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## MODELLING AND SIMULATION OF BATCH PROCESSES: CRYSTALLISATION SECTION OF A SUGAR FACTORY

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### Abstract

*In this project, EcosimPro is used to build a dynamic model and simulate an essential part of a sugar factory — the sugar house. The Benavente Sugar Mill has been used as a reference for this work.*

**Key words:** Object-oriented modelling, simulation, EcosimPro, ZONE, WHEN, batch processes, crystallisation.

### 1 OBJECTIVES

According to ISA-S88 (1995), batch or semibatch processes are those that lead to the production of finite product quantities based on a quantity of input materials. Using one or more parts of the equipment, these input materials are put through a series of processes in a finite period of time. The difference between batch or semibatch processing depends on whether product input is maintained for the entire batch. During semibatch processing product input is continuous, whereas during batch processing it is not.

The objective of this project is to build a dynamic model and simulate the sugar house of a sugar factory in order to carry out operation studies and control system tests.

Different stages have been established to reach this objective:

- Study the process unit
- Write the dynamic model of the unit. The first step in this study is to obtain the equations that govern unit behaviour
- Simulate it in object-oriented simulation language EcosimPro (EL). Using a computer, it is possible to simulate different situations in the real plant and observe the behaviour of process real instruments. This enables us to

anticipate different situations and to know a priori how the process is going to respond in certain situations.

- Estimate rational parameters
- Verify correct operation

### 2 MATHEMATICAL-PHYSICAL MODEL OF THE VACUUM PAN STATION

Crystallisation is carried out in *the sugar house*, comprising the 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> vacuum pans (known as A, B and C-vacuum pans), the tanks, the centrifugals, the crystallisers, the melter stations, the afination centrifugals and the necessary tanks and pipes. The structure of the sugar house is similar to that shown in Figure 1:

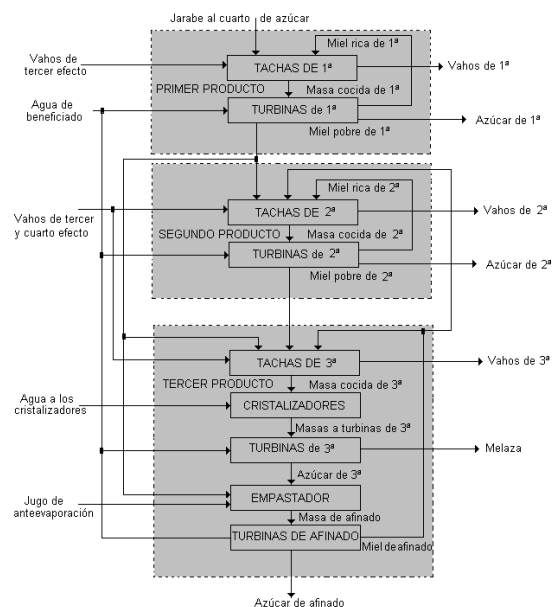


Figure 1: Components of the sugar house and flow lines

The crystallisation process can be subdivided into the following stages:

a) Melting

The *syrup* resulting from the evaporation stage is passed on to the melting station where the *B-sugar* and the *purified sugar* are dissolved to produce *standard syrup*. The standard syrup is then filtered and pumped to the *A-vacuum pans*.

b) First Crystallisation Process

Crystallisation is carried out in order to obtain sugar crystals that are as pure as possible. The first crystallisation takes place in the vacuum pans, where part of the sucrose dissolved in the standard syrup crystallises as the water in the juice evaporates. The vacuum pan becomes full of what is known as the *A-massecuite* which is formed by crystallised sucrose, sucrose and non-sugars dissolved in a solution known as *mother liquor*. All the pans operate in vacuum conditions, in order to lower the boiling point of the products being processed in them and thus prevent thermal decomposition of the sucrose (loss of sucrose).

c) A-Product Centrifugation

The *A-massecuite* is discharged to the centrifugals where the crystals are separated from the mother liquor. This operation is carried out in centrifugals where, during a second centrifugal stage, the sucrose crystals are washed with pressurised water and steam. For this reason, the mother liquor separated in the centrifugals is divided into two types:

- *Syrup for seed magma*: First-stage centrifuge
- *Syrup for massecuite*: That produced after the second-stage crystal wash

d) Drying and Conditioning of the Sugar

The sucrose crystals separated in the A centrifugals constitute what is known as *white sugar*. These crystals are then put through a drying, cooling and subsequent screening process before being packed.

Stages b) and c) are repeated in the B and C vacuum pans with the following modifications: The B vacuum pans receive syrup from the A product centrifugals and the resulting massecuite is known as *B product massecuite*. The B product massecuite is centrifuged to obtain *B sugar* and *B syrup*. This process is carried out in continuous centrifugals, the effect of which is analogous to that of the first product.

The C vacuum pans are fed first with syrup for seed magma to make up the vacuum pan level and then with B syrup and *purified syrup*. The product obtained is *C massecuite* which, after centrifugation, produces *C sugar* and *molasses*. The

C sugar and the purified liquor are mixed during a crystal washing process in the purifier. The resulting mass is centrifuged and a purified sugar and the purified liquor are obtained.

Lastly, the molasses obtained is converted into alcohol in an annexed factory to the sugar factory.

So, this is a closed cycle process where the majority of the obtained products are reprocessed, with the exception of the A sugar (the objective of the process) and the molasses (a by-product).

The following is a description of the mathematical models of the vacuum pans, centrifugals and crystallisers, which are the most important components of this process section.

## 2.1 VACUUM PAN MODELLING

### 2.1.1 Vacuum Pan Environment

Operating in semibatch mode, it is in the vacuum pans where the sugar is separated from the juice which is extracted from the sugar beets by means of a crystallisation method controlled by evaporation in a vacuum environment.

Initially, a subsaturated sugary juice known as standard liquor which is stored in standard liquor tanks is pumped into the vacuum pan. This standard liquor is then heated in vacuum conditions in order to reduce the boiling point and prevent thermal decomposition of the sucrose (a process known as *caramelisation*). When this juice becomes supersaturated, it is seeded into small crystals and grown by adding more liquor and maintaining the supersaturated conditions. When the maximum level is reached in the vacuum pan, the contents are discharged and the pan is cleaned, ready for a new cycle.

To heat the juice and evaporate part of the water, the vacuum pans are equipped with a heating element known as the *calandria*. Steam flows through the calandria at a pressure above that of atmospheric pressure and as it condenses, it releases heat to the massecuite in the vacuum pan. The steam is supplied to the vacuum pans through steam supply pipes which form a closed circuit that runs around the complete industrial plant.

To maintain a partial vacuum (0.2-0.3 bar) in the vacuum pan in order to evaporate the water at low temperature (65-70°C), the vacuum pan must be connected to a *barometric condenser*. This condenser maintains a determined vacuum as it absorbs the steam coming from the vacuum pans and condenses it by means of cooling. The cooling

effect is obtained by the entry of water which is carried via pipes from the outside. The vacuum produced in the condenser depends on the outside temperature, which means it works better in winter.

Once the crystallisation process of the sucrose in the vacuum pan is completed, the resulting massecuite is discharged into *horizontal tanks*. In the tanks it is kept moving at a determined temperature so as to maintain its consistency until it can proceed to one of the *centrifugals*.

In the centrifugals the crystallised sugar is separated from the mother liquor as the batch is centrifuged at high speed, leaving the crystals retained by a screen. The process takes just a few minutes. The mother liquor is separated into syrup for seed magna and syrup for massecuite which is distributed according to the needs of the plant. Figure 2 shows what a vacuum pan looks like:

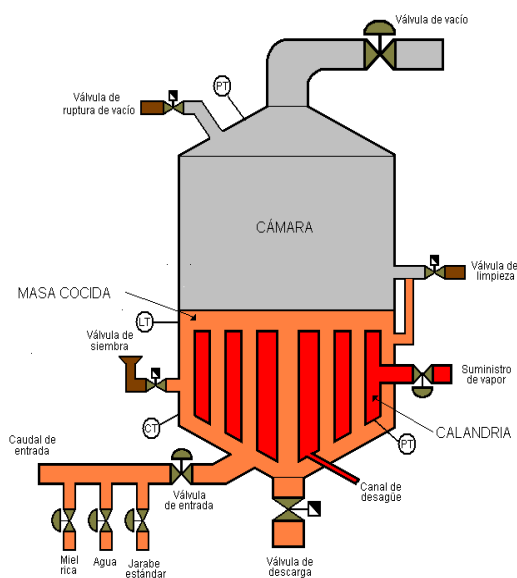


Figure 2. Sketch of a Vacuum Pan

### 2.1.2 Stages of the Process

A vacuum pan process is divided into the following stages:

**Prepared Vacuum Pan.** The objective is to get the vacuum pan ready for start of operation. The vacuum pan is empty and a reference pressure of 0.20-0.25 bar is established in the chamber. It is the operator who decides when to end this stage and pass on to the next one.

**Loading.** The chamber of the vacuum pan is filled with standard liquor up to a certain level known as the *vacuum pan level* which amounts to approximately 50% of the vacuum pan level and 35% of the maximum volume of the syrup it contains (the calandria occupies a certain volume of

this area). At the same time that the standard liquor enters the vacuum pan, a hot steam supply valve opens, increasing the temperature of the liquor. When part of the water in the liquor starts to evaporate, the pressure in the chamber increases. The operator will decide when the loading stage is to begin, depending on the availability of standard liquor and other raw materials of the process, and taking into account the synchronisation with the other vacuum pans of the plant. The process concludes when the liquor reaches the *vacuum pan level*.

**Concentration I.** The objective of this stage and the next one is to concentrate the initial subsaturated standard liquor (concentration: 0.6-0.7) to the levels required for the seed, the supersaturation of seed (concentration 1.2-1.3). The liquor valve level is regulated to maintain vacuum pan level and the steam supply valve stays open. In this way, greater juice concentration is produced by evaporating part of the water it contains. The process ends when juice supersaturation reaches a determined value which is slightly lower (normally 95%) than seed supersaturation (1.2).

**Concentration II.** In this stage the juice is concentrated until it reaches the seed supersaturation value (concentration: 1.2). The inlet flow valve closes and causes the liquor level to drop slightly below the *vacuum pan level*. To ensure that the transition towards seed supersaturation is as smooth as possible, the steam supply valve remains partially closed. This stage is of short duration. It ends when seed supersaturation is achieved.

**Seed.** In this stage, the seeds for the sucrose crystals are dissolved in an alcoholic solution ready for growing in the subsequent stages and their ultimate conversion into the final vacuum pan product. It is assumed that, before this stage, no crystals have formed or grown in the vacuum pan. The sucrose mass that has been seeded is very small (about 10 grammes) and the crystals measure about 5 micrometres (5  $\mu\text{m}$ ). Theoretically, the total number of seeded crystals remains constant up to the end of the process. It ends with the seeding process.

**Stabilisation.** The objective is to guarantee stable conditions during the first moments of crystal growth. This is achieved by keeping the steam supply valve partially closed so that crystallisation predominates over evaporation, and by keeping supersaturation constant at its main value by controlling the inlet flow. This stage ends when the crystals measure an average of 200 micrometres (0.2  $\mu\text{m}$ ). However, this criterion cannot be automated because it depends on visual observation

of the crystals which is the responsibility of the operator.

**Boiling.** The boiling stage is the most important in the process. It is during this stage that the crystals are grown to their final size (about 0.5  $\mu\text{m}$ ). The crystallisation process removes sucrose from the mother liquor surrounding the crystals which decreases its concentration. To replace it, subsaturated standard liquor is introduced from which the correct amount of water must be removed by means of evaporation. The flow of standard liquor into the vacuum pan must be regulated so as to guarantee that certain supersaturation conditions in the mother liquor are maintained to allow crystal growth. In addition, since the objective is to obtain as much massecuite as possible, care must be taken to ensure that the crystals reach their final size by the time they get to the maximum level of the vacuum pan.

Whether the crystals reach their final size before the vacuum pan is filled or whether the vacuum pan is filled before the crystals reach their final size, the vacuum pan level during discharge is less than the maximum (in the latter case, the crystals should be left to grow to their final size by evaporating water and, in order to make the level drop, no liquor should be introduced).

Therefore, two conditions exist when it comes to regulating the flow of standard liquor: the first, to maintain a determined concentration in the mother liquor and the second, to try to obtain maximum vacuum pan level together with optimum crystal size. Depending on the characteristics of the vacuum pan (above all, the capacity of evaporation of the calandria and the rate of growth of the crystals), both objectives may or may not be compatible. If they are, then the inlet flow should be adjusted to make it feasible.

To efficiently control the process in order to achieve the above-mentioned objectives, we have to know both the supersaturation of the mother liquor and the actual size of the crystals or, failing that, the quantity of massecuite in the vacuum pan at a given moment. The supersaturation of the mother liquor is determined by measuring its conductivity. In addition, each vacuum pan has a curve which provides adequate supersaturation for each value of the level reached in the vacuum pan. Knowing this curve, the actual level in the vacuum pan is measured and the inlet flow is adjusted so that the measurement of supersaturation in the vacuum pan (obtained by measuring the conductivity of the mother liquor) is in accordance with the value provided by the curve.

There are two possible conditions in the concluding process: the first is that maximum level has been reached in the vacuum pan, in which case the process will go on to the next stage (pressing). The second is that a determined total Brix has been obtained in the vacuum pan (90.4). This datum indicates that the size of the crystals is the desired final size, and it is related to the total content of crystals in the vacuum pan and to the concentration of the mother liquor. If the total Brix condition is reached first, the pressing stage will be skipped and the process will go directly on to the waiting stage.

**Pressing.** This stage is only relevant in the event that the total Brix required in the boiling stage has not been achieved. The objective is to allow the crystals to grow to their desired final size. The standard liquor valve is closed completely to stimulate growth of the crystals by evaporating the water and increasing supersaturation. This causes the level in the vacuum pan to drop.

This stage ends when a total Brix of 90.4 (consistency criterion) is reached, which corresponds to a determined value of conductivity measurement which, in turn, corresponds to the desired final size of the sugar crystals.

**Waiting.** After the massecuite is obtained, situations may arise that make it necessary to wait for the discharge process to be carried out. This is called the waiting stage, which consists in introducing water into the vacuum pan where it is evaporated by the heat from the calandria. This has to be done because the calandria cannot be disabled. Disabling the calandria would give rise to a decrease in the temperature and a subsequent increase in supersaturation followed by mass crystallisation. This way it is attempted to keep the vacuum pan parameters constant, without causing further growth of the crystals. This stage is ended by the operator on the basis of plant needs.

**Vacuum break.** The objective of breaking the vacuum is to re-establish atmospheric pressure in the vacuum pan to be able to discharge the massecuite. To prepare and facilitate discharge of the massecuite, the vacuum is broken by introducing steam through the vacuum break valve until the pressure in the chamber differs from that of atmospheric pressure by less than 10%. This stage ends when chamber pressure reaches 0.9 bar.

**Discharge.** In this stage the massecuite is left to fall into one of the available presses. The process is stopped when the massecuite which is left in the vacuum pan occupies less than 6% of the total volume. It ends when the volume of massecuite in the vacuum pan is less than 6% of the volume of the vacuum pan.

**Cleaning / Washing.** The objective in this stage is to eliminate the remains of the massecuite stuck to the walls of the vacuum pan. To achieve this, steam is passed through cleaning valve at 90°C which causes the remains to dissolve. The process ends when a pre-established time has elapsed.

**Prepare Vacuum Pan.** The objective is to get the vacuum pan ready for another cycle. To do this, the discharge valve is closed. It is the operator who decides when to pass from this stage on to the loading stage. This process ends when a new cycle begins.

### 2.1.3 Mathematical Model of the Vacuum Pan

The massecuite (characterised by the total mass,  $m_T$ ) consists of two phases, the crystals and the liquor (characterised by the crystal mass,  $m_C$ , and the liquor mass,  $m_J$ ).

The liquor consists of water, sucrose and dissolved impurities. Therefore, to characterise the state of the vacuum pan we need four magnitudes, the quantities of mass of each species existing at a given moment:

$$\text{Masa cocida}(m_T) \left\{ \begin{array}{l} \text{Masa de Jarabe}(m_J) \left\{ \begin{array}{l} \text{Masa de agua}(m_A) \\ \text{Masa de soluto}(m_{SOL}) \left\{ \begin{array}{l} \text{Masa de sacarosa disuelta}(m_S) \\ \text{Masa de impurezas disueltas}(m_I) \end{array} \right. \\ \text{Masa de cristales de sacarosa}(m_C) \end{array} \right. \end{array} \right.$$

According to this sketch, we have the following ratios:

$$m_{SOL} = m_S + m_I \quad (1)$$

$$m_J = m_A + m_{SOL} = m_A + m_S + m_I \quad (2)$$

$$m_T = m_C + m_J = m_C + m_A + m_S + m_I \quad (3)$$

We also have in the chamber a certain quantity of steam mass ( $m_V$ ), which is in relation to the pressure and the temperature.

Empirical ratios of interest:

**Brix**, percentage of dissolved solute with respect to the total solution.

$$bx = 100 \frac{m_{SOL}}{m_J} \quad (4)$$

**Purity of the solution**, percentage of dissolved sucrose with respect to the total mass of solute.

$$px = 100 \frac{m_S}{m_{SOL}} \quad (5)$$

**The content of sugar in the massecuite ( $W_C$ )**, percentage of sucrose crystals with respect to the total massecuite.

$$W_C = 100 \frac{m_C}{m_T} = \frac{100}{100 - bx} (bx_i - bx) \quad (6)$$

**Total Brix of the massecuite**, dry residue obtained from 100 g of massecuite.

$$bx_i = 100 \frac{m_{SOL} + m_C}{m_T} = bx + (1 - \frac{bx}{100}) W_C \quad (7)$$

**Concentration of the solution**, grammes of dissolved sucrose for every 100 g of water.

$$C = 100 \frac{m_S}{m_A} \quad (8)$$

**Ratio of Impurities-Water**, modification of the saturation concentration due to impurities.

$$R_n = \frac{m_I}{m_A} \quad (9)$$

## FLUID FLOWS

### Input flow ( $q_e$ )

The flow through a control valve depends on the size of the valve, the pressure drop through the valve, the position of the needle and the properties of the fluid. The design equation for liquids is:

$$q_e = C_v f(x) \sqrt{\frac{\Delta P_v}{\gamma}} \quad (10)$$

Where  $q_e$  is the flow of the liquid,  $C_v$  is the coefficient of the size of the valve,  $f(x)$  is the fraction of the area of total flow of the valve,  $\gamma$  is the specific weight of the fluid (relative to the water) and  $\Delta P$  is the pressure drop through the valve.

Depending on which valve is open, we can insert the following substances through the inlet pipe:

- Standard liquor: This is the habitual input, except during the waiting stage. It is characterised by the following parameters: Brix ( $bx_j$ ), purity ( $px_j$ ), temperature ( $T_j$ ), valve coefficient ( $Cv_j$ ), and the level in the tank with respect to zero level in the vacuum pan ( $L_j$ ).
- Syrup for massecuite: This is added if the standard liquor tank becomes empty or it is

mixed with the standard liquor. Vacuum pan performance decreases as the sugar content lessens and there are more impurities. It is characterised by the following parameters: Brix ( $bx_M$ ), purity ( $px_M$ ), temperature ( $T_M$ ), the valve coefficient ( $Cv_M$ ), and the level in the tank with respect to zero level in the vacuum pan ( $L_M$ ).

- **Water:** This is added in the following circumstances: During the waiting stage, at any moment if the mass is seen to be too compact or the crystals are unevenly distributed, in extreme case of depletion of liquor and syrup for massecuite, and when false grains form due to spontaneous nucleation to diminish the Brix. It is characterised by the following parameters: Brix ( $bx_A=0\%$ ), purity ( $px_A=100\%$ ), temperature ( $T_A$ ), the valve coefficient ( $Cv_A$ ), and the level in the tank with respect to zero level in the vacuum pan ( $L_A$ ).

We divide the overall flow  $q_e$ , into partial flows for each of the species present in the process:

Flow of sucrose:

$$q_e^S = \frac{bx_e}{100} \frac{px_e}{100} q_e \quad (11)$$

Flow of impurities:

$$q_e^I = \frac{bx_e}{100} \left( 1 - \frac{px_e}{100} \right) q_e \quad (12)$$

Flow of water:

$$q_e^A = \left( 1 - \frac{bx_e}{100} \right) q_e \quad (13)$$

Because crystals are not supplied with the inlet flow, the overall flow has been identified with the mass of syrup.

#### Flow of evaporation (Fev)

Water is transformed into steam by the heat emitted by the calandria. It only affects the mass of water ( $m_A$ ).

#### Flow of crystals in the seeding stage ( $q_{siem}$ )

This is produced by the external supply of crystals during the seeding stage, and it is calculated using the seeding crystal mass ( $m_{C0}$ ) and the seeding time ( $t_{siem}$ ), with which we obtain:

$$q_{siem} = \frac{m_{C0}}{t_{siem}} \quad (14)$$

#### Discharge flow ( $q_d$ )

This occurs during the discharge stage. Knowing the time it takes to discharge a given weight of massecuite, we can obtain an approximation of  $q_d$ . To simulate discharge, we have to divide this flow into its components for each of the species present in the massecuite. Let us assume that discharge is uniform, or in other words, that the ratios between the species are maintained in the portion that is not discharged:

$$q_d = \frac{m_{if}}{t_d} \quad (15)$$

Where  $m_{if}$  is the total mass at the moment of discharge and  $t_d$  is the time required to discharge the total mass.

The following are the discharge flows for each of the species.

Flow of crystals:

$$q_d^C = \frac{W_{Cf}}{100} q_d \quad (16)$$

Flow of syrup (sucrose, impurities and water) (17):

$$q_d^J = \left( 1 - \frac{W_{Cf}}{100} \right) q_d \rightarrow \begin{cases} q_d^S = \left( 1 - \frac{W_{Cf}}{100} \right) \frac{bx_f}{100} \frac{px_f}{100} q_d \\ q_d^I = \left( 1 - \frac{W_{Cf}}{100} \right) \frac{bx_f}{100} \left( 1 - \frac{px_f}{100} \right) q_d \\ q_d^A = \left( 1 - \frac{W_{Cf}}{100} \right) \left( 1 - \frac{bx_f}{100} \right) q_d \end{cases}$$

Where  $W_{Cf}$ ,  $bx_f$  and  $px_f$  are the final mass ratios.

#### BALANCE OF SUCROSE IN THE JUICE

The sucrose mass receives its part of the inlet flow, and is transformed into crystallised sucrose during the crystallisation process:

$$\frac{dm_S}{dt} = q_e^S - \frac{dm_C}{dt} \quad (18)$$

#### BALANCE OF IMPURITIES

The inlet flow is the only source of impurities, and there is no process which eliminates them (apart from an insignificant fraction which evaporates in the form of incondensable elements).

$$\frac{dm_I}{dt} = q_e^I \quad (19)$$

## BALANCE OF WATER

The mass of water receives its portion of the inlet flow and is eliminated through evaporation due to the heat emitted by the calandria.

$$\frac{dm_A}{dt} = q_e^A - F_{ev} \quad (20)$$

## GROWTH OF CRYSTALS

The inlet flow does not affect the sucrose crystals. There are three different situations:

- An initial period during which the seed is produced, when the number of sucrose crystals is insignificant and spontaneous nucleation is the only form of generation (almost nil due to the existing subsaturation conditions).
- The seeding period, of short duration, with a constant supply of sucrose crystals.
- After seeding, the size of the crystals gradually increases due to the crystallised sucrose.

The following is the equation for mass variation of a crystal:

$$\frac{dm_{cris}}{dt} = f_T(T) f_Y(Y) f_{px}(p_x) f_{ag}(rpm) A_{cris} \quad (21)$$

The following explains the main factors which affect the speed of crystal growth:

### Dependency on the temperature

For their incorporation into the crystal surface, the sucrose molecules must overcome an energy barrier because of the need to break the links of the crystal cell:

$$f_T(T) = A e^{-\frac{E^*}{R(T+273.15)}} \quad (22)$$

Where A is the frequency factor, E\* the activation energy needed for the sucrose molecule to become incorporated into the crystal, R the constant of the ideal gases and T the temperature.

### Dependency on supersaturation

Crystallisation is the transformation of sucrose from the liquid phase to the solid phase.

Crystal growing is a process of diffusion modified by the effect that the solid surfaces have on the surfaces where the crystals are grown. The molecules of ions of the solute reach the growing surfaces of a crystal by means of diffusion during the liquid phase. At this stage, the usual coefficient for mass transfer is applied K<sub>y</sub>. Once the molecules or ions reach the surface, they have to be accepted

by the crystal and organised within the network. The reaction takes place on the surface at a finite speed and the overall process consists of two stages in series. Neither of the two stages -diffusion nor interface- is carried out if the solution is not supersaturated.

Both processes help to determine the speed of growth of the crystal, but as long as resistance to molecular transformation is predominant with 'normal' supersaturation and high temperatures (higher than 50°C), the resistance to molecular incorporation will have an effect at low temperatures and supersaturation. We can therefore use the ranges of the above equations and write an overall equation as follows:

$$f_y(y) = \begin{cases} -K_{dis}|y-1|^{K_{ydis}} & \text{paray} < 1 \\ K_{red}(y-1)^{K_{yred}} & \text{para } T < 50^\circ\text{C}, 1 < y < 1.1 \\ K_{nor}(y-1)^{K_{ynor}} & \text{para } T > 50^\circ\text{C}, 1.1 < y < 1.4 \\ K_{nuc}(y-1)^{K_{ynuc}} & \text{paray} > 1.4 \end{cases} \quad (23)$$

The constants are adjusted according to the range within which the supersaturation and temperature are placed.

Based on the supersaturation, four areas of crystal growth can be defined:

Subsaturated area: Supersaturation is less than the unit and, therefore, crystal growth is negative and dissolution takes place. The exponent is slightly greater than 2, and is represented by the constant K<sub>ydis</sub>.

Metastable area: Supersaturation is in a range of 1 to 1.35. This is the normal area of work. In the event that supersaturation is less than 1.1 or the temperature is less than 50°C, we will use the exponent K<sub>yred</sub> (slightly less than 2). Otherwise we will use K<sub>ynor</sub>, which is close to the unit and represents the normal working conditions in the batch type and full seed crystallisers, like the one we are analysing.

Spontaneous nucleation area: When supersaturation exceeds a determined level (around 1.4), the sucrose molecules may spontaneously gather around the impurities to form crystal seeds which can grow. This is the normal area of work in continuous type crystallisers.

Labile area: This area falls within the limits between the metastable area and the spontaneous nucleation area. No spontaneous nucleation takes place in the labile area, but it could be subject to the effects of secondary nucleation or false grain or, in other words, the formation of seeds produced by a previous crystal seed.

### Dependence on the shaking of the medium

Shaking the medium reduces the energy need for the incorporation of the crystal molecules and also diminishes the resistance to transformation and consequently accelerates crystal growth. The following is the empirical formula used to model this effect:

$$f_a(rpm) = (1 + rpm)^{K_{rpm}} \quad (24)$$

### Dependence on the presence of impurities

Impurities have very different effects on the growth of crystals. In small quantities they favour crystallisation by acting as crystal formation nuclei and creating surface defects which promote the growth of the facets of the crystals. In significant quantities, however, they generally have an inhibiting effect. The following equation expresses the inhibiting effect on growth due to diminishing purity:

$$f_{px}(px) = e^{-K_{px}(1-\frac{px}{100})} \quad (25)$$

### Crystallisation equation

Gathering together all the effects on crystal growth, we obtain an overall equation for mass growth of a crystal. Such growth will depend mainly on the surface that the crystal presents for the incorporation of new molecules, and the excess sucrose in the medium, quantified as a measurement of supersaturation. The equation is designed for standard working conditions, that is, supersaturation is in the metastable area but may take into account the growth of crystals in the nucleation area and even in the solution area (in the event that  $y$  is less than the unit), accordingly adjusting the constants  $K_Y$  and the overall constant  $K$ . The following effect on importance resides in the temperature, and the effects of shaking and of purity have to be adjusted for each particular case, because there is no overall theory concerning these effects.

$$\frac{dm_{cris}}{dt} = K(1 + rpm)^{K_{rpm}} e^{-K_{px}(1-\frac{px}{100})} \frac{E^*}{(T+273.15)} (y-1)^{K_Y} A_{cris} \quad (26)$$

By substituting  $m_{cris} = \rho_c K_v Ma^3$ , and simplifying and rearranging the formula, we have:

$$\frac{dl_{cris}}{dt} = \frac{KK_s}{3r_c k_v} (1 + rpm)^{K_{rpm}} e^{-K_{px}(1-\frac{px}{100})} \frac{E^*}{(T+273.15)} (y-1)^{K_Y} \quad (27)$$

It can be seen that the speed of growth of the average size depends only on external parameters (temperature, saturation, etc) and if the

surroundings remain constant, the speed of growth will remain constant regardless of the size of the crystal. In addition, if the crystals have the same surroundings, they will all grow at the same speed.

The bibliography usually defines a function denominated  $G$ , which covers the rate of linear growth of the crystals, and which is defined in the expression below (28):

$$G(y, T, px, rpm) = \frac{KK_s}{3r_c k_v} (1 + rpm)^{K_{rpm}} e^{-K_{px}(1-\frac{px}{100})} \frac{E^*}{(T+273.15)} (y-1)^{K_Y}$$

The above differential equation can therefore be defined as follows:

$$\frac{dl_{cris}}{dt} = G(y, T, px, rpm) \quad (29)$$

And expressing the growth in mass of each crystal as a function of  $G$ , we obtain the following equation:

$$\frac{dm_{cris}}{dt} = \frac{3r_c K_v}{K_s} GA_{cris} = R_G A_{cris} \quad (30)$$

For the evolution of the total mass of crystals, we implement a uniform growth up to the value of the initial mass during the seeding stage, and we take into account the discharge stage, which is reflected in the equation below (31):

$$\frac{dm_C}{dt} = \begin{cases} 0 & \text{Etapas anteriores} \\ \frac{m_{C0}}{t_S} & \text{Etapa de siembra} \\ \frac{3r_c K_v}{K_s} G(y, T, \dots) A_C & \text{Etapas posteriores} \end{cases} \quad (31)$$

During the seeding stage, growth is gradual so that when it ends the mass of crystals is equal to that of the seed,  $m_{C0}$ .  $t_S$  represents the duration of the stage.

### BALANCE OF LIQUOR

$$\frac{dm_J}{dt} = q_e - F_{ev} - \frac{dm_C}{dt} \quad (32)$$

### BALANCE OF TOTAL MASS

$$\frac{dm_T}{dt} = q_e - F_{ev} \quad (33)$$

### MEASUREMENT OF SUPERSATURATION

Saturation concentration for pure solutions (34):

$$C_{sat}^p(T) = 181.5 + 0.602319T + 0.014362T^2 + 9.142 \cdot 10^{-5}T^3$$

The following is the saturation concentration that is taken into account for the effect of impurities (35)

$$C_{sat}(T, R_n) = [0.82 + 0.178R_n + 0.18e^{-2.1R_n}] C_{sat}^p(T)$$

The supersaturation equation is:

$$y = \frac{C}{C_{sat}} \quad (36)$$

#### MEASUREMENT OF VACUUM PAN LEVEL

One of the measurements that can determine the state of the vacuum pan level is that which refers to the level of the massecuite. This level is measured on a scale given in relative units (percentage), and made flush to a certain level so as to leave part of the vacuum pan without being measured (minimum volume), the maximum volume of which is calculated on the basis of the maximum volume of massecuite stored in the vacuum pan.

The volume of massecuite in the vacuum pan at any given moment is calculated by adding together the volumes of syrup and crystals:

$$V = \frac{m_J}{r_J(T, bx)} + \frac{m_C}{r_C} \quad (37)$$

To determine the ratio of the volume and the vacuum pan level measurement, L, we are going to assume that the vacuum pan is cylindrical and has a constant surface with either end finishing in a cone. We can divide the vacuum pans into different parts:

- Minimum volume area, which is the dead area not contemplated in the level.
- The next area houses the calandria. The volume of massecuite which covers the vacuum pan level minus the minimum volume is called the vacuum pan level volume. To calculate the level in this area we are going to take into account the volume of the calandria. When the level covers the calandria it is called the vacuum pan level.
- In the upper part of the vacuum pan the calandria does not occupy any volume.
- Lastly, the vacuum pan volume which is never occupied by the massecuite is called the residual volume which constitutes the minimum volume of gases where the dynamics of syrup evaporation takes place.

This is shown in figures (3) and (4):

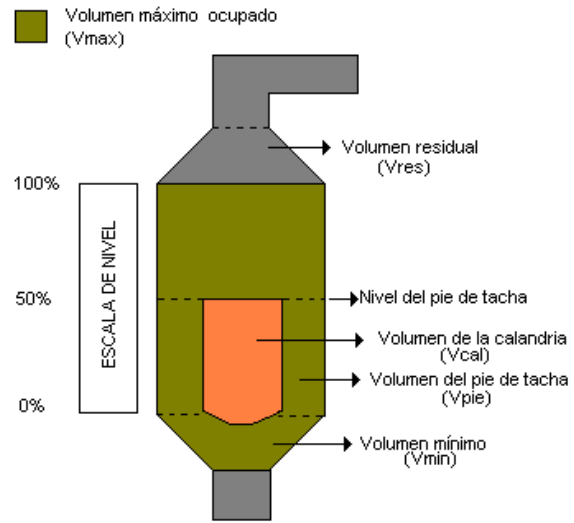


Figure 3. Measurement of the vacuum pan level

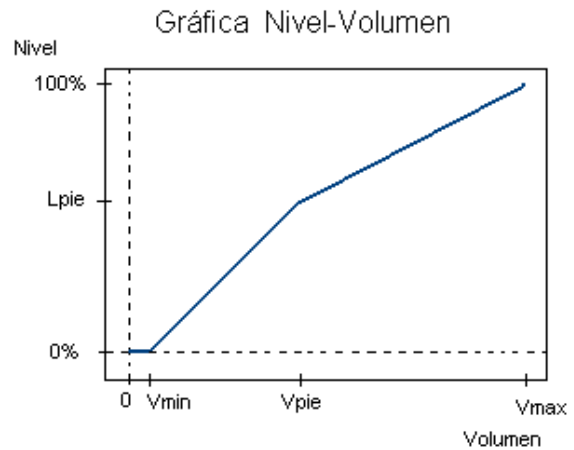


Figure 4. Measurement of the vacuum pan level

Therefore, the level-volume ratio will be represented by three straight lines with different slopes, depending to what extent the vacuum pan is filled:

$$\frac{d(m_T h_T)}{dt} = Q_{cal} - K_p A(T - T_{ext}) - F_{ev} H_v + q_e h_J(T_e, bx_e) + Q$$

$$L_R = \begin{cases} 0 & \text{si } V \leq V_{min} \\ L_{pie} \frac{V - V_{min}}{V_{pie}} & \text{si } V_{min} < V \leq V_{pie} + V_{min} \\ L_{pie} + (100 - L_{pie}) \frac{V - V_{pie} - V_{min}}{V_{max} - V_{pie} - V_{min}} & \text{si } V > V_{pie} + V_{min} \end{cases} \quad (28)$$

$L_{pie}$  is the level (in percentage) of the vacuum pan level. We must have data on the minimum volumes, ie, the vacuum pan level and the calandria, as well as the maximum volume of massecuite.

Another important parameter is the volume of the chamber,  $V_{cam}$ , which represents the free area of massecuite where the steam dynamics take place:

$$V_{CAM} = V_{max} + V_{res} - V \quad (39)$$

**CONSERVATION OF HEAT**

Since the dynamics of steam flows in the chamber are much faster than the temperature variation, we will assume that the flow of steam is determined by the dynamic equations of the chambers and that the temperature variable used by the equations is constant in any significant variation in steam flow.

**Heat transfer in the vacuum pan**

From the energy point of view, generally the process consists in the evaporation of water, first to reach certain supersaturation conditions and then to maintain them. Because sucrose is lost during the crystallisation process, the corresponding amount of water has to be evaporated to maintain the concentration of the juice.

The heat needed to produce the evaporation of water is supplied by the calandria which exchanges heat with the system by condensing steam at temperatures and pressures greater than those in the vacuum pan. Figure (5) shows the main heat flows in the vacuum pan.

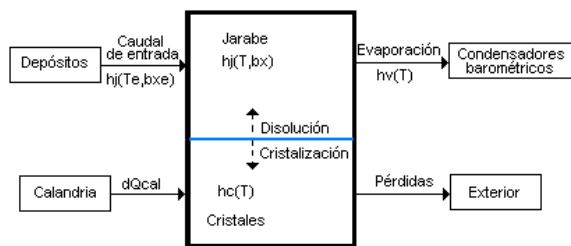


Figure 5. Heat flows in the vacuum pan

This is shown mathematically in the equation (40):

$$\frac{d(m_T h_T)}{dt} = Q_{cal} - K_p A(T - T_{ext}) - F_{ev} H_v + q_e h_J (T_e, b x_e) + Q_{crista}$$

**Calandria dynamics**

We are now going to develop the equations that govern the calandria dynamics. See the sketch in Figure (6).

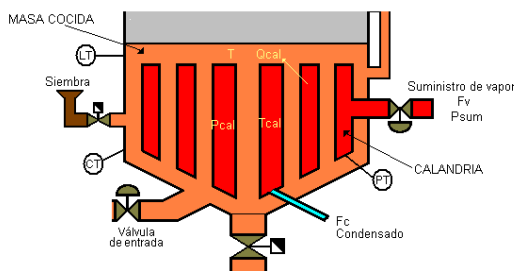


Figure 6. Sketch of the calandria dynamics

Flow of heat towards the vacuum pan:

$$Q_{cal} = A_{cal} U_{cal} (T_{cal} - T) \quad (41)$$

Steam flow

To calculate the heating steam flow, we have to bear in mind that the heat provided by the calandria comes from the condensation of that steam. Therefore, the heat must be equal to the steam mass times the condensation enthalpy:

$$Q_{cal} = F_v I(T_{cal}) \quad (42)$$

**Chamber dynamics**

Chamber is the name given to the top part of the vacuum pan limited by the juice level, full of steam. The chamber dynamics have similar characteristics to those of the calandria, but with the following differences:

- Unlike that of the calandria, the volume of the chamber  $V_{cam}$ , is not constant but, rather, varies with the vacuum pan level. However, compared with the chamber processes this variation is very slow and its derivative with respect to time can therefore be considered as negligible.
- The direct contact of the chamber with the massecuite gives rise to appropriate conditions which create a thermal balance between the two. It can therefore be assumed that the temperature of the chamber is equal to that of the massecuite, or in other words:  $T_{cam}=T$ .
- In addition, given the chamber dynamics, we can assume that the outlet flow of steam towards the condenser,  $F_{vc}$ , will be equal to the flow of evaporated steam,  $F_{ev}$ , with the exception of transient periods lasting just seconds during which the pressures will be re-established. The study of the chamber dynamics is going to be divided into two different situations: when we have saturation conditions (there is a net evaporation flow), and non-saturation conditions (during the first stages, when the calandria is not in operation). Figure (7) shows a sketch of the processes which take place in the chamber.

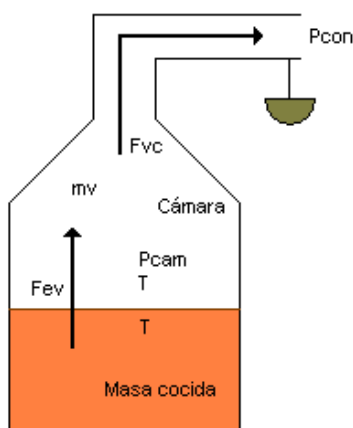


Figure 7. Dynamics of the chamber processes

Saturation conditions

In saturation conditions, the evaporation and steam flows towards the condensers can be equalised.

$$F_{ev} = F_{vc} = C_v f(x) \sqrt{P_{cam}^2 - P_{con}^2} \quad (43)$$

Assuming that we have saturation (boiling) conditions at all times, the pressure in the chamber would be determined by the pressure of equilibrium of a juice solution with a determined Brix and a given temperature:

$$P_{cam} = P_{eq} = f(T_s) \quad (44)$$

Non-saturation conditions

These conditions arise when the massecuite is not at the temperature required to keep it boiling. If we apply the above sketch, because the temperature of the massecuite is significantly less than the boiling temperature at the pressure of the barometric condensers, there would be a backflow of steam, ie, from the condensers to the chamber. The heat equations would also reflect an inflow of heat due to the condensation of steam from the condensers.

This is not physically acceptable. What happens in this case is that the flow of evaporation is negligible and the pressure in the chamber quickly reaches equilibrium with the pressure in the barometric condensers. This situation is maintained until the temperature reaches the value of the boiling temperature at that pressure, which is a necessary step because the pressure of equilibrium is greater than that of the condensers.

The variation in the steam mass will be equal to:

$$\frac{dm_v}{dt} = F_{ev} - F_{vc} = -F_{vc} \quad (45)$$

$$\frac{dP_{cam}}{dt} = \frac{RT}{MV_{cam}} \frac{dm_v}{dt} = -\frac{RT}{MV_{cam}} F_{vc} \quad (46)$$

It is assumed that the variation with time of the volume and the temperature is sufficiently small as to be insignificant.

This equation leads us to  $P_{cam} = P_{con}$  after a transient period, generally of short duration.

Due to the speed with which equilibrium is reached, we can simplify matters by directly making the pressure in the chamber equal to that in the condenser for the non-saturation case. This will give us the following equation for the chamber pressure in the overall process:

$$P_{cam}(T, bx) = \begin{cases} P_{eq}(T, bx) & \text{Si } P_{eq} \geq P_{con} \\ P_{con} & \text{Si } P_{eq} \leq P_{con} \end{cases} \quad (47)$$

**2.2 MODELLING A CENTRIFUGAL**

The centrifugal process is a batch process which depends on different factors, such as the state of the turbine, the crystal content of the mass to be centrifuged and the syrup. These factors can be reflected in an overall balance which includes the three typical balances (mass, dry mass and sugar) considering the two inputs (mass and syrup) and the two outputs (syrup and sugar). Alternatively, they can be reflected in partial balances based on the two outputs from the centrifuge (honey and sugar) considering that the centrifugal receives three products (the mother liquor, sugar crystals and water) which are distributed between the resulting honey and the resulting sugar, based on the characteristics of the centrifugal.

This is shown in Figure (8).

The cycle of a discontinuous centrifugal consists in the following stages:

1. Filling the centrifugal with massecuite and centrifuging it at 150 rpm. The centrifugal action presses the massecuite against the wall.
2. Acceleration to the maximum speed (1100 rpm). The majority of the syrup around the crystals becomes separated by the centrifugal force and passes through the centrifugal screens.
3. The sugar is washed with water. Hot water is injected against the wall of sugar in the centrifugal to eliminate the remains of the syrup around the crystals.
4. The speed of rotation is decreased to 100 rpm., the sugar is then discharged and dried.

Each cycle lasts for approximately 4 minutes. When the sugar is discharged from the centrifugals it contains about 1% humidity.

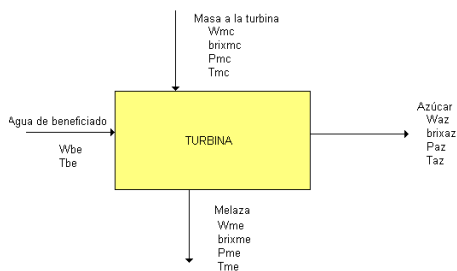


Figure 8. Centrifugal without syrup separation

We are now going to take a look at the mass balances:

### Mass overall balance

Mass

$$M_{mc} + M_{be} = M_{me} + M_c \quad (48)$$

Dry mass

$$Brix_{mc} * M_{mc} = Brix_{me} * M_{me} + Brix_c * M_c \quad (49)$$

Sugar

$$Pol_{mc} * M_{mc} = Pol_{me} * M_{me} + Pol_c * M_c \quad (50)$$

### Separation of syrup

The separation of syrup discharged from the centrifugals into syrup for massecuite and syrup for seed magma is brought about by the operating mode (timed) of the discontinuous centrifugals and because the properties of the syrup are not uniform in the continuous centrifugals. In a continuous centrifugal, the syrup for massecuite is obtained from the upper half. In either case, the syrup discharged from the centrifugals is separated into two products, the syrup for massecuite and the syrup for seed magma, with different properties which can be reflected in the following balances (mass, dry mass and sugar).

Where the proportion of syrup depends on the centrifugal cycle and on the proportion of juice to the mass to be centrifuged. Therefore, regardless of whether the centrifugal is continuous or discontinuous, it can be considered that the percentage  $R_{mmp}$  defines the separation of syrup in a centrifugal.

### Balance in the discharged syrup

Mass

$$M_{me} = M_{mp} + M_{mr} \quad (51)$$

$$M_{mp} = M_{mm} * R_{mmp} + M_{be} * R_{bemp} + M_c * R_{cmp} \quad (52)$$

$$M_{mr} = M_{mm} * R_{mmmr} + M_{be} * R_{bemr} + M_c * R_{cmr} \quad (53)$$

Dry mass

$$Brix_{me} * M_{me} = Brix_{mp} * M_{mp} + Brix_{mr} * M_{mr} \quad (54)$$

Sugar

$$Pol_{me} * M_{me} = Pol_{mp} * M_{mp} + Pol_{mr} * M_{mr} \quad (55)$$

### Balance in the discharged sugar

Mass

$$M_{cf} = M_c * (1 - R_{cmp} - R_{cmr}) + M_{be} * (1 - R_{bemr} - R_{bemp}) \quad (56)$$

Dry mass

$$M_{cf} * Brix_{cf} = M_c * (1 - R_{cmp} - R_{cmr}) * Brix_c \quad (57)$$

Sugar

$$M_{cf} * Pol_{cf} = M_c * (1 - R_{cmp} - R_{cmr}) * Pol_c \quad (58)$$

The mother liquor is separated from the crystals in the discontinuous centrifugals.

## 2.3 MODELLING OF A CRYSTALLISER

The crystalliser has two tasks; 1) to serve as a storage tank for the massecuite to be discharged to the centrifugals, 2) to allow the percentage of crystals to increase. The latter is a direct consequence of the cooling of the massecuite and, therefore, of the time it resides in the crystalliser. A certain flow of water is usually added to the massecuite to prevent it from becoming too thick.

From the balance point of view, therefore, a crystalliser receives a flow of massecuite with certain Brix, polarisation and temperature characteristics, and contains mother liquor and crystals, and a flow of water. From the crystalliser a flow of mass with other Brix, polarisation and temperature characteristics is discharged to the centrifugals at a lower temperature.

Taking into account that both the inlet mass ( $M_c$ ) to the crystalliser and the outlet mass ( $M_t$ ) will each have their corresponding parts of water (ag), of non-sugars (na) and of sugar (az), for mass conservation the following ratios can be established:

$$W_{mr} = W_{agc} + W_{mc} \quad (59)$$

$$W_{agmt} = W_{agc} + W_{agmc} \quad (60)$$

$$W_{namt} = W_{namc} \quad (61)$$

$$W_{azmt} = W_{azmc} \quad (62)$$

But if it is also taken into consideration that both the inlet mass and the outlet mass contain their part of the mother liquor (mm) and the crystals (ac), ie:

$$W_{mc} = W_{mme} + W_{ace} \quad (63)$$

$$W_{mt} = W_{mms} + W_{acs} \quad (64)$$

The crystallisation process can be expressed as follows:

$$W_{mms} = W_{agc} + W_{mme} \frac{100 - R_c}{100} + W_{ace} \frac{R_d}{100} \quad (65)$$

$$W_{acs} = W_{mme} \frac{R_c}{100} + W_{ace} \frac{100 - R_d}{100} \quad (66)$$

On the one hand, the first equation reflects:

- that all the water added to the inlet mass will be in the syrup that is discharged
- that a percentage of the sugar which was in the inlet syrup has crystallised and will therefore not be in the syrup that is discharged
- that a percentage of the crystals in the inlet syrup has dissolved and will therefore appear in the syrup that is discharged

On the other hand, the second equation reflects the complementary phenomenon:

- that the percentage of sugar which was in the inlet syrup has crystallised and will therefore appear in the form of crystals in the mass that is discharged
- that a percentage of the syrup inlet crystals have dissolved and will therefore not be in the honey that is discharged

In this respect two factors have been introduced,  $R_c$  (in %) to indicate the percentage of inlet mother liquor which has crystallised and  $R_d$  (in %) to indicate the percentage of crystals which has been dissolved. From now on, these two factors will be used to characterise the process which takes place in a crystalliser:

$R_c$  depends on the residence time of the mass in the crystalliser, on the conditions in which the mass reaches the crystalliser (temperature, saturation, etc), on the environmental conditions of the crystalliser (environmental temperature, exchange with the outside) and also on the quantity of water which is added. However, this dependency can be regarded as insignificant because the proportion of water added is very small compared to the volume of mass.

$R_d$  depends mainly on the amount of water added in proportion to the percentage of crystals, but it

also depends on the shaking in the crystalliser and on the temperature conditions (of the mass, the water and the environment).

However, in view of the small amount of water which is added compared to the volume of mass and because the large crystals are protected from being dissolved by the layer of mother liquor that surrounds them, we believe that the phenomenon of dissolution as opposed to crystallisation can be disregarded in the crystalliser. For this reason, only the  $R_c$  factor will be used to characterise the process which takes place in the crystalliser.

### 3 DEVELOPMENT OF THE MODEL INTO ECOSIMPRO

We have developed into EcosimPro the mathematical model of each of the equipment items that take part in the process unit (vacuum pans, horizontal tanks, continuous and discontinuous centrifugals, crystallisers and tanks), we have created a library containing the physical properties of the involved chemical compositions (*PHYSICAL PROPERTIES*) and some special connecting elements have been developed. Subsequently, a component was built -*SUGARHOUSE.EL*- to which all the equipment items are connected as shown in the factory flow diagram, all conform the *CRYSTALLISATION* library. The use of the *EL* language was avoided in the case of the components and physical properties because it would have involved a great amount of work. We will now comment on the essential statements in the modelling of batch processes, as well as on continuous (semibatch) processes and the specific ports that have been created.

#### 3.1 ESSENTIAL STATEMENTS: WHEN AND ZONE

The fundamental statements used in the modelling are: *ZONE* for continuous equations, and *WHEN* for discrete events. Each of these is described below.

*ZONE*, permits us to change between alternative equations while the simulation is being run, depending on the value of a condition. For example, we have a crystal growth function whereby, depending on the saturation zone in question, the kinetic parameters are assigned one value or another; this can be implemented with the *ZONE* statement:

```
--Speed of crystal growth
F_s= ZONE (s>0. AND s<1.)-Ks4*abs((s-1)**Ks4
      ZONE (s>=1. AND s<1.1) Ks2*(s-1)**Ks2
      ZONE (s>=1.1 AND s<1.4) Ks1*(s-1)**Ks1
```

```
ZONE (s>=1.4) Ks3*(s-1)**Kes3
OTHERS 0.
```

The resolvers of EcosimPro are responsible for detecting the precise time it takes for the change of condition, for detecting the new ZONE branch and for continuing to integrate the model.

WHEN is used to express discrete events. We need it to model the change of stage in the vacuum pans, and in the centrifugals. It is also of interest because it allows us to simulate cycles, which makes it an indispensable statement in the modelling of batch processes. For example:

```
WHEN (Ma>=0.00050 AND etapa==7) THEN
  --Apretado----->Descarga
  M_tc=M_t
  M_solc=M_sol
  M_cc=M_c
  etapa=8
END WHEN
```

### 3.2 CONNECTION: THE PORTS

Some special ports have been built for use in the modelling of this section of the sugar house: the syrup port, the massecuite port and the crystal port.

The following are the groups of chemical components that intervene in the process:

```
-----
Grupos de componentes químicos que se van a usar
-----
```

```
ENUM Chemical ={H2O, sucrose, cristales, impz, CaO,
CaOH2, O2, N2, CH4, C3H8, CO, CO2}
SET_OF(Chemical)jarabes={H2O, sucrose, impz}
SET_OF(Chemical)masacocida={H2O,sucrose, impz,
cristales}
SET_OF(Chemical)cristalitos={cristales,H2O, impz}
```

The massecuite port is used in the sugar house from the outlet of the vacuum pans. The massecuite contains syrup and crystals.

```
-----
--Puerto massecuite
-----
```

```
PORT masa_cocida(SET_OF(Chemical)Mix)
```

```
EQUAL REAL P "Presión(bar)"
REAL T "Temperatura(°C)"
EQUAL OUT REAL H "Entalpía del jarabe(KJ/Kg)"
SUM REAL W "Flujo másico de vapor(Kg/s)"
SUM IN REAL Wi[Mix] "Flujo másico individual (Kg/s)"
EQUAL OUT REAL C[Mix] "Concentraciones (%1 en peso)"
REAL F "Flujo volumétrico de vapor(m3/s)"
REAL Brix "Fracción de sólido (% en peso)"
REAL BrixT "Fracción de sólido de la massecuite(%
en peso)"
REAL Pureza "Pureza(% en peso)"
```

```
REAL Pol "Polaridad (%1 en peso)"
REAL cc "Masa de cristales(% Kg)"
SUM IN REAL f_energ "Flujo de energía(Kw)"
REAL Rho "Densidad (Kg/m3)"
EQUAL REAL Ma "Tamaño del cristal(m)"
```

CONTINUOUS

```
1. = SUM (j IN Mix EXCEPT setofElem(Mix,4); C[j])
EXPAND(j IN Mix EXCEPT setofElem(Mix,4)) Wi[j] = C[j] *
W*(1-cc/100.)
```

```
W=SUM(j IN Mix;Wi[j])
cc=C[cristales]*100.
Pol = (Pureza/100.) * (Brix/100.)
Pol = C[sucrose]
Brix = 100 * (C[sucrose]+C[impz])
BrixT=Brix+(1-Brix/100.)*cc
Rho=Den_masacocida(T, Brix, BrixT, Pureza)
H=Entalpia_masacocida(T, Brix, BrixT,Pureza)
f_energ=W*H
W=F*Rho
```

END PORT

The crystal port is used at the discharge of the centrifugals, where the syrup is separated from the sugar:

```
-----
--Puerto cristal
-----
```

```
PORT cristal(SET_OF(Chemical)Mix)
```

```
REAL T "Temperatura(°C)"
EQUAL OUT REAL H "Entalpía del jarabe(KJ/Kg)"
SUM REAL W "Flujo másico de vapor(Kg/s)"
SUM IN REAL Wi[Mix] "Flujo másico individual (Kg/s)"
EQUAL OUT REAL C[Mix] "Concentraciones (%1 en peso)"
REAL Brix "Fracción de sólido de las aguas
madres(% en peso)"
REAL Pureza "Pureza(% en peso)"
REAL F "Flujo volumétrico de vapor(m3/s)"
REAL Rho "Densidad (Kg/m3)"
REAL Ma "Tamaño del cristal(m)"
SUM IN REAL f_energ "Flujo de energía(Kw)"
```

CONTINUOUS

```
1. = SUM (j IN Mix; C[j])
EXPAND(j IN Mix EXCEPT setofElem(Mix,3)) Wi[j] =
C[j]*W
```

```
W=SUM(j IN Mix;Wi[j])
Brix=(C[cristales]+C[impz])*100.
C[impz]=(100./Pureza-1)*C[cristales]
H=Entalpia_cris(T)
f_energ=W*H
Rho=Den_cris(T)
W=F*Rho
```

END PORT

## 4 DIFFICULTIES

Just like any other batch operation, tough obstacles have to be overcome to simulate crystallisation. These processes are extremely non-linear and the operating conditions vary significantly during the course of a single batch. These characteristics, together with the requirements for flexibility and versatility and with the added high value of the productions involved in these processes, make them

very different from continuous processes. There is a high number of variables involved (6426 real variables, 28 boolean variables, 312 state variables and 13 boundary variables) and very many equations (5122) which define the systems and the relationships between them. These relationships are differential and algebraic equations, as well as the empirical relationships, the use of which cannot be avoided. The fundamental problem involved in the simulation of processes, and which conditions the choice of the theoretical model, is the resolution of the mathematical equations that represent the physical model.

## 5 GRAPHICAL RESULTS

The simulation was run for the maximum length of time so that we could observe the cyclic nature of the process. Some of the graphical results are shown in the following figures.

Figure (9) shows the evolution of the mass (of the complete mass, of the sucrose, the impurities, the water and the crystals) in the A-sugar vacuum pans. It can clearly be seen where the filling stage ends and where the crystal growth and the discharge stages begin. The figure shows the graphs of two cycles.

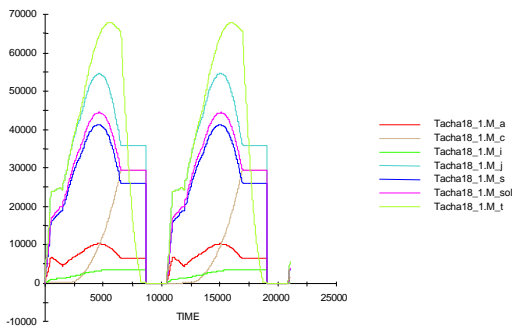


Figure 9. Evolution in two cycles of the masses in the A-sugar vacuum pan

Figure (10) shows the evolution of the Brix and the total Brix in the A-sugar vacuum pans. We can see how the total Brix is greater than the Brix from the concentration stage, because the formation of crystals is taken into account. The figure shows the graphs of two cycles.

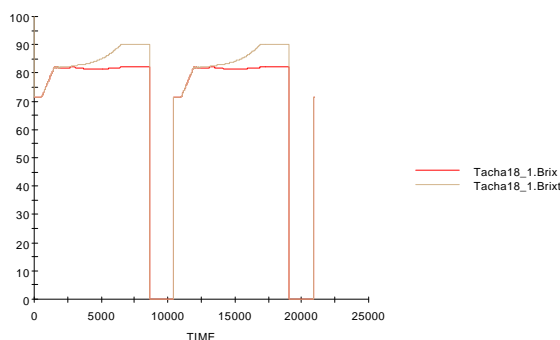


Figure 10. Evolution in two cycles of the Brix and of the total Brix in the A-sugar vacuum pan

Figure (11) shows the evolution of the temperature in the vacuum pan, the temperature in the calandria and the temperature in the barometric condenser in the A-sugar vacuum pans. The changes from one stage to another are clearly marked by the jumps in the variables. The figure shows the graphs of two cycles.

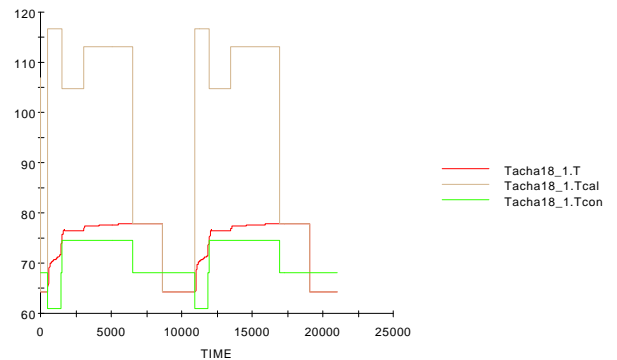


Figure 11. Evolution in two cycles of the temperature of the chamber, the temperature of the condenser, the temperature of the calandria in the A-sugar vacuum pan

Figure (12) shows the evolution of the inlet flow, the discharge flow of syrup for seed magma, the discharge flow of syrup for massecuite and the discharge flow of crystals in the A-sugar centrifugals. The graph shows the duration of a centrifugal cycle, three cycles can be seen.

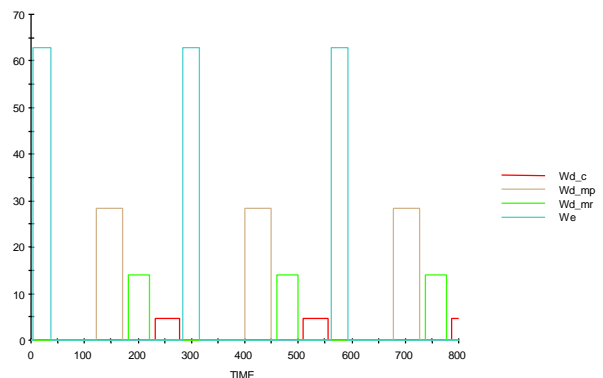


Figure 12. Evolution in three cycles of the inlet flow, the discharge flow of syrup for seed magma, the discharge flow of syrup for massecuite and the flow of crystals in the A-sugar centrifugals

## 6 CONCLUSIONS

The following is a summary of the conclusions of this project:

- The dynamic model of the sugar house presented is the most realistic for simulating the behaviour of a sugar house.
- This mathematical model has been incorporated into an object-oriented simulation tool, EcosimPro.
- The process has been simulated and its correct behaviour has been verified.
- An analysis has been carried out of the response of the process to interferences in different process input variables.

Based on the foregoing, it is concluded that we have a tool with which future work can be carried out:

- Comparison with experimental data for a more precise adjustment of the parameters used in the simulation.
- Study of the dynamic response of the system to other interferences in the process.
- Testing of different control strategies and analysis of their behaviour.
- Study of the feasibility of different modelling alternatives.

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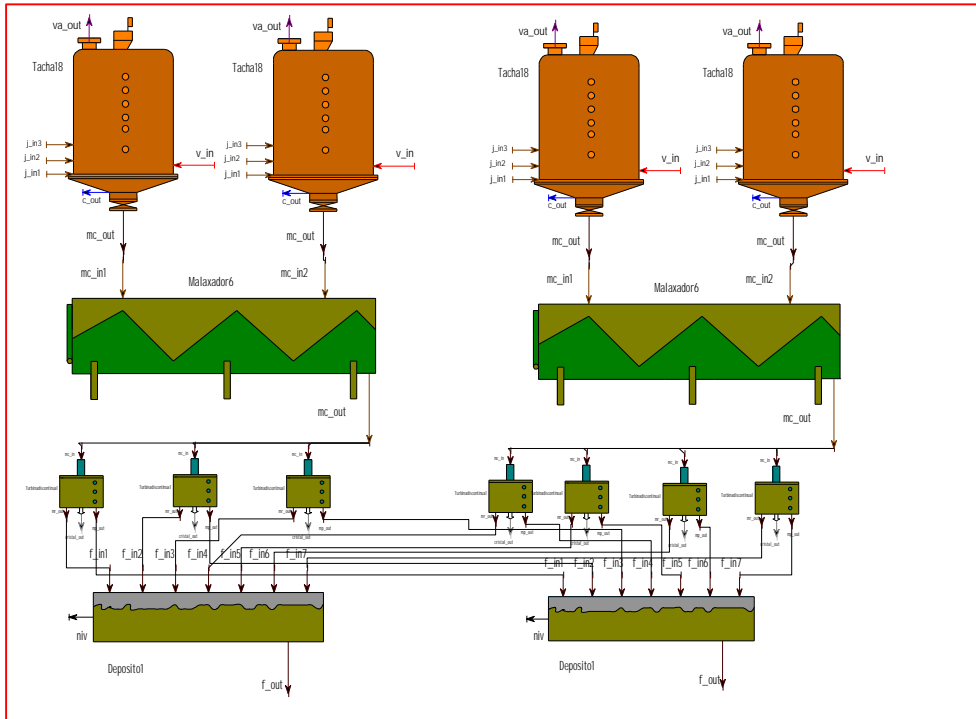


Figure 13. Connection of equipment integrating the A-sugar section of the sugar house

