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Design and Evaluation of a Full Control Program for Sucrose Crystallization Based on Soft Sensor Approach

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Abstract— ***The well-controlled sugar crystallization process is a success key for all sugar production industries to achieve maximum production rate and minimum cost so this work aims to crystallization control improvement.Solubility and supersaturation coefficient curves of pure sucrose and technical sugar solution achieved using sugar solubility values of both Vavrinecz and Bubnik through this the feed control parameters (e.g. seed brix, end boiling brix) concluded by mathematical formulas. Setting up an integrated controlling program with using other formulas that control liquor feed and crystallization rates based on the required sugar quality and batch time. Another mathematical model for online calculation of crystal content, supersaturation, crystal size, mother liquor purity, and evaporation rate incorporated. The main advantages are the auto scientific selection of all crystallization parameters needed for controlling feed rate based on safe limits of supersaturation and achievement the required batch time and sugar quality. Further it monitors all strike's parameters e.g. sugar and massecuite quantity, level, brix and purity, syrup brix and purity, supersaturation, crystal content, crystal size, evaporated water quantity,…etc. followed by correction any deviation in the superstauration or crystallization rat. Overview of crystallization theoretically done by the program for both refined and recovery sugars at the United Sugar's refinery and the findings from simulation were presented and next stage is the practical implementation.***

Keywords: Crystallization control, crystallization parameters, online monitoring of crystallization parameters, soft sensor approach, supersaturation control.

I. INTRODUCTION

Sugar Boiling is one of the most important parameters in producing sugar. There is awareness in the sugar industry regarding the importance of product quality and the cost of production. Both are related to energy consumption and sugar losses and depend to a large degree on the instrumentation employed for process control in sugar crystallization. It is generally agreed that the most important parameter in crystallization control is supersaturation, followed by crystal content [1].

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A. Solubility and Supersaturation

Sucrose is highly soluble in water. A saturated solution of sucrose contain two parts of sucrose to one part of sucrose at room temperature, and almost five parts sucrose to one part of water at 100 ºC. In order to crystallize sucrose, it is necessary to raise concentration of sucrose above that of saturated solution, and control it at the high concentration to achieve the required crystallization quality. Therefore it is important to establish the sucrose concentration at saturation under the operating conditions [2].

The saturation coefficient q sat, p is the solubility at saturation of pure sucrose in water, expressed in g sucrose/g water thus:

$$q_{sat,p} = w_{s,sat,p} / (100 - w_{s,sat,p}) \quad (1)$$

The solubility coefficient SC is used to represent the ratio of the concentration of sucrose in an impure saturated solution to the concentration in a pure solution saturated at the same temperature, and defined as:

$$SC = (W_s/W_w)_{sat,i} / (W_s/W_w)_{sat,p} = q_{sat,I} / q_{sat,p} \quad (2)$$

For a supersaturated solution, whether pure or impure, the degree of supersaturation is expressed by the supersaturation coefficient y. calculated by dividing the sucrose /water ratio of supersaturated solution by sucrose/water ratio of a saturated solution under the same conditions of temperature and purity[3]. The supersaturation coefficient indicates whether the solution is unsaturated (y<1), saturated (y=1), supersaturated (y>1).

It is defined as:

$$y = (W_s/W_w) / (W_s/W_w)_{sat} \quad (3)$$

Zones of saturation for pure sucrose solution:

1. Stable zones: Sucrose solution is still under saturated, no nucleation or crystal growth occurs and any added crystals will dissolve.
2. Meta stable zone: sucrose solution is slightly supersaturated and if left in this condition no change will occur, sugar crystals added will grow.
3. Intermediate Zone: Sucrose solution is over supersaturated and new crystals will form in the presence of existing crystals.
4. Labile Zone: Solution is very unstable and spontaneous nucleation can occur.

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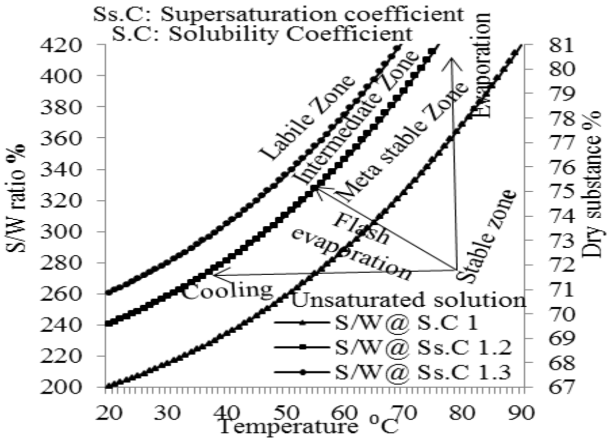

Fig. 1,Solubility of pure sucrose in water as function of temperature.

The solubility and supersaturation coefficients of pure sucrose solution by Vavrinecz [4]. Shown in fig. 1 Saturation is represented for the curve Ss.C =1 .The meta stable region of supersaturation coefficient between 1 and 1.2. In this region, sugar crystals added will grow but no new sugar nuclei will form. This is the region the crystallization should be controlled. The intermediate region lie between Sc.C1.2 and 1.3, in which the crystals will continue to grow but new nuclei will form in the presence of sugar crystals (secondary nucleation). The labile region above a supersaturation of 1.3 is, in this region nucleation will occur spontaneously (primary nucleation). Solutions of lower purity will require a higher degree of supersaturation to induce nucleation than that of high purity that has narrow zones of saturation.

For an under saturated solution at appoint below saturation curve "fig. 1", the solution can be moved into the supersaturated region by evaporation at constant temperature or by cooling at a constant dissolved solid content..

B. Supersaturation "SS" measurement

Boiling point elevation remains a simple and inexpensive means for monitoring supersaturation over full range of massecuite purity. BPE is the difference between the temperature of a boiling solution and that of the vapor leaving it. BPE decrease as the temperature decrease, increase as the purity decrease, and at given purity and temperature it is proportional to the solids dissolved per 100 parts of water. Thus by knowing BPE at saturation it is easy to determine supersaturation by dividing the measured BPE by the BPE at saturation. Different correlative equation for BPE determinations is available [5,15].

Electrical conductivity used for SS and CC measurements firstly by Honig and Alwijn 1959 [6]. They considered the electrical conductivity as a direct approach to the degree of SS.

It relates to the mobility of ions, and there is a relationship between electrical conductivity and the viscosity: conductivity * viscosity n = constant

In which n depends on juice characteristics.

Electrical conductivity still of use in automatic control of B,C(after product) while was not successful in the control of white sugar and high grade raw sugar crystallization because of low ash content [7].

C. Crystal content "CRc."

Besides supersaturation, which is the most important parameter of crystallization, crystal content has important role, too. The growth of crystal mass is proportional to the crystal surface or to the second power of crystal size [1].

The two principal factors that establish the viscosity of a massecuite are the viscosity of the mother liquor and the crystal content. A higher mother liquor viscosity to some extent lowers the permissible crystal content. It is therefore important to have some kind of indication on crystal content. In practice, the crystal content of massecuite should be set at the highest level that, with a high viscosity of mother liquor, will give massecuite of maximum viscosity, consistent with workability.

D. Optimization of sugar crystallization control efficiency

Optimization of a crystallization batch process aims to maximizing the grown seed mass, while keeping the unwanted nucleated mass at a sufficiently low level, most of recent optimization techniques based on soft sensor. A soft sensor is actually a software computer program of the vacuum pan that uses other available process measurements to predict the values for the SS, CC, and grain size in the pan. The following paragraphs summaries some of the sugar crystallization control development researches includes mathematical models and soft sensor approach.

Vacuum pan boiling time can be accurately estimated by application of automatic controls and Equation provided that the boiling is to be conducted at constant supersaturation and constant pressure [8]. A measurement of the changes in electrical properties of massecuite using radio frequencies has been developed in which can be used on all grades of boiling, including high grade refinery products. It can also be used for syrup or molasses brix control [9].

A rule-based expert system for control crystallization through adjusting characteristic conductivity implemented in the Lovosice sugar factory 1993 [10].

Seed Master controller has been designed to provide objective and reliable information on supersaturation to either the pan man or to the control system in use. It relies on the use of set of equations developed to calculate supersaturation on-line, also syrup concentration and temperature measured [11].

Development of the crystal growth rate model according to two approaches (hybrid modeling), the first approach is classical and consists of determining the parameters of the empirical expressions of the growth rate and second is a novel modeling strategy that combines an artificial neural network (ANN) as an approximator of the growth rate with prior knowledge represented by the mass balance of sucrose crystals. The first results show that the first type of model performs local fitting while the second offers a greater flexibility. The two models were developed with industrial data collected from a 60 m3 batch evaporative crystallizer [12]. Using the simultaneous integration and optimization technique for a batch raw sugar vacuum pan, the optimal control scheme is solved by minimizing the time required for the crystals to reach the target average size. The results show fairly well the operation of the pan in the plant such as no feed added to the pan during Initiation or the switch between two feeds: liquor and A molasses. However, better correlations for heat transfer in massecuite boiling, which relates the boiling rate to other measurable variables must be developed. [13].

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Set-point trajectories are implemented within a vacuum pan simulation with two control loops, which manipulate the feed and steam policies. Two control schemes were proposed. The mass controller is selected as the primary loop, to monitor the feed flow. The secondary can be either the CRc or SS controller to monitor the steam flow. The M-SS loops can handle variations in feed and initial conditions but some other logic conditions are required to halt the batch. Another drawback is a possibly greater error in SS calculation, due to errors in the correlations describing it. Moreover the variation of batch time, from the slowest to the fastest batch is large, twofold greater than using the M-CC loops [14].

A series of boiling point elevation measurements was made with sugarcane liquors at three purity levels and three absolute pressures, and an equation for determination BPE developed that fits well the experimental data. Through an introduction of the solubility and supersaturation concepts a general equation and a series of graphs were produced that are suitable for use in, or direct incorporation into the software of, automatic control of sugar boiling in the sugarcane industry [15].

An alternative vacuum pan control scheme, based on the control of massecuite and mother molasses brix, is proposed. By controlling massecuite and mother molasses Brix to constant values, crystal content in the pan is maintained at a constant value, giving improved process control. It is also feasible to control only the massecuite Brix (using feed flow rate) and manually set the steam rate to the pan [16].

Microprocessor-based vacuum pan monitoring control system developed provides a suitable computational facility by configuring an Intel 8085A CPU with an 8231A arithmetic processing unit. The measurable and computed parameters (SS, mother liquor purity and brix) are then displayed on seven-segment LED displays. The system is designed around a universal bus configuration designated PBIB (pan boiling system internal bus) [17].

Knowledge-based hybrid (KBH) modeling control is applied to an industrial scale batch evaporative crystallization process in cane sugar refining. First, principles models of the process lead in general to good description of process state, except for the prediction of the main crystal size distribution (CSD) parameters mean size and the coefficient of variation. This is due to difficulties in expressing accurately nucleation and crystal growth rates and especially the complex phenomena of agglomeration in the relevant population balance. Results obtained demonstrate a better agreement between experimental data and hybrid model predictions than that observed with the complete mechanistic model [18].

A comparative evaluation of four statistical process control (SPC) techniques for the on-line monitoring of an industrial sugar crystallization process studied. The methods investigated include classical on-line univariate statistical process control, batch dynamic principal component analysis (BDPCA), moving window principal component analysis (MWPCA), batch observation level analysis (BOL) and time-varying state space modeling (TVSS). The study is focused on issues of on-line detection of changes resulted from non-linear and dynamic effects between the variables in crystallization process operation. The results obtained demonstrate the superior performance of the TVSS approach to successfully detect abnormal events and periods of bad operation early enough to allow bad batches and related losses in amounts of recycled sucrose to be significantly reduced [19].

The use of virtual apparatus technique to set up on-line detection and control system of sugar boiling process, using the measured value of electrical-conductivity sensor, measured value of Brix and temperatures as the inputs, the network is trained by improvement BP algorithm to achieve the comparatively precision and stabilization output. The results of test shows that the data fusion method based on the artificial neural network could effectively eliminate the change of Brix and temperatures has influenced on the super saturation [20]. A model-based optimization of an industrial fed-batch sugar crystallization process is considered to define the optimal profiles of the process inputs, the feeding rate of liquor/syrup and the steam supply rate, such that the crystal content and the crystal size distribution (CSD) measures at the end of the batch cycle reach the reference values. A knowledge-based hybrid model is implemented, which combines a partial first principle model reflecting the mass, energy and population balances with an artificial neural network (ANN) to estimate the kinetics parameters - particle growth rate, nucleation rate and the agglomeration kernel. The simulation results demonstrate that the very tight and conflicting end-point objectives are simultaneously feasible in the presence of hard process constrains [21]. The analysis of images taken from massecuite samples has revealed the fractal character of the crystal ensemble and the correlation between their fractal dimension and their size distribution. A method for crystal size distribution estimation based on this correlation is best suited for the control of crystallization process. Like other methods based on image analysis, it is fast and avoids the labour and time intensive classical sieving so that it can be used to provide on-line feedback [22]. The control objective of artificial neural networks (ANNs) is to force the operation into following optimal supersaturation trajectory. It is achieved by manipulating the feed flow rate of sugar liquor/syrup, considered as the control input. Two control alternatives are considered – model predictive control (MPC) and feedback linearizing control (FLC). Adequate ANN process models are first built as part of the controller structures. The MPC is computationally much more involved since it requires an online numerical optimization; while for the FLC an analytical control solution was determined [23].

A control principle employed in achieving the objectives of supersaturation control of the crystallization process at Worthy Park Estate Jamaica, highlighting factors that impede optimal sucrose recovery. Proposed solutions utilize two classes of the Supersaturation Parameter for optimizing the control mechanism during periods of extreme process dynamics. The results of pan boiling following a simulation are analyzed statistically to highlight the hypothetical gains and benefits, and suitability of the proposed solution [24].

Sugar crystallization should be controlled automatically, with a minimum human intervention in real time. This naturally should be based on real-time information on the most important parameters of the process that really count: most of all on supersaturation and crystal content which were previously un-available in real-time. Combination refractometer tool with the Seed Master 2 software, enable real insight in the inner workings of a crystallizer in real time, and to implement more advanced ways of sugar crystallization [25].

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Monitoring and control of cane sugar crystallization processes depend on the stability of the supersaturation state. To improve the process control efficiency, additional information is necessary. The mass of crystals in the solution (mc) and the solubility (mass ratio of sugar to water ms/ mw) are relevant to complete information. The main problem is that mc and ms/mw are not available on-line. A model based soft-sensor is presented for a final crystallization stage (C sugar). Simulation results obtained on industrial data show the reliability of this approach, mc and the crystal content (CC) being estimated with a sufficient accuracy for achieving on-line monitoring in industry [26].

A neural-network-based approximate dynamic programming (ADP) method, namely, the action dependent heuristic dynamic programming (ADHDP), applied to an industrial sucrose crystallization optimal control problem. A neural network model of the crystallization developed based on the data from the actual sugar boiling process of sugar refinery. The ADHDP is learning- and approximation-based approach which can solve the optimization control problem of nonlinear system. The result of simulation shows the controller based on action dependent heuristic dynamic programming approach can optimizing industrial sucrose crystallization [27].

II. EXPERIMENTAL WORK

The main objective of crystallization processes control to maintain crystal growth rate in linearity as possible with lowest level of unwanted crystals, and this could be achieved by the right selection of liquor feed rate parameters based on scientific basis. Accurate auto scientific selection of level brix curve constituents needed for liquor feed rate control (start and end boiling level, brix) from solubility and supersaturation curve of pure or impure sucrose solution using solubility's values of Vavrinecz, Bubnik [28] respectively and pan working volume and good tracking of crystal quality and crystal growth rate controlling parameters. The most important one are SS of mother liquor and massecuite crystal content that cannot be detected directly through the traditional methods but could be estimated by using mathematical models. The control strategy is applied in four stages:

A. Sugar crystallization control strategy

a. Seeding brix derivation from corresponding, supersaturation SS, feed purity, and S/W ratio

If: feed purity FEp99 % at 75 ° C and SS 1.05, Sugar Solubility S/W = 343%, seed brix (Y) =?

$$1.05 = \frac{S/W \; @SS\; 1.05}{S/W}$$

$$S/W = 1.05 \times 343 = 360.15\ \%$$

$$S/W = (\text{Sugar content CRc}/ \text{Water content Wc})*100$$

$$360.15 = \frac{(FEp \times Y) \times 100}{(100 - Y)}$$

$$360.15\times100 - 360.15\ Y = 99\ Y$$

$$36015 = (360.15 + 99)\ Y$$

$$Y = 36015/ 459.15$$

$$= 78.438\ \ \%$$

$$\text{Seeding brix} = \frac{\text{Corresponding S/W ratio} \times 100}{\text{Corresponding S/W ratio} + FEp} \qquad (4)$$

b. End Mother Liquor purity derivation from feed liquor purity, sugar purity and crystal content by Ozein division pattern

If: feed purity FEp= 99%, sugar purity SUp = 99.85%, and crystal content CRc = 55%

Massecuite solids MSCso
100%

↓ Sugar
SU
(CRc × SUp)/100

(55 × 99.85) /100
54.92 %

↓ Mother Liquor solids
MLso
(MSCs – CRc)

(100 - 55)
45 %

↓ Mother Liquor sugar
MLsu
(FEpu –SU)
(99 - 54.92)
44.08%

↓ Mother liquor non sugar
MLnsu
(MLso – MLsu)
(45 – 44.08)
0.92

$$\text{Mother Liquor Purity MLp} = (MLsu / MLso) \times 100$$

$$= (44.08/45) \times 100$$

$$= 97.96\ \ \%$$

$$\text{End MLp} = \frac{FEp - (CRc\times SUp/100) \times 100}{100 - CRc} \qquad (5)$$

c. End mother liquor brix MLbx derivation from end Mother Liquor purity and corresponding S/W ratio

For FEp= 99% , S/W = 366% at 80 ºC, at SS =1.05

$$S/W = 366\times 1.05 = 384.3\%$$

$$MLp = (CRc / MLbx) \times 100$$

$$MLbx = 100 - Wc$$

$$CRc = S/W\% \times Wc$$

$$MLp = \frac{(S/W \times Wc) /100 \times 100}{100 - Wc}$$

$$MLp \times100 - MLp \times Wc = S/W \times Wc$$

$$Wc = \frac{MLp \times 100}{MLp + S/W}$$

$$MLbx = 100 - (9796.11/482.26)$$

$$= 79.69\ \%$$

$$\text{End MLbx} = 100 - \frac{(\text{End MLp} \times 100)}{(\text{End ML p} + S/W)} \qquad (6)$$

d. End massecuite brix MSCbx derivation from end mother liquor brix

Let end MSCbx = X

Mother liquor solid MLso= 100 - CRc

$$MLbx = \frac{MLso \times 100}{MLso + Wc}$$

$$MLbx = \frac{(MSCbx*MLso/100) \times 100}{(MSCbx \times ML\ so/100) + Wc}$$

$$79.68 = \frac{(0.45\ X) \times 100}{(0.45\ X) + (100 - X)}$$

$$45\ X = (79.6871\times0.45X) + 7968.71 - 79.6871\ X$$

$$45\ X = 35.8592X - 79.6781\ X + 7967.81$$

$$45\ X = -43.82791X + 7968.71$$

$$45X + 43.82791\ X = 7968.71$$

$$X = 7968.71 /88.82791$$

$$= 89.709\ \ \%$$

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$$\text{End MSCbx} = \frac{\text{End MLbx} \times 100}{\text{End MLbx} - \text{End MLbx} \times \text{MLso}/100 + \text{MLso}} \quad (7)$$

B. Formulate operating rates and master controller of crystallization (feed rate control)

Crystallization process is a nonlinear and non-stationary process, and the main process nonlinearities are represented by the crystal growth rate, control optimization attempt to reduce the variables that impede the linearity of process [12].

It consists in the exhaustion of a liquor to produce crystals. Extraction is induced by seeding the liquor in vacuum pans. During this operation, both the liquor and growing crystals are mixed together to obtain a homogeneous supersaturated magma. Supersaturation of the magma is obtained by vacuum evaporation [26]. The control of crystal growth rate to be proceeded in a linear rate and SS of mother liquor within Meta stable zone depends on regular liquor feed and evaporation rates that could be easily achieved by formulating linear level /brix relationship.

Feed rate control OZein formula (master controller of the crystallization process)

Let Seed brix SDbx , Mascuite level MSCl, seeding level SDl Level rate Lrt, Brixing rate BXrt

MSCbx= seeding brix +increscent degree in brix from seeding brix to massecuite brix %

= SDbx% + (time "min." from seeding brix to massecuite brix × brix rate " ^{0} brix /min.")

$$= \frac{\text{SDbx} + (\text{MSCl} - \text{SDL})}{{}^{0}\,\%\ /\ \text{min. level rate}} \times {}^{0}\,\%\ /\ \text{min. brix rate}$$

$$\text{MSCbx} = \text{SDbx} + \left[\frac{(\text{MSCl} - \text{SDl})}{\text{Lrt}} \times \text{BXrt}\right]\% \quad (8)$$

C. Online monitoring of crystallization parameters using Soft Sensor approach

Online monitoring of crystallization parameters (massecuite level MSCl, massecuite brix MSCbx, mother liquor brix MLbx, mother liquor purity MLp, supersaturation of mother liquor ML SS, crystal content % massecuite solids CRc % MSCso, massecuite temperature MSCt, evaporated water..etc.) to ensure proceeding crystallization process in Meta stable zone as the trajectory theoretical set control parameters and crystallization progress. Measurement feedback from the process is based on massecuite Brix (microwave sensor), mother liquor Brix (refractometer sensor) and massecuite level. This measurement feedback affords inputs to the soft sensor for calculations crystallization parameters and simulation with the theoretical set control values.

CRc % MSCso= fx (MSCbx, MLbx) (9)

ML SS = fx (FEp, CRc % MSCso, MSCt, SUp, MLbx) (10)

D. Correction the deviations in SS value or crystallization rate than set theoretical control values.

Ts: set boiling time corresponding to set crystallization rate minutes

Tac: actual time of boiling minutes

SS1: actual mother liquor supersaturation %

Tdv: boiling time deviation than set =Tac –Ts ±minutes (11)

Pcl: steam pressure rate control =fx (SS1,Tdv) ±bar g (12)

Vcl: vacuum pressure rate control =fx (SS1,Tdv)±mbar a (13)

P1: steam pressure of boiling bar

V1: vacuum of boiling mbar

P2: Corrective steam pressure = P1+Pcl bar g (14)

V2: Corrective vacuum pressure = V1 + Vcl mbar a (15)

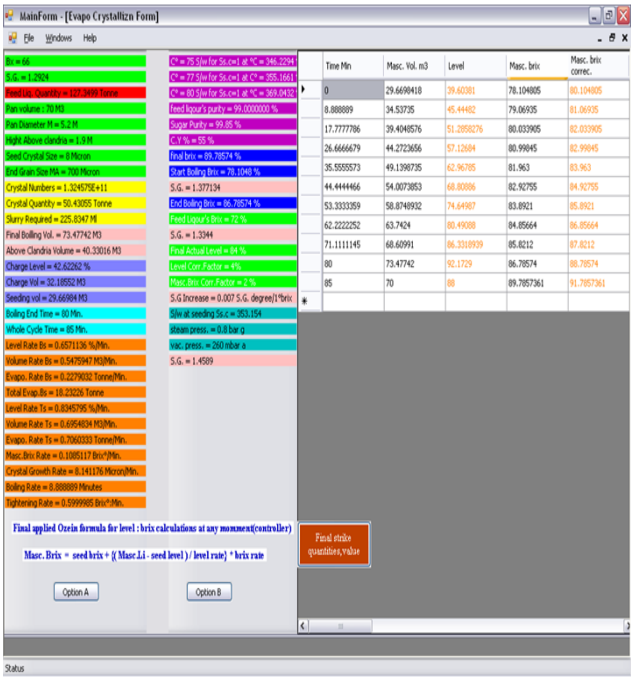

Fig. 2 Control loops and monitored parameters screen

III. RESULTS AND DISCUSSIONS

Theoretical implementation of program for crystallization of different sugar grades R1, R4, and recovery C, and simulation the results with that of theoretical design solid balance calculations of each grade and actual one in United sugar company of Egypt USCE.

Theoretical application includes input the feed liquor purity, pan dimensions, boiling cycle time and crystal size target, seeding and boiling temperatures same as USCE. For online monitoring control loop boiling rate monitored at a definite value of massecuite level and boiling time 70 min. from seed point and the actual mother liquor brix which supposed to be measured by refractometer set at same fixed value (81.8%) for R1, R2 cases to show the efficiency of program for set the reference parameter values for each sugar grade crystallization and the corrections in case of the deviation in boiling rate or SS value which reflected on crystal quality and crystal content CRc.

A. Applying program for crystallization R1 sugar

a. Basic Inputs, set controlling parameter, and operation rates

FEp 99 %, seeding temperature=75 ºC, Seed SS 1.05, end ML SS 1.05, CRc % MSCso 55%

Crystal size 9mm, end crystal size wanted 0,65mm, crystallization time wanted 80 minutes

Feed liquor quantity: 127.19 Ton	Pan Volume: 70 m3
Feed liquor's purity: 99 %	Pan Diameter: 5.2m
Sugar purity: 99.85 %	Height above clandoria 1.9 m
CRc % MSCso: 55 %	S/W of seeding point: 360.15 %
Start boiling brix:78.4 %	Seed crystal size:9 micron
End boiling brix: 86.7%	End crystal size :650 micron
End MSCbx: 89.7 %	Crystal number: 1.65235E+11
Feed liquor brix: 72%	Crystal quantity: 50.37 Ton
End actual level: 84 %	Slurry quantity: 401.12 ml

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Level correction factor:+4% Charge volume: 33.41 m3
End boiling volume73.48 m3 Charge level: 44.10 %
MSCbx correction factor: +2 % Seed volume: 29.6 m3
Above clandoria volume: 40.33 m3 ºC S/W %
Evaporation rate: 0.45 Ton/min. 75 343 %
Batch cycle time: 117.88 min. 77 352.2 %
Feed liquor rate: 0.774 m3/hr. 80 366 %
Volume rate boiling stage Bs: 0.548 m3/min.
Level rate of boiling stage Bs : 0.657 % / min.
Massecuite brix rate of boiling stage Bs: 0.103 brix/min.
Total Evaporation of boiling stage Bs: 17.92 Ton
Evaporation rate of boiling stage Bs: 0.224 Ton/min.
Crystal growth rate: 7.29 micron/min. Volume rate of tightening stage Ts: 0.441 m3/min.
Level rate of tightening stage Ts: 0.53 %/min.
Massecuite brix rate of tightening stageTs: 0.38brix/min.

b. Set quantities and parameters at massecuite level 85.605 % as example

Time minutes	70.00	Crystal content	30.87
MSC volume m3	68.00	ML sugar ton	56.80
MSC level %	85.61	ML solids ton	57.60
MSC brix %	85.68	ML water ton	13.93
MSC brix correction	87.68	ML brix %	80.52
MSC specific gravity	1.43	ML purity %	98.62
MSC quantity ton	97.25	MLSU solubility	407.8
MSC solids ton	83.32	ML SS g : g	1.00
MSC sugar ton	82.49	ML quantity ton	71.53
Crystal size micron	519.6	Evaporation ton	19.34
Wt. of one crystal gm.	0.000 1	S/W at 80 ° C %	366.0
Crystal quantity ton	25.72	Steam pressure b	0.80

c. Monitored quantities and parameters at measured brix values of massecuite and mother liqour by microwave and refractometer

If actual MLbx = 81.8%, the quantities and parameters will be displayed as follow

Time minutes	70.00	Crystal content	24.86
MSC volume m3	68.00	ML sugar ton	61.81
MSC level %	85.61	ML solids ton	62.61
MSC brix %	85.68	ML water ton	13.93
MSC brix correction	87.68	ML brix %	81.81
MSC specific gravity	1.43	ML purity %	98.72
MSC quantity ton	97.25	ML SU solubility	443.7
MSC solids ton	83.32	ML SS g : g	1.21
MSC sugar ton	82.49	ML quantity ton	76.54
Crystal size micron	483.3	Evaporation ton	19.34
Wt. of one crystal gm.	0.0001	S/W at 80 ° C %	366.0
Crystal quantity ton	20.71	Steam pressure b	0.80

d. Corrections in process control loops based on deviation in SS or crystallization rate

1. If actual boiling time is faster than set time for example 65 minutes, boiling status alarm: **boiling rate faster than the set** and slowing action of evaporation rate occurred through modulations steam and vacuum control loops:

Boiling time difference = -5.0009 minutes, steam pressure rate control = -0.1 bar a, vacuum pressure rate control = +10 mbar a

Steam pressure bar g	Steam pressure correction	Vacuum Pressure Mbar a	Vacuum pressure correction	Temperature ° C
0.8	0.7	260	270	80

2. If actual boiling time is slower than set time for example 75 minutes, boiling status alarm: boiling rate slower than the set and raising up action of evaporation rate through modulation of steam and vacuum control loops:

Boiling time difference = 4.9915minutes, steam pressure rate control = 0.1 bar a, vacuum rate control = +10 mbar a

Steam pressure bar g	Steam pressure correction	Vacuum Pressure Mbar a	Vacuum pressure correction	Temp. ° C
0.8	0.9	260	250	80

3. If actual boiling time the same as the set time but supersaturation of mother liquor > 1.2 for example 1.21,

SS higher value alarm appears and controlling action for boiling rate as point 1.

e. R1 Sugar crystallization curves

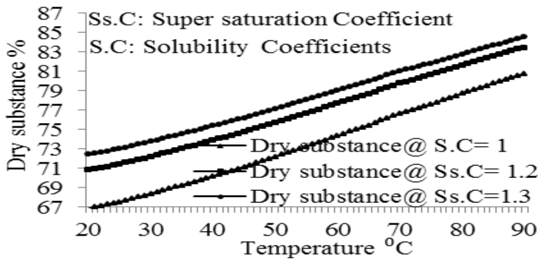

Fig. 3 Brix temperature curves at different supersaturation for R1sugar crystallization from 99% purity solution

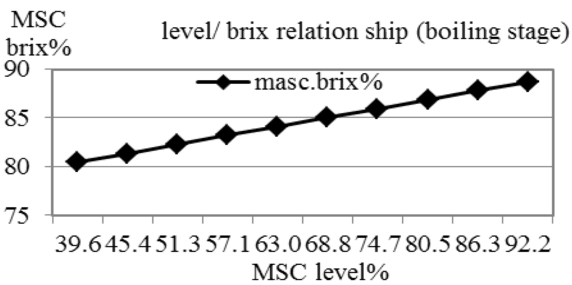

Fig. 4 Level/brix linear relation (+2 brix correction factor) of R1 sugar crystallization from 99% purity solution

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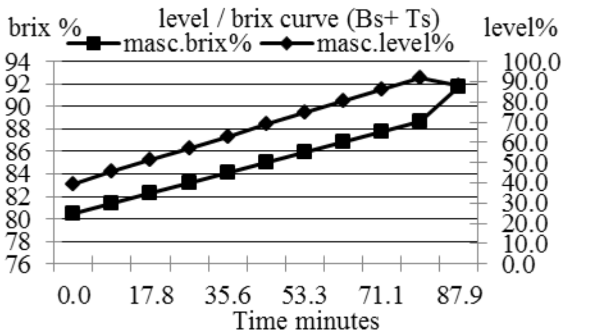

Fig. 5 Level / brix trend (+2 brix correction factor) of R1 sugar crystallization from 99 % purity sugar solution

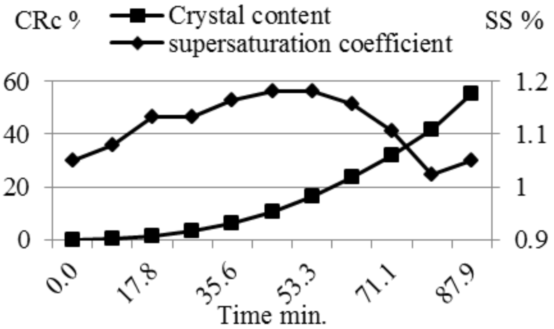

Fig. 6 Crystal content and supersaturation trend of R1 sugar crystallization from 99 % purity sugar solution

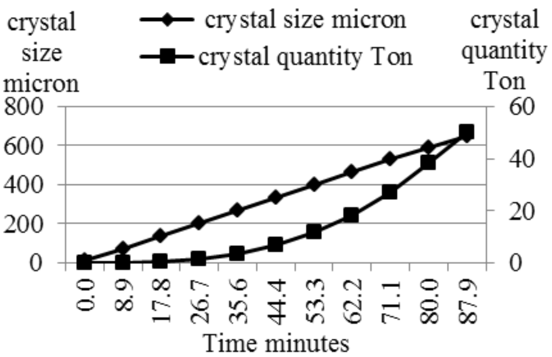

Fig. 7 Crystal growth rate and crystal quantity trend for R1 sugar crystallization from 99% purity sugar solution

Fig. 3 showing saturation zones at wide range of temperatures for crystallization of R1 sugar from 99% purity sugar solution. While Fig. 4,5 showing a linear relation between Massecuite level and brix which assure regular feeding and evaporation, accordingly maintain crystal growth rate linearly and SS at certain limits in meta stable zone. Fig. 6 indicating the program efficiency in controlling of SS within meta stable zone through the whole boiling cycle and also regular ascending of crystal content, and last Fig. 7 showing the linearity of crystal growth rate and crystal quantity in Ton.

f. Strike solid balance before and after centrifuging for R1sugar crystallization

Quantity	Before Cent.	After Cent.	After Cent. USCE
MSC ton	102.09	-	-
MSCso ton	91.58	-	-
Water content ton	10.51	-	-
MSC sugar ton	90.67	-	-
MSC non sugar ton	0.916	-	
Sugar crystals ton	50.37	45.72	43.52
CRc % MSCso %	55	50	47.60
ML so ton	41.21	45.86	48.06
ML sugar ton	40.37	44.95	47.15
ML non sugar ton	0.84	0.912	0.911
ML quantity ton	51.72	63.70	65.83
ML purity %	97.96	98.01	98.10
ML brix %	79.69	72	73
Sugar purity %	99.85	99.99	99.99
Wash water quantity ton	-	7.33	7.27

g. Strike solid balance before and after centrifuging for R4 sugar crystallization

Quantity	Before Cent.	After Cent.	After Cent. USCE
MSC ton	102.70	-	-
MSCso ton	93.43	-	-
Water content ton	9.28	-	-
MSC sugar ton	85.95	-	-
MSC non sugar ton	7.47	-	
Sugar crystals ton	51.38	46.52	39.04
CRc % MSCso %	55	50	42
ML so ton	42.04	46.91	54.38
ML sugar ton	34.77	39.44	46.92
ML non sugar ton	7.27	7.46	7.46
ML quantity ton	51.32	65.15	73.48
ML purity %	82.71	84.09	86.27
ML brix %	81.92	72	74
Sugar purity %	99.60	99.91	99.99
Wash water quantity ton	-	8.97	9.83

From the results of crystallization R1 and R4 sugar mentioned previous it is cleared the efficiency of the program in accurate selection of seed and end brix at the specific temperature and the required end crystal content based on supersaturation fig. 3. Full controlling the crystallization to be occurred in Meta stable zone as shown in fig. 6 by set the right level / brix curve values corresponding to SS safe limits of mother liquor and slowing the rate of crystallization some minutes without effect in boiling time in case of high limit of SS as shown in corrections based on SS deviation case point 3.The obtained results after centrifugals not completely similar to the actual one due to excessive washing to control refined sugar color accordingly decreasing the CRc than supposed: R1 runoff purity 98.01 %, CRc 47.6 %, sugar purity 99.99 % and for R4 runoff purity 86.27%, CRc 42 %, and sugar purity 99.99 %.

B. Applying program for crystallization C recovery sugar 3rd and final recovery sugar

a. Basic Inputs, set controlling parameter, and operation rates

FEp 65 %, seeding temperature=75 ºC, Seed SS 1.03, end ML SS 1.1, CRc % MSCso 36%
Crystal size 9mm, end crystal size wanted 0,40mm, crystallization time wanted 420 minutes
Feed liquor quantity: 127.19 Ton Pan Volume: 33.5 m3

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Feed liquor's purity: 65 % Pan Diameter: 3.6m
Sugar purity: 85 % Height above clandoria 1.9 m
CRc % MSCso: 36 % S/W of seeding point: 439.81 %
Start boiling brix:87.12 % Seed crystal size:9 micron
End boiling brix: 91.88% End crystal size :400 micron
End MSCbx: 93.88% Crystal number: 2.37091E+11
Feed liquor brix: 72% Crystal quantity: 16.84 Ton
End actual level: 84 % Slurry quantity: 575.55 ml
Level correction factor:+4% Charge volume: 18.51 m3
End boiling volume34.54 m3 Charge level: 50.41 %
MSCbx correction factor: +2 % Seed volume: 14.17 m3
Above clandoria volume: 19.33 m3 ºC S/W %
Evaporation rate : 0.04 Ton/min. 75 427 %
Batch cycle time: 473.30 min. 77 444.3 %
Feed liquor rate: 0.072 m3/hr. 80 480 %
Volume rate boiling stage Bs: 0.049 m3/min.
Level rate of boiling stage Bs : 0.122 % / min.
Massecuite brix rate of boiling stage Bs: 0.011 brix/min.
Total Evaporation of boiling stage Bs: 9.77 Ton
Evaporation rate of boiling stage Bs: 0.176 Ton/min.
Crystal growth rate: 0.882 micron/min.
Volume rate of tightening stage Ts: 0.045 m3/min.
Level rate of tightening stage Ts: 0.113 %/min.
Massecuite brix rate of tightening stageTs: 0.08brix/min.

b. Set quantities and parameters at massecuite level 66 % as example

Time minutes	217.50	Crystal content	6.60
MSC volume m3	24.73	ML sugar ton	19.17
MSC level %	66.00	ML solids ton	30.15
MSC brix %	89.59	ML water ton	3.75
MSC brix correction	91.59	ML brix %	88.93
MSC specific gravity	1.46	ML purity %	63.59
MSC quantity ton	36.04	ML SU solubility	511.0
MSC solids ton	32.29	ML SS g : g	1.06
MSC sugar ton	20.99	ML quantity ton	33.91
Crystal size micron	200.8	Evaporation ton	9.335
Wt. of one crystal gm.	9E-06	S/W at 80 ° C %	480
Crystal quantity ton	2.13	Steam pressure b	0.30

c. Monitored quantities and parameters at measured brix values of massecuite and mother liqour by microwave and refractometer

If actual MLbx = 89.5%, the quantities and parameters will be displayed as follow

Time minutes	217.50	Crystal content	0.942
MSC volume m3	24.73	ML sugar ton	20.73
MSC level %	66.0	ML solids ton	31.98
MSC brix %	89.59	ML water ton	3.75
MSC brix correction	91.59	ML brix %	89.5
MSC specific gravity	1.46	ML purity %	64.81
MSC quantity ton	36.04	ML SU solubility	552.8
MSC solids ton	32.29	ML SS g : g	1.13
MSC sugar ton	20.99	ML quantity ton	35.73
Crystal size micron	104.9	Evaporation ton	9.35
Wt. of one crystal gm.	1E-06	S/W at 80 ° C %	480
Crystal quantity ton	0.304	Steam pressure b	0.30

d. Recovery C sugar Crystallization curves

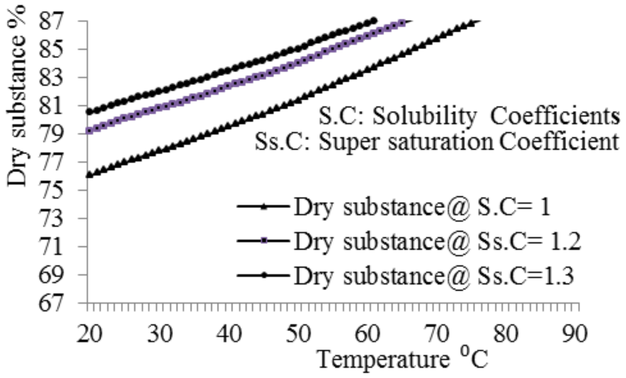

Fig. 8 Brix temperature curves at different supersaturation for C sugar crystallization from 65 % purity solution

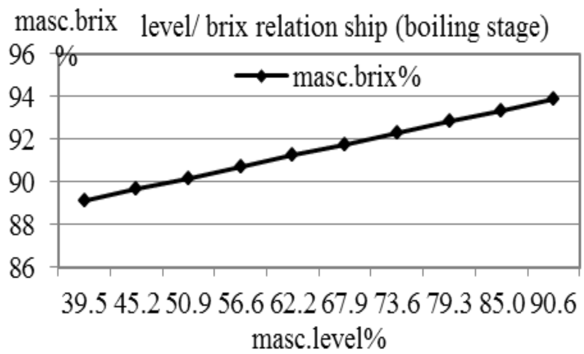

Fig. 9 Level / brix linear relation (+2 brix correction factor) of C sugar crystallization from 65 % purity solution

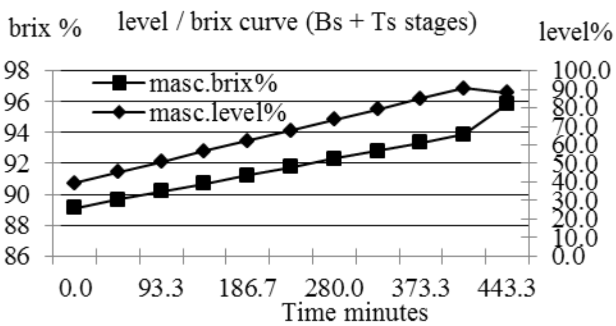

Fig. 10 Level / brix trend (+2 brix correction factor) of C sugar crystallization from 65 % purity sugar solution

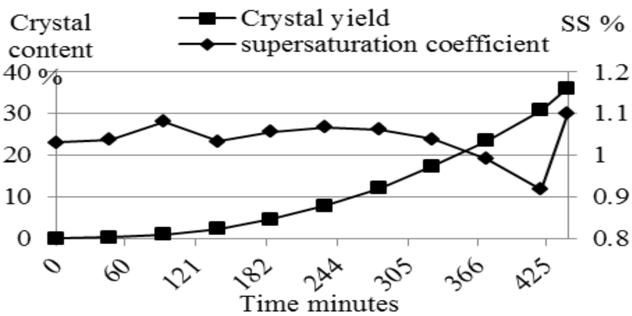

Fig. 11 Crystal content and supersaturation trend of C recovery sugar crystallization from 65% purity solution

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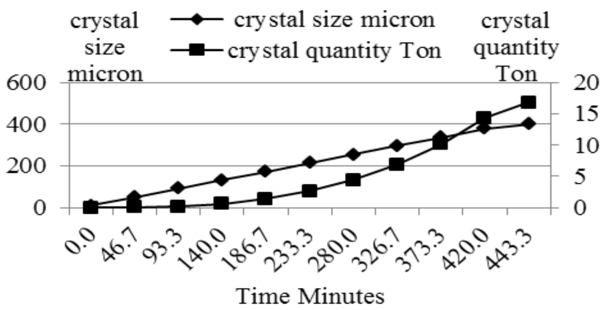

Fig. 12 Crystal growth rate and crystal quantity trend for C sugar crystallization from 65 % purity sugar solution

e. Strike solid balance before and after centrifuging for C recovery sugar crystallization

Quantity	Before Cent.	After Cent.	After Cent. USCE
MSC ton	49.83	-	-
MSCso ton	29.94	-	-
Water content ton	3.05	-	-
MSC sugar ton	30.41	-	-
MSC non sugar ton	16.38	-	
Sugar crystals ton	16.84	19.05	16.25
CRc % MSCso %	36	44	38
ML so ton	29.94	27.73	30.54
ML sugar ton	16.09	12.35	15.15
ML non sugar ton	13.85	15.38	15.38
ML quantity ton	32.99	34.24	39.14
ML purity %	53.72	44.54	49.64
ML brix %	90.76	81	78
Sugar purity %	85	91.04	90.06
Wash water quantity ton	-	3.45	5.55

Obtained simulation results for crystallization C recovery sugar with actual results showed that the efficiency of program for achievement reference values of CRc and produced molasses that fits the solid balance calculations of C sugar strike. While the actual CRc and molasses purity differs than the estimated values by the effect of failure of cooling crystallization system

C. Program efficiency for crystallization of different sugar grades

With implement functional analysis on program for crystallization the previous three different sugar grades, it could be judge on the program efficiency for the well controlling of critical crystallization parameters e.g. SS and crystallization rate .The functional analysis done via comparison between theoretical set trajectories of the crystallization parameters for the three sugar grade and the fit with the crystallization figure reference values of each

Parameter	R1	R4	C
Feed liquor purity%	92	94	65
Seeding point brix%	78.44	29.27	87.12
End MSCbx %	86.71	87.98	91.88
End MLp %	97.96	82.71	53.73
End MLbx %	79.69	81.92	90.76
End MSCbx %	89.71	90.98	93.88
Slurry seed quantity ml	401.1	409.2	575.5
Liquor feed rate m3/min.	0.774	0.792	0.072
MSCbx at70% level	85.22	86.3	91.96
Total evaporation ton	17.92	19.4	9.77
Evaporation rate ton/min.	0.224	0.243	0.023
Crystal growth rate micron/min.	7.29	7.35	0.882
Crystal quantity ton	50.37	51.38	16.84
Boiling time mn.	80	100	420
Overall batch time	117.9	149.9	473.3
End CRc %MSCso %	55	55	36
End ML SS %	1.05	1.05	1.1

IV. CONCLUSION

Achieving standard crystallization parameters from supersaturation coefficient curves of pure and technical sugar solutions by means of set of mathematical formulas, and set up a full sugar crystallization control program consisting of two loops 1st master controller for feed rate control and 2nd slave controller for evaporation rate control based on deviations between actual crystallization rate or calculated SS values (by soft sensor) and set point parameters, and advantages of the program shown as following:

1. The crystallization controlled safely by maintain SS of mother liquor in Meta stable zone through accurate detection of feed rate control parameters (using solubility and supersaturation coefficient curves of sucrose) that based on feed liquor purity and reference CRc value of each crystallization grade.
2. 2.Only three inputs required: feed liquor purity, crystal size and strike's boiling time needed beside pan's dimensions, and the program automatically drawing the supersaturation curves and detects all required parameters needed for feed rate controller settings e.g. seeding brix, end boiling brix, charge volume, charge level, seeding level, end boiling level, heating steam pressure for each step, slurry quantity...etc., thus avoiding the faults arisen from non-accuracy of manually inputted parameters.
3. Online monitoring for supersaturation ,purity, brix of mother liquor, crystal size and quantity, crystal content, evaporated water quantity, massecuite level and brix…etc. using measured brix values of massecuite and mother liquor (soft sensor mathematical model).
4. Reactive controlling program i.e. accelerate or slowdown boiling rate based on the deviation between actual boiling time or SS and the set control values through modulation slave control loop of evaporation rate to achieve the targeted boiling time and crystal quality.
5. Estimate the required wash water quantity needed for centrifuging processes based on the reference value of sugar color and syrup brix also the quantities and purities of both sugar crystals and runoff after centrifugal.

The obtained simulation results for R1 and recovery C sugar crystallizations fits reference values and design solid balance calculations for each in USCE while the actual results of crystal content and syrup purity are slightly converse. The next work of this project is the practical implementation with the help of sugar institutes and companies working in the same that field.

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