose, water and organics.

The slope of the line was taken as $m=1$; while the constant or y-intercept was given a value of 0.745.

The following mass balance was applied:

Sugar cane + Water = Juice + Bagasse

$$\text{SugarCane} \cdot x_i + \text{Water} \cdot x_{w,i} = \text{Juice} \cdot x_{j,i} + \text{Bagasse} \cdot x_{b,i}$$

$i=1, n; j=1$

$$\sum_{i=1}^n x_i = 1 \quad (13)$$

$$\sum_{i=1}^n x_{b,i} = 1 \quad (14)$$

$$\sum_{i=1}^n x_{j,i} = 1 \quad \dots\dots (15)$$

The recovery equations were also specified:

$$R_i = R_i^{\text{base}} + c_{c,ij}(u_j - u_j^{\text{base}}) + c_{w,i}(w_i - w_i^{\text{base}}) \quad (16)$$

for all specie $i; j=1$ for Steam.

However, there were a lot of model errors and complications aroused; therefore a different technique of modelling the system was developed.

5. Considering Crusher Efficiency

If it is assumed that the crusher has an efficiency by which some material is passed through "completely crushed" while some material is not crushed and passes as such; then a convenient way of relating crushing efficiency with product composition could be developed. It is also important to mention here that the material that passes through the crusher uncrushed, remains uncrushed in the milling because, crusher has a greater tendency of crushing than the mills. Thus

we define an "index of preparation" of the crusher that relates to how much the material is crushed.

For this there are two assumptions:

- The crusher efficiency remains constant throughout the operation
- The feed material remains at a constant composition during operation.

Index of preparation Relationship:

$$I.P. = I.P.^{\text{base}} + c_{o,j}(u_j - u_j^{\text{base}}) \quad (17)$$

where I.P. is the index of preparation or in other words, the Efficiency.

I.P. is the base case index of preparation or efficiency value

$c_{o,j}$ is the coefficient between steam pressure and efficiency variation.

The mass balance of the shredder can be explained as follows:

$$F_{\text{out},1} = I.P. \cdot F_{\text{in}} \quad (18)$$

$$F_{\text{out},1} + F_{\text{out},2} = F_{\text{in}} \quad (19)$$

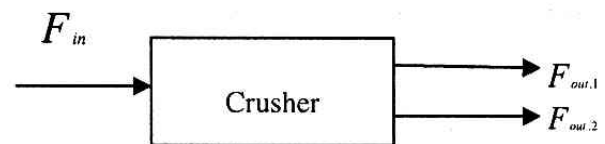


Figure 7. Mass balance at Crusher

Where $F_{\text{out},1}$ represents the Efficient Stream and $F_{\text{out},2}$ represents the Waste stream that remains uncrushed even in the milling and is discharged into the solids as bagasse.

The composition of both the stream, $F_{\text{out},1}$ and $F_{\text{out},2}$, can be regarded to be the same. This method helps us in determining the recovery of sucrose from outlet streams.

The recovery equation for this process yields,

$$R_{1,j} = \frac{F_{\text{out},1} x_{\text{out},1,j}}{F_{\text{in}} x_{\text{in},j}} \quad (20)$$

for $i = 1, n$. where n is the no. of Component; sucrose, water, organics and bagasse.

$X_{out,1,i}$ is the composition of the outlet stream $F_{out,1}$

$X_{in,i}$ is the composition of the inlet feed stream $F_{in,i}$

the values of $F_{in,i}$ are assigned in the process entity of the model of gPROMs.

In the milling operation, the following mass balance approach is applied.

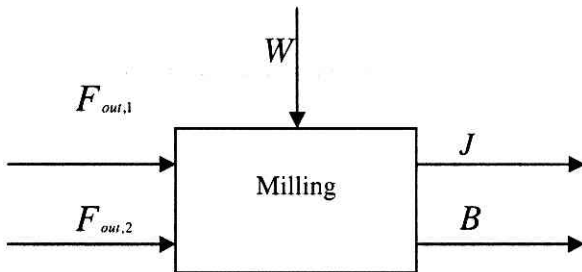


Figure 8. Mass Balance at Milling

$$F_{out,1} + F_{out,2} + W = J + B$$

$$F_{out,1} X_{out,1,i-1} + F_{out,2} X_{out,2,i-1} + F_w X_{w,i-1} = J X_{juice,i-1} + B X_{bagasse,i-1}$$

The juice flow rate can be specified as:

$$J = 0.95 \left(\sum_{i=1}^{n-1} X_{out,1,i} \times F_{out,1} \right) + 0.95 W$$

$$\sum_{i=1}^{n-1} X_{juice} = 1$$

$$\sum_{i=1}^n X_{bagasse} = 1$$

The recovery equations were specified as:

$$R_{2,i-1} = \frac{J X_{juice,i-1}}{F_{out,1} X_{out,1,i-1} + F_{out,2} X_{out,2,i-1}}$$

for all except bagasse; the fourth component.

For bagasse:

$$R_{2,i} = \frac{B X_{bagasse,i}}{F_{out,1} X_{out,1,i} + F_{out,2} X_{out,2,i}}$$

where $i = \text{bagasse}$.

$$\forall i = 1, n$$

$$\forall j = 1$$

n is the number of components.

The above model was defined in Model Entity program1 along with some specifications in Process Entity program1.

There are four components in all; i.e. Sucrose, Water, Organic Impurities and Bagasse. The Bagasse or solids are separated after Milling and do not appear in the mass balance equations later on; so the value of the bagasse component for clarification process is neglected; as seen from the mass balances equations described above. Also the other component removed is Organic Impurities; which are separated after Defecation. So the components remaining after Defecation are only sucrose and water. These assignments are defined in the Process Entity of the gPROMs model.

It is important to note here, however that there is usually a third component called non-sugars is present in the liquid stream but its percentage is very low and at this preliminary stage it was neglected. However provision can be made for a 5th component in the model very easily. This component, called non-sugars consists of compounds like, glucose, fructose, dextrose etc. which are separated during the crystallisation process. There are other minor impurities like fly ash (ash coming from boiler chimney) and other insoluble solid impurities can also add during the process which are separated in the Deep bed filter, pressure filters and ion exchange process. Provision can be made in the model for these components.

Apart from four components, there is only one utility; live steam but provision is left for more utilities, such as, exhaust steam which comes through Refinery pans and is used for heating in the Evaporators. So, there was no need to add this utility at this stage till Defecation. Also the mass balances were defined earlier for heating equipments such as primary heaters and secondary heaters; but since their usefulness is in

the efficient mixing and reaction with lime and polyelectrolyte, they are neglected from modelling equations. However, this assumption could not be carried out in Evaporation, when the liquid mixture of sucrose and water is heated to an appreciable degree and water removal takes place. The energy and mass balance at this stage become vital; and also is the inclusion of exhaust steam.*

The other specifications were the feed inlet flow rate at crusher. Since the sugar industry considered here has a crushing capacity of 3500 tons per day; it is equivalent to 40.509 kg/s. Based upon this, an inlet flow rate of water could be specified as about 20% of the feed flow rate ≈ 8.1 ; as the initial guess. The initial guess of steam pressure was taken as upper value of 16.8 (from base value of 16, allowing an $\pm 5\%$ allowance).

The efficiency of the crusher was fixed as 0.90 which remains constant throughout the operation. Also is the coefficient C_{cr} which relates the crusher efficiency with steam pressure, is fixed. The initial guess of water was 8.4 and since water is a pure component; other components were absent. The feed compositions at the inlet of shredder we specified as follows:

Table 6. Inlet feed composition

| Sucrose (%) | Water (%) | Organics (%) | Bagasse(%) |
|-------------|-----------|--------------|------------|
| 0.11 | 0.75 | 0.05 | 0.09 |

There are two specifications which are necessary to consider here. It was assumed that the moisture in bagasse is about one half of the total composition. Since, more water addition may cause the moisture in bagasse (also water in juice) to exceed, its value was altered in that case; however when a Monte Carlo simulation was carried out (discussed later), this specification was not altered. The recovery of the sucrose in the final stream was assigned to be almost 95%; which was based upon recovery obtained after first separation of the components in Mills.

Simulation in gPROMs

Under the above mentioned conditions, simulation was carried out in gPROMs. It was

* Exhaust steam coming through Refinery Pans.

found that under different operating characteristics i.e. steam pressure, lime addition and water flow rate; different qualities of end products were obtained. This behaviour showed the effect of operating conditions on product specifications. The target product quality was 8%, which means that the sucrose in the final stream (after defecation) should be above 8% (remaining water) to describe our product as satisfying management objective. Some values were found to lie closer or slightly below the specification of 0.08 and were also included in the solution to better characterise our realization of feasible region. There were also cases when gPROMs simulation failed to find a solution within the bounds of the variables specified, meaning an infeasible solution.

6. Control Strategy on Defecation

In the Defecation Process, mixing of lime takes place. Our purpose is to control the lime flow rate with pH meter installed at the downstream unit of the Defecation Process, as shown in figure below.

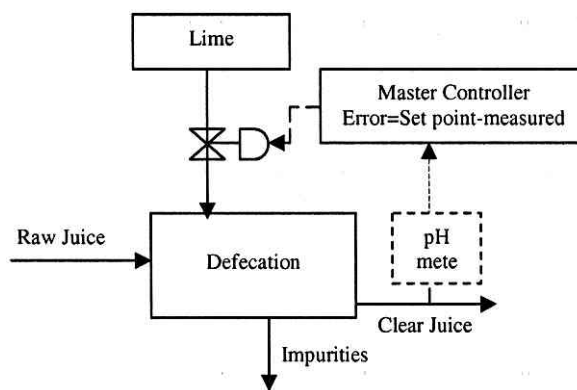


Figure 9. Control Loop on Defecation Process.

7. Conclusion

Out of all the modelling approaches tried; the last one, taking into account the efficiencies of various equipments remained the most suitable especially for the crusher. The assignments in gPROMs of different variables could be altered; such as instead of specifying the percentage of water in the bagasse, we can specify the percentage of sucrose or organics in the bagasse. Similarly, the recovery of water could be specified instead of the recovery of sucrose at the final discharge (Defecation).

Since there should be a way to characterise the product(s), it is suitable to state that our products

lie within certain range, based upon management objectives. We characterised that the final product purity should be more than 8% of the total composition. Based upon this we can find different operating points where the product composition satisfies or fails to meet our requirements and we can characterise them in to different regions. The feasible regions are the ones which give some certain values of the product composition while infeasible regions are where the design does not allow the operation to take place. If the control is not able to take into account the operational changes (i.e. in case of infeasible operation), the control will cause the plant to shut down.

Abbreviations

$I.P.^{base}$ is the base case index of preparation or efficiency value

$C_{o,j}$ is the coefficient between steam pressure and index of preparation variation.

F_{in} = Feed inlet to the crusher

$F_{out,1}$ = Flow rate of Efficient Stream from crusher (shredder) $F_{out,1}$

$F_{out,2}$ = Flow rate of waste stream from crusher (shredder)

W = Water Inlet in Milling operation (kg/s)

J = Flow rate of Juice after milling

B = Bagasse Flow rate

$x_{out1,i-1}$ = Composition of Individual specie minus bagasse in the juice flow rate

$x_{out2,i-1}$ = Composition of Individual specie minus bagasse in the waste stream

$x_{w,i-1}$ = composition of water in Water Stream

$x_{juice,i-1}$ = Composition of species in juice minus bagasse

$x_{bagasse,i}$ = Composition of bagasse

$x_{out1,i}$ = Composition of juice (after crushing)

x_{juice} = Composition of Juice

$x_{bagasse}$ = Composition of Bagasse

U = Flow rate of Utility (Steam, Exhaust Steam)

FL = Flow rate of Lime

XCJ = Composition of Clear juice (after defecation)

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