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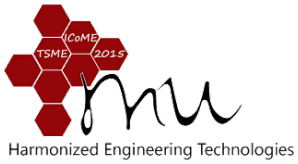

CST003

Thermodynamics for Batch Sugar Crystallizers

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Abstract

This work presents a one-dimensional modeling for batch sugar crystallizer in which the crystal growth model is coupled with thermodynamics state of the pan and the heat transfer inside the calendria. The whole volume of the crystallizer is taken as the system of three-phase material. To the best of our knowledge this is the first model of this kind. The result of the modeling is validated against the real data taken from Mitrphol's Phukeaw plant. The final mean aperture deviate from the real data by 10%. The proposed model can be used as a virtual crystallizer for training as well as problem identification and improvement testing.

Keywords: Sugar crystallization, Computational Modeling, Industrial process modeling, thermodynamics modeling, crystal growth

1. Introduction

Sugar crystallization is the most critical step in sugar industry. The final size and shape of sugar crystal are strongly influenced by the physical condition of the crystallization. During this process, the sugar content in syrup are increased to supersaturated solution and the seed which serves as the core for the crystal is fed into the crystallization pan. The concentration process can be done in two ways. The first is to remove the water from the solution and another way is to decrease the temperature of the solution. The apparatuses using the first techniques are thus called evaporative crystallizer which are the most widely used globally. The modeling of crystallization process in evaporative crystallizer has been a research subject for a long time. However, the crystallization process is a transient nonlinear multi-physics and multi-phases and three-dimensional problem. The reduction of such complex process to one-dimensional model is thus required many assumptions have been made to make the modeling feasible and tractable. The pioneer work of Wright [1, 2] laid the foundation of evaporative batch crystallizer. His model based on the mass and energy conservation coupled by several empirical equations of syrup properties and crystal growth model. This predictive type model is then used to control sugar crystallization [3]. The strength of the predictive model which based by physical governing equations and empirical properties is that it can predict out-of-design operating conditions and likewise it should be able to predict the real world optimal operating condition. However, many researchers found that the crystal growth rate and ultimately, the final crystal size significantly differ from the one predicted by the model. This shortcomings lie in the fact that many empirical constants are site-dependent and must be tuned carefully. Some research suggests that we could omit such tuning altogether and then construct a new empirical rule based on the data of the crystallization. In this data-based model, one can use multiple linear regression, principal component regression and the artificial neural network (ANN) models among other to construct the relationship between the input conditions and the output such gas crystal growth rate. This approach however cannot be used when the conditions fall outside the identification. Therefore recent the new knowledge-based hybrid (KNB) model are proposed in [4, 5]. This approach uses data-based model whenever the conditions fall within the identification and uses conservation law otherwise.

In contrast to the data-based model, we could call the first approach as principle-based model. Perhaps, the data-based model is more suited for control or prediction of daily operating condition of the crystallizer where no problem occurs. However, the principle-based model plays an important role when developing a new crystallization procedure or predicting and analyzing the effects of new improvements as well as what-if scenario. Therefore a correct mathematics model of the crystallizer is very important. Furthermore, the existing principle model aims at predicting what are happening in the massecuite while neglecting the behavior of the crystallizer as a whole. Thus the existing model cannot help us to decide what action should be done to achieve the desired condition. For example, if one wishes to increase the temperature to a certain value, the steam flow rate has to be increased. This in turn changes the pressure inside the crystallizer which is then required a stronger suction by the vacuum pump. In this work we present a thermodynamics model of a batch crystallizer which models the crystallizer as a whole. This model is a three-phase model of batch sugar crystallizer by incorporating the water vapor and the metallic part of the pan into the control volume.

In addition to the existing model, the proposed model can be used as a virtual crystallizer which can be used for personnel training.

2. Thermodynamics Model of Batch Crystallizer

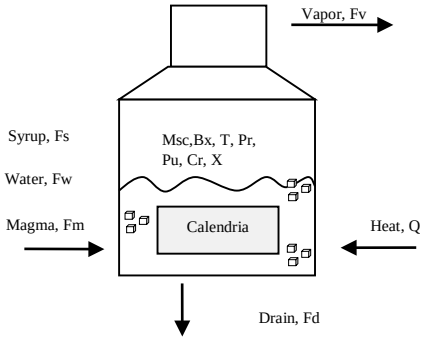

Fig. 1 Schematic of Batch sugar crystallizer displaying the mass flow in and out the crystallizer.

The schematic of batch sugar crystallizer is shown in Fig.1. All previous works in principal-based modeling of batch sugar crystallizer took only the massecuite as the control volume. The control volume are thus consists of the liquid phase (syrup) and the solid phase (sugar crystal). The pressure above the massecuite is usually taken as input parameter rather than one property of the crystallizer Therefor the pressure inside the crystallizer (pan) is not a variable of the simulation but the outside parameter. In other words, the existing principled based model does not predict the physics inside the pan, but only the crystal growth rate as a function of external parameters. In order to predict the response of the pan due to the controllable parameter, we need a new model which represents the whole pan. To develop a model for the whole pan, we need to include the water vapor inside the pan and the lump mass of the pan into the model as well.

The mass conservation of the material inside the pan are as follows:

$$\frac{dMsc}{dt} = Fm + Fw + Fs - Fv - Fd \quad (1)$$

$$\frac{dMw}{dt} = \left(1 - \frac{BxMa}{100}\right) \cdot Fm + Fw + \left(1 - \frac{BxS}{100}\right) \cdot Fs - Fv - \left(1 - \frac{BxMsc}{100}\right) \cdot Fd \quad (2)$$

$$\frac{dMs}{dt} = \frac{BxMa}{100} \cdot Fm + \frac{BxS}{100} \cdot Fs - \frac{BxMsc}{100} \cdot Fd \quad (3)$$

$$\frac{dMi}{dt} = \left(1 - \frac{PuMa}{100}\right) \cdot \frac{BxMa}{100} \cdot Fm + \left(1 - \frac{PuS}{100}\right) \cdot \frac{BxS}{100} \cdot Fs - \left(1 - \frac{PuMsc}{100}\right) \cdot \frac{BxMsc}{100} \cdot Fd \quad (4)$$

Where Msc stands for mass of massecuite whose brix is $BxMsc$. The brix of magma is $BxMa$ with the purity specified by $PuMa$. Likewise, the brix and the purity of the syrup are denoted by BxS and PuS, respectively. The Massecuite (Msc) comprises of water, sugar and the impurities which are denoted by Mw, Ms and Mi respectively. Next, the conservation equations of energy are

$$\frac{dU}{dt} = Q + Hm \cdot Fm + Hw \cdot Fw + Hs \cdot Fs - Hv \cdot Fv - Hmsc \cdot Fd \quad (5)$$

$$U = Mmsc \cdot Hmsc + Mv \cdot Hv + Mp \cdot Hp \quad (6)$$

$$Q = Fsteam \cdot (Hfg(Tsteam) + Hf(Tsteam) - Hf(Tmsc)) \quad (7)$$

In the above equations, the enthalpy of the magma, the water, the syrup, the water vapor, the massecuite and the pan are $Hm, Hw, Hs, Hb, Hmsc, Hp, Hsteam$, respectively. Equation (6) states that the total internal energy comes from three masses, i.massecuite ($Mmsc$), ii.water vapor inside the pan (Mv) and iii.the pan (Mp). The heat transfer from steam to the calendria is a condensing heat transfer which is very efficient, therefore in Eq. (7) which assumes that all the latent heat of evaporation and the sensible heat of the steam are transferred to the pan. Note that the enthalpy of the pan (Hp) can be replaced by the internal energy. It should be emphasized that the above energy equations are nonlinear and have to be solved by iterative method.

In the previous equations, the massecuite and the water vapor inside the pan are two independent variables. However, if we assume that the pan is in saturation condition, then we can link $Mmsc$ and Mv through

$$Vtot = (Vpan - Vc \cdot Mc)/Mw, \quad (8)$$

$$X = (Vtot - Vsol)/(Vg - Vsol), \quad (9)$$

$$Mv = X \cdot Mw, \quad (10)$$

$$Mw = (1 - X) \cdot Mw. \quad (11)$$

Where, $Vtot$ is overall specific volume of the mixture inside the pan, the pan volume minus the volume of all crystals. Since the fluid part here is no longer pure water, we have to take $Vsol$ as the specific volume of the mother liquid while we assume that the vapor inside the pan is pure water. Thus Vg is the specific volume of pure water. The vapor quality (X) defined by the relation between the water vapor and the mother liquid. Note that the X here is just a mass fraction defined specifically as in Eq. (8). The term vapor quality is used here analogously. It does not mean the mass ratio between the water vapor and the total water, but it means the mass ratio between the water vapor and the mother liquid.

The evaporation is assumed to happen when the temperature of the water saturation temperature at the pan pressure (Tsat@Pr). If the heat input is enough sufficient to bring the system to saturation condition, the only unknown in equations (5)-(11) is T. If the heat is sufficient to go beyond this point, we can first advance the system to the saturation point and then go forward along the saturation line. For convenient, we assume the purity is constant throughout the process. This is standard assumption used in [1, 2, 4, 5].

3. Sugar crystal growth model

In this work we use a standard linear growth rate model:

$$\mathrm{Gd} = K_1(\sigma - (1 + K0)\,)\exp(K2 - K3 * NSpW) \quad (12)$$

where

K_1 is the growth rate factor,
σ is the supersaturation coefficient,
$K0$ is the minimum additional supersaturation allowing crystal to grow.
$K2$ represents the effects of temperature and
$K3$ represents the effects impurity.

There are some empirical formulas such as boiling point elevation, saturation concentration of sugar as well as numerical formulas for steam table. The reader can consults [4, 6] for empirical formula and IAPWS-IF97 for the water properties.

4. Setup of simulation

In most of sugar plant, the process of sugar production consists of three parts, the production of A, B and C sugar. The A sugar is then stored to be used for refined sugar production. In this work we present the simulation of A sugar and refined sugar. The normal operating conditions of batch crystallizer for sugar A usually set the vacuum pressure at 640 mmHg. The steam temperature is 105°C. The condition of the feed is listed in Table 1.

	Bx(%)	T(°C)	Pu(%)	Cr(%)	MA (mm)
Syrup	65	65	92	---	---
Magma	92	65	92	52	0.8
Water	---	65	92	---	---

Table 1 Specification of feeds in a crystallization of refined sugar.

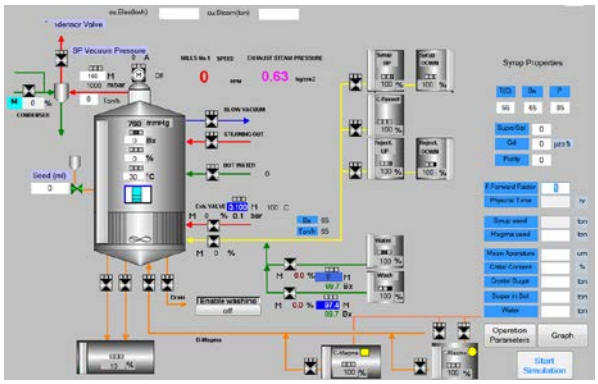

Fig. 2 Interface of Virtual Pan program.

The simulation program mimics the control software of batch crystallizer (Fig.2). Flow rate of feeds, steam and the removal of water vapor are determined by the valve function whose input is the percent valve opening, difference pressure and the valve constant. This way, the program acts as a virtual pan and the users can feel the response of the system through their actions. Figure 3 shows the condition of the massecuite through the process. The procedure of sugar crystallization is as follows

1.Syrup footing at 30% of the pan volume.
2.Start raising brix and level upto the setpoint.
3.After the brix and level points are reached, put in the slurry seed.
4.Wash out the fine seed particle by injecting some hot water until the brix drops by 2.
5.Continue increasing the brix and level.
6.Once the desired brix has met and the level is satisfactory, release the massecuite to the separator.

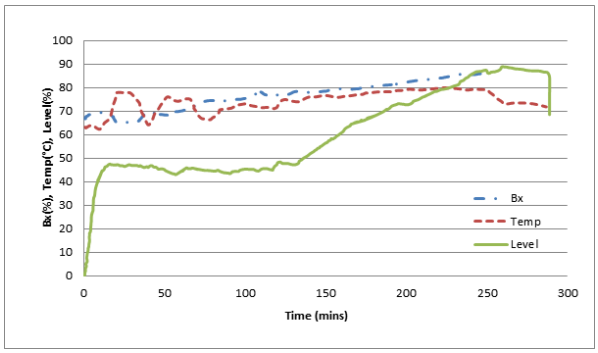

Fig.3 Brix, temperature and the level of massecuite during the crystallization.

5. Results

In principle, we can to find the crystal growth parameter in Eq. (12) by statistic or regression method. By using real recorded data and find the best set coefficients matching the initial and final crystal sizes. However the recorded information is limited and we have to perform a video record and extract the data. Therefore we only have one set of recorded data and thus only K1 was tuned. In Fig. 5, we seen the final size of the crystal where the process undergoes the condition shown in Fig.3. The K1 less than 5000 μm/hr and causes all the crystal to dissolve in the fourth step. Surprisingly, continue increasing the K1 does not seem to alter the final size of the crystal. The reason of this is revealed in Fig.6. The increment in K1 causes the crystal to grow very fast which then draw out all the sugar in the mother liquid which turns the supersaturation solution into an undersaturation one. Thus such too fast growing eventually led to dissolution immediately afterwards. The simulation has to wait until the crystal was sufficiently dissolved and the syrup was fed in enough for it to regrow again. The final MA obtained from our model using the real condition differs from the real MA by 10%.

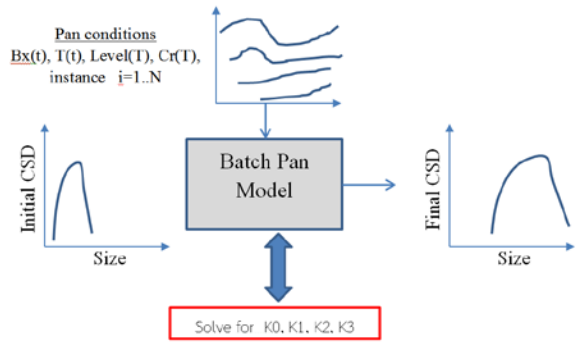

Fig. 4 Tuning of simulation coefficients.

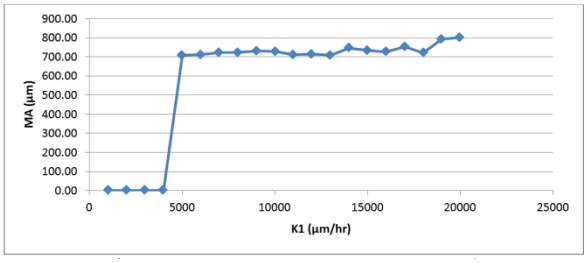

Fig. 5 Effects of K1 on the final MA of the sugar crystal.

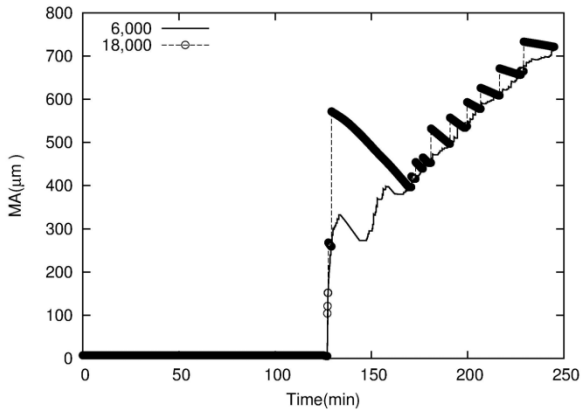

Fig. 6 Crystal size during the process (Fig.3) from two simulation. One was done with K1 equals to 6,000 and in the simulation K1 was 18,000.

7 References

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