OPTIMIZATION OF SUCROSE LOSS FROM SUGAR INDUSTRY

Jibril Goli[a] and Omprakash Sahu[b]*

Keywords: Boiling, crystallizer, economical, Massecuite, purity.

The aim of work is process optimization of a milling plant in order to minimize sucrose loss with final bagasse as another option. The experiment was carried out with design expert software. By identifying main factors i.e. imbibitions of water and hydraulic pressure effect on response variable i. e percentage sucrose in bagasse, it was applied to the process optimization in order to get the optimum process condition in which the sucrose loss is minimum. This is achieved at maximum imbibitions of water (62.6 $m^3 h^{-1}$) and maximum hydraulic pressure (110 kg cm^{-2}). Under these optimum conditions, the minimum sucrose in bagasse is 3.4 % unit. This results in sucrose saving of 0.04 ton h^{-1}.

* Corresponding Authors
Phone: +251933520653
E-Mail: ops0121@gmail.com
[a] Department of Chemical Engineering, KIOT, Wollo University, South Wollo, Ethiopia
[b] School of Chemical and Food Engineering, Bihar Dar Institute of Technology, Bahir Dar, Ethiopia

INTRODUCTION

Sugar industry is one of the major agro-industries and competitive sectors for the Ethiopian economy. The country has suitable weather conditions at different areas for cane plantation and sugar production.[1] There are three sugar factories with total production of about 3000,000 tons of plantation white sugar per year. Nowadays there are a number of projects in Ethiopia to expand the existing and to install new sugar factories (Metahara Sugar Factory Strategic Plan Manual, 2008). The goal of sugar cane factory is to have an efficient and profitable operation with the required sugar quality and maximum sugar recovery. One of the biggest problems in sugar industries is the loss of sucrose in different forms. The monetary value of the losses of sucrose is of extreme importance because of the direct impact on profitability. Generally, two types of sucrose losses exist in sugar factory, namely known/determined and unknown/undetermined losses.[2] The determined loss consists of losses of sucrose with by-products i.e. losses in bagasse, losses in filter cake losses in molasses. Undetermined sucrose losses include chemical (inversion), biological and mechanical losses (i.e. sucrose that is unaccounted for when completing a mass balance over the mill). All of these components need to be minimized to maximize sugar recovery. The sucrose loss in molasses is particularly important because it is normally by far the largest of the four components of total loss.[3]

For the sugar factory to be competitive and profitable, more attention must be paid to overall recovery of sugar. The cost of production of sugar is increasing from time to time due to escalating cost of spare parts and chemicals. The establishment of new sugar factories in Ethiopia and the globalization issues, including the COMESA agreement, may result in high competition among sugar factories. Therefore, the existing sugar factories need to improve their internal efficiency, particularly the recovery of sucrose, to become competitive, profitable and to assure sustainability.[4] One of the biggest problems in the sugar industries which challenge their profitability is the loss of sucrose with bagasse, with filter cake and with final molasses. At present, in Metahara Sugar Factory (MSF) 9.1 to 9.3 % of the sugar that enters the factory with the cane are lost with final molasses. This is a big loss which should be minimized.[5] The company is losing sugar that is expected to be recovered and there is a need to increase the efficiency of sugar factory. The causes of the high sucrose loss with final molasses are not clearly identified for MSF. The aim of this project is therefore to identify the most significant loss areas and apply process optimization and equipment modification techniques to minimize the losses.

The main objective of this work is to investigate and study the process conditions at milling plant and D-massecuite processing line and finding the optimum point at low grade boiling, crystallization, reheating and centrifugal plant to reduce sucrose loss with final molasses.

EXPERIMENTALS

Cooling temperature, reheating temperature, brix, polarization (*pol*), and purity of final molasses, D massecuite and of liquor extracted from D massecuite at different steps were the study variables.

The study was conducted in two parts. First, assessment of the existing purity drop across each unit of D massecuite processing line (boiling, cooling, reheating and centrifugal separation) was conducted. This was done by intensive nutch filtration and analysis. After identifying the most significant loss areas, process optimization options were applied for each step.

MATERIALS

Samples of D–massecuite, final molasses and D-fore worker magma, seed for D-massecuite boiling were taken from different process steps. The study was conducted on-line using the existing D-vacuum pans, cooling crystallize, massecuite re-heater and D-centrifugal machines at MSF.

DOI: 10.17628/ECB.2016.5.441

Optimization of D-massecuite boiling

Response surface methodology (RSM) was adopted in the design of experimental combinations.

The main advantage of RSM is the reduced number of experimental runs needed to provide sufficient information for statistically acceptable results.[6] A three-variable (three levels of each variable) Box Behnken experimental design was employed.[6] The parameters and their levels were chosen based on the practical experience and related literature available on molasses exhaustion. The independent variables included massecuite final brix (98-102), purity (54 – 58), and seed volume (1000-2000 mL) each at three levels. Higher the brix and seed volume the higher the purity drop, but the viscosity also increases. It was practically observed that discharging from pan is difficult with brix of more than 1020. With seed volume higher than 2000 mL, the grain size of the massecuite becomes very small which can pass through the centrifugal sieves and will cause high sucrose loss with molasses. It is also difficult to handle in crystallizers and pumps due high solidity of the massecuite. Hence seed volume of 2000 mL and massecuite brix of 102 are taken as maximum practical values.[7] Response variables were purity drop between the massecuite and its mother liquor, mother liquor purity and massecuite viscosity. By inserting minimum and maximum values into Design expert response surface Box Behnken program, the following combinations of the factors have been obtained.

Optimization of D-massecuite cooling

The effect of cooling temperature (43 – 49 ^{0}C) and time (18 – 36 h) on purity drop is studied. Cooling of final massecuite is usually done in the temperature range of 40-50 ^{0}C depending on the nature of the massecuite. Based on this fact, cooling experiment was aimed to be done in continuous crystallizers at massecuite temperatures of 40 – 50 ^{0}C by controlling the cooling water flow rate. But it was found that nutsch filtration was difficult with the existing compressed air pressure (6.0 bars) for massecuite temperature less than 43 ^{0}C. Therefore, a minimum temperature of 43 ^{0}C was kept for the experiment. Maximum and minimum limit of cooling time is taken from Mauritius experience. The experimental design was using design expert response surface.

Optimization on reheater

Two factors, cooling temperature of massecuite (43 – 49 ^{0}C) and reheating temperature (50 – 56 ^{0}C) each at three levels and three responses (purity rise across the re-heater, nutsch purity after reheater and massecuite flow rate) were considered. Reheating time is calculated from flow rate and reheater volume. Design Expert-Response surface- ‘User Defined’ is applied to analyze the data and to find optimum solution.

Optimization on centrifugal separation

The amount of water has been optimized based on the final molasses purity and D-fore worker sugar purity. Amount of spray water in flow % Massecuite (1 – 10 %) is a factor, and the responses are purity rise across DFW centrifugal machine and DFW magma purity. Design Expert-Response surface- One Factor Design is employed to analyze the data. With given minimum and maximum values of the factor.

Sample preparation and analysis

All analyses have been conducted according to International Commission for Uniform Methods of Sugar Analyses (ICUMSA) method for pol, brix and viscosity. Relative Viscosity of massecuite at discharge from pan has been done using the new HAAKE 6Plus viscometer. Purity is obtained from calculation of pol and brix. Infrared temperature sensor and thermometer were used temperature measurements. Horne’s Dry Lead acetate, watch glass, and Whattmann No. 91 filter paper were used to clarify the samples for analysis of polarization. Weighing balance, Brix hydrometer, 200 mm polarization tubes, saccharometer, were used for measurement of the samples. Nutch bomb was used for pressure filtration (5.5-6 bar) of mother liquor from D-massecuite at different steps to study the purity drop. HAAKE 6Plus viscometer was used to measure viscosity of massecuite.

RESULTS AND DISCUSSION

Purity drop for the existing conditions

Sampling and purity analyses for massecuite and its respective mother liquor at pan discharge, inlet and outlet of each continuous crystallizers, reheaters and centrifugal machine were done. About 15 experiments were executed for each point to get reliable average values. The average values are given in Tables 1-3.

Table 1. Average purity drop across 1st battery of crystallizers.

S.No.	Unit	Temp. °C	Nutch Purity	Pty drop
1	*Discharge from pan (average massecuite purity= 57.35, brix = 101.3)	65.3	36.0	21.35
2	12 outlet/13 inlet	54.7	33.72	2.28
3	13 outlet /14 inlet	51.2	32.18	1.54
4	14 outlet /reheater inlet	48.8	31.66	0.52
5	Reheater outlet	53.6	32.52	-0.86
6	Centrifugal machine outlet (final molasses)	52.5	34.09	-1.57

Table 2. Average purity drop across 2nd battery of crystallizers

S.No.	Unit	Temp. °C	Nutch Purity	Pty drop
1	Pan	65.3	36.10	21.25
2	15 outlet/16 inlet	58.50	33.13	2.97
3	16 outlet /17 inlet	52.10	32.48	0.65
4	17outlet /reheater inlet	50.60	32.02	0.46
5	Reheater outlet	55.82	33.09	-1.07
6	Centrifugal machine outlet	55.60	35.61	-2.52

Table 3. Average purity drop for both the batteries of crystallizers.

S.No.	Unit	Temp. °C	Nutch purity	Pty drop
1	Pan	65.3	36.05	21.30
2	1st crystallizer	56.6	34.425	2.625
3	2nd crystallizer	51.65	32.33	1.1
4	3rd crystallizer	49.7	31.84	0.49
5	Reheater	54.71	32.81	-0.97
6	Centrifugal machine	54.05	34.86	-2.05

From the assessment it is seen that the purity drop across crystallizers is lower, only about 4.21 against standard of 5 – 7 in modern vertical crystallizers. The purity rise across centrifugal machine is acceptable (less than 2). The purity rise across the reheater is also higher than the standard values of less than 0.5 units. Assessment of the existing operation shows that there was lose control of the operation parameters at all D-massecuite processing steps and resulted in high loss of sucrose with final molasses. The average brix and purity of D-massecuite after boiling were 101.3 and 57.35 respectively, and the purity of mother liquor extracted from this massecuite (nutch purity at pan discharge) was 36.05. The massecuite was boiled with slurry volume of 2000 mL. The nutch purity obtained was higher than the required and ultimately contributed to the increase in final molasses purity. Therefore, optimization of boiling parameters (massecuite purity, seed volume and massecuite brix) was necessary to minimize the nutch purity on boiling.

At massecuite cooling, the final cooled temperature of the massecuite was only 49 °C, which resulted in low purity drop across crystallizers (only 4.21 units against the standard of more than 6 units). Here, the assessment results indicated that there was room for improvement at massecuite cooling to minimize sucrose loss with final molasses by increasing purity drop across cooling crystallizers. This can be achieved by cooling the massecuite to lower possible temperatures. Based on this fact, process optimization was carried out on massecuite cooling to obtain optimum cooling temperature and time at which high purity drop is achieved.

Considering the assessment study of D-massecuite reheating, there was an average mother liquor purity rise of 0.97 across reheater at reheating temperature of 54.71 ^{0}C. The purity rise obtained was higher than the required standard of 0 – 0.50 units. The purity rise should be reduced by controlling and optimizing the necessary parameters (cooling and reheating temperatures).[8]

For D-massecuite centrifugal separation, the average purity rise across centrifugal machines was 2.05 units. Purity rise in the “D” centrifuges should not be higher than 3 and it is better if it is lower than 2. The purity rise obtained from the assessment study was acceptable value when compared with the standard limits recommended on literatures. But during this test, the DFW sugar purity was on the low side (82 – 83), which will cause high recirculation of non-sucrose back to the boiling house. Therefore, optimization was required to improve the DFW magma (sugar) purity to the standard value of 84 or more without incurring high purity rise the mother liquor across centrifugal machines. The final molasses purity during the assessment study was also 34.86 which show a high sucrose loss.

Optimization of D-massecuite boiling

Based on the factors combination, series of experiment was done and the values of the responses at each factor level combination were taken. Boiling of D- massecuite was done in one pan, the massecuite and its mother liquor was analyzed for purity. The corresponding viscosity was also measured.

Data were modelled by multiple regression analysis and the statistical significance of the terms was examined by analysis of variance for each response. The adequacy of regression model was checked by R^2, Adj R^2, Pred R^2, Adeq Precision and F-test.[9] The significance of F value was judged at 95 % confidence level. Quadratic model is suggested by the design program for this response to test for its adequacy and to describe its variation with independent variables. From ANOVA test the Model F-value of 15363.10 implies the model is significant. There is only a 0.01 % chance that a "Model F-Value" this large could occur due to noise.

The graph indicates (Figure 1a) that purity drop increases with increase in massecuite brix at constant massecuite purity and seed volume (optimum seed volume and optimum massecuite purity). Examination of the response surface plots indicates that, purity drop increases with increase in seed volume and massecuite brix. At higher brix, more sucrose in the solution will be absorbed to the crystals due to high supersaturation and this will increase purity drop between the massecuite and its mother liquor (nutsch). More seed volume implies that there is Response surface plot for purity drop at boiling (with constant massecuite brix) large number of sugar crystals available in the solution for the sucrose molecule to be absorbed to. This is why the purity drop increases with seed volume (Figure 1b). From this graph we interpreted that, at constant massecuite brix and seed volume, as massecuite purity increase the purity drop is increased.The Model F-value of 2099.52 implies the model is significant. There is only a 0.01 % chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant.In this case A, B, C, AB, BC, A^2, B^2, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The "Lack of Fit F-value" of 2.07 implies the Lack of Fit is not significant relative to the pure error. There is a 24.68 % chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is shown in the good-fit model (Figure 1c).

Model equation for nutch purity at boiling

Equation in terms of coded factors:

$$\text{Nutch purity} = 36.47 + 0.21A - 0.49B - 0.39C - 0.040AB + 3.750\times10^{-3}AC - 0.060BC + 0.52A^2 - 0.082B^2 + 0.044C^2 \quad (1)$$

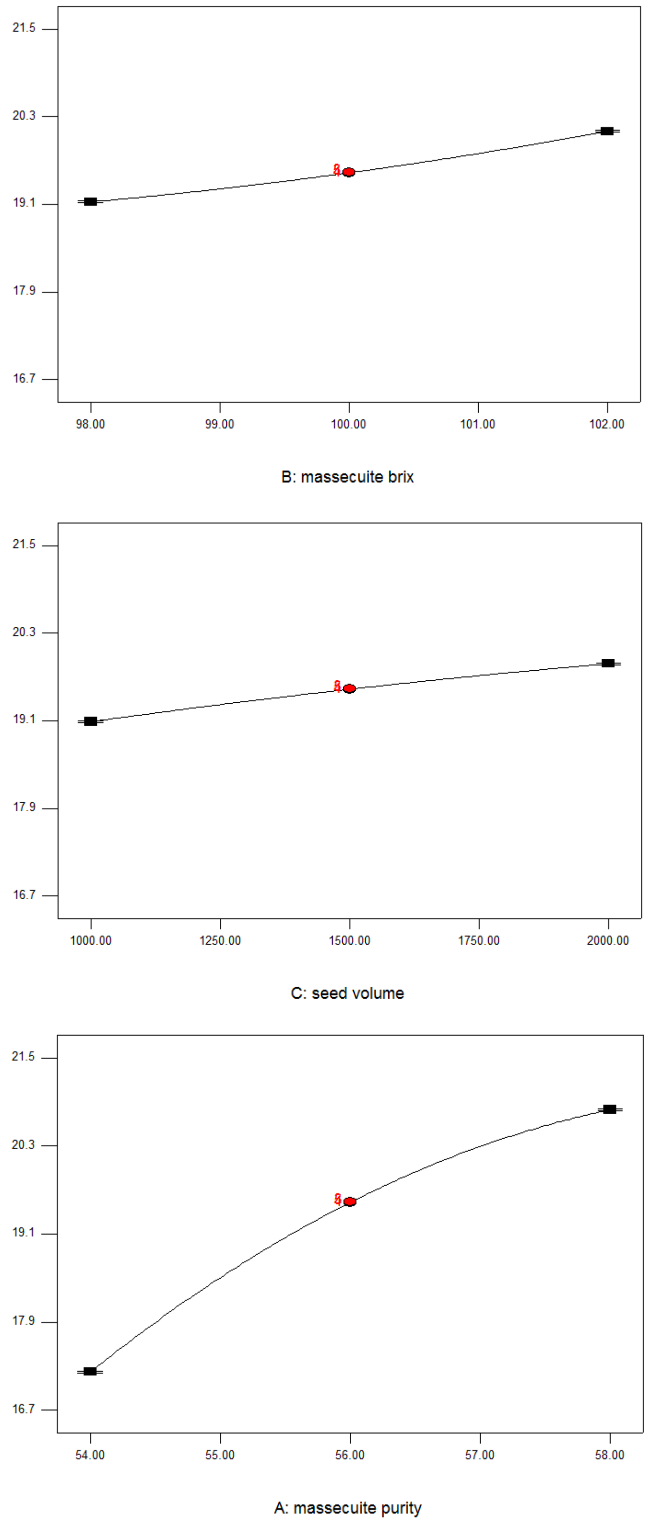

Figure 1. (a) Effect of massecuite brix on purity drop at constant seed volume and massecuite purity, (b) Effect of seed volume on purity drop, (c) Effect of massecuite purity on purity drop

Equation in terms of actual factors:

$$\text{Nutch purity} = 197.35225 - 13.57644\mathit{Pty} + 4.51375\mathit{Bx} + 4.4717\text{x}10^{-3}S' - 0.01000\mathit{PtyBx} + 3.75\text{x}10^{6}\mathit{PtyS} - 6\text{x}10^{-5}\mathit{BxS} + 0.13103\mathit{Pty}^{2} - 0.020531\mathit{Bx}^{2} + 1.76500\text{x}10^{-7}S^{2} \quad (2)$$

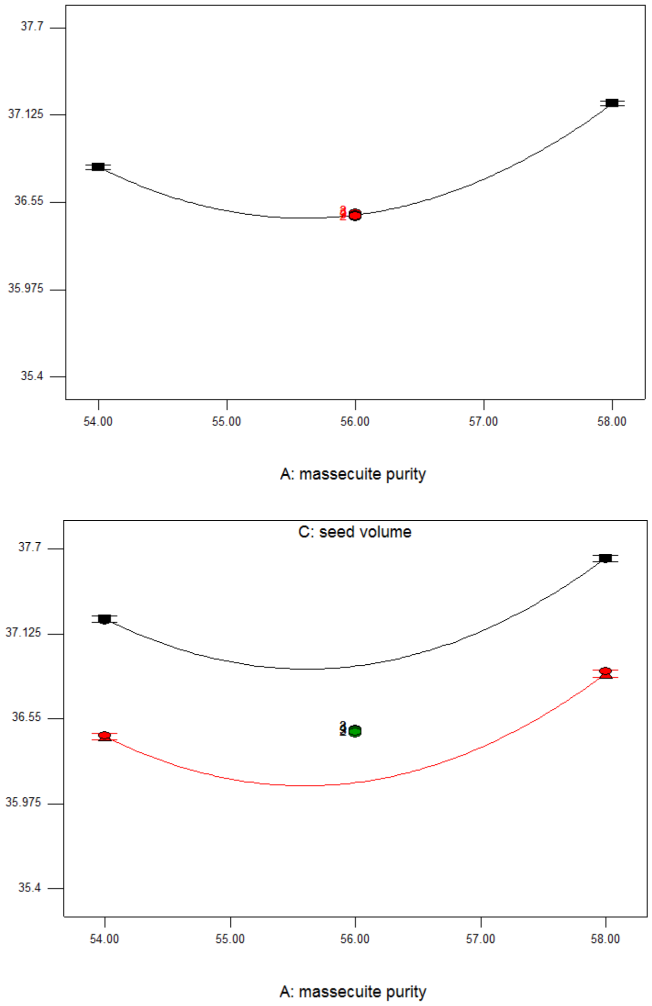

Figure2. (a) Effect of massecuite purity on nutch purity (b) Effect of seed volume and massecuite brix on nutch purity.

Analysis for nutch purity

The effects variation of factors on nutch purity is also observed, which showed in Figure 2a and b. At constant massecuite brix and seed volume, the nutch purity decreases with increases in massecuite purity for the massecuite purity of up to 56 and then increases with increase in massecuite purity. Minimum nutch purity is obtained at massecuite purity of about 56.

Analysis for massecuite viscosity

Linear model is suggested by the design program for this response. All statistical analysis including ANOVA test, post ANOVA statistics, lack of fit test are done for the Nutch purity data. All the tests indicated that the model is statistically acceptable.[10] All the Data analyses results indicate that the data are statistically valid, which presented in Table 4.

Model equation for viscosity optimization

Equation in terms of coded factors:

$$\text{Relative viscosity} = 201.39 - 58.10A + 31.58B + 35.43C \quad (3)$$

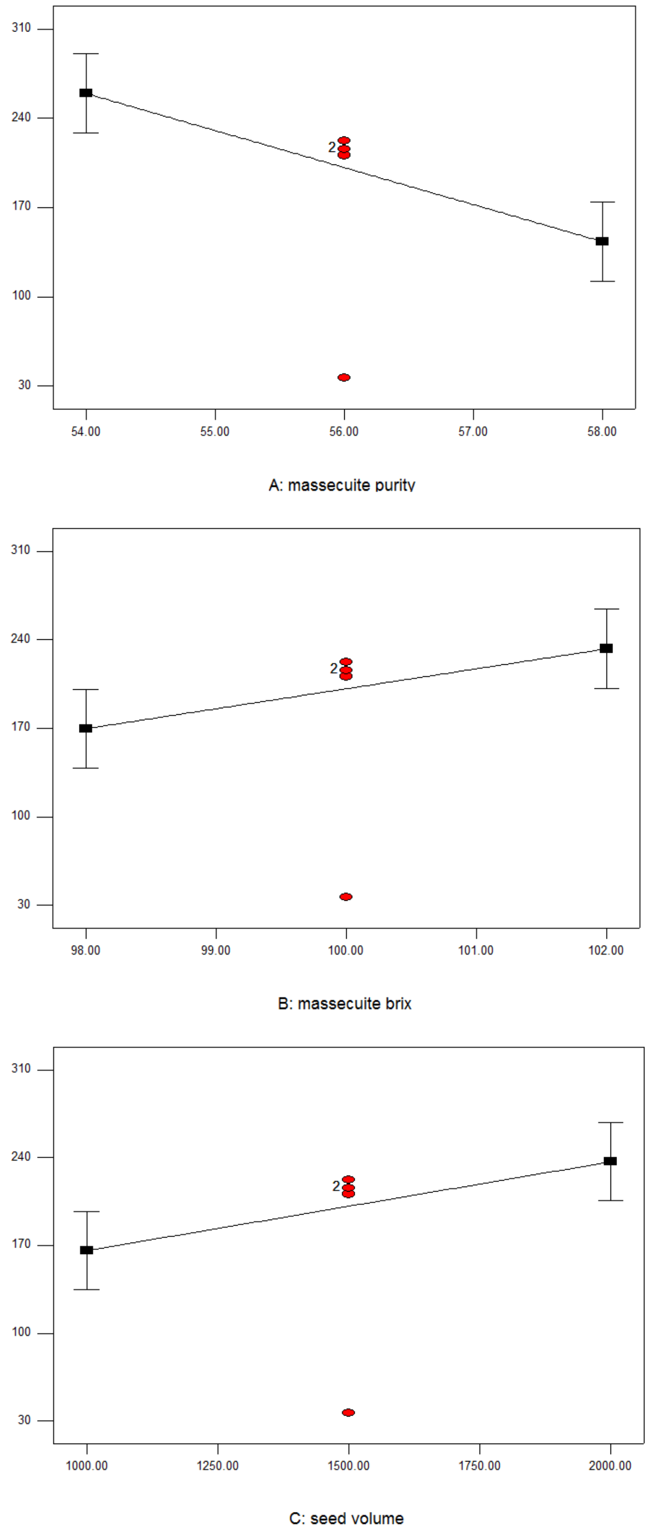

Figure3. (a) Effect of massecuite purity on viscosity, (b) Effect of seed volume on viscosity and (c) Effect of massecuite brix on viscosity

Equation in terms of actual factors:

$$\text{Relative viscosity} = 143.16676 - 29.05000Pty + 15.78750Bx + 0.070850S \quad (4)$$

The effects variation of factors on massecuite viscosity was also observed from the model equations and response surface plots shown in Figure 3. It is observed that the viscosity of the massecuite has a linear relationship with all the factors. It increases linearly with brix and seed volume and decreases with the purity of massecuite. The viscosity of D-massecuite increases almost linearly with increase in brix and decrease in purity. At low purity the proportion of non-sucrose impurities is high causing increase in the viscosity of the massecuite.

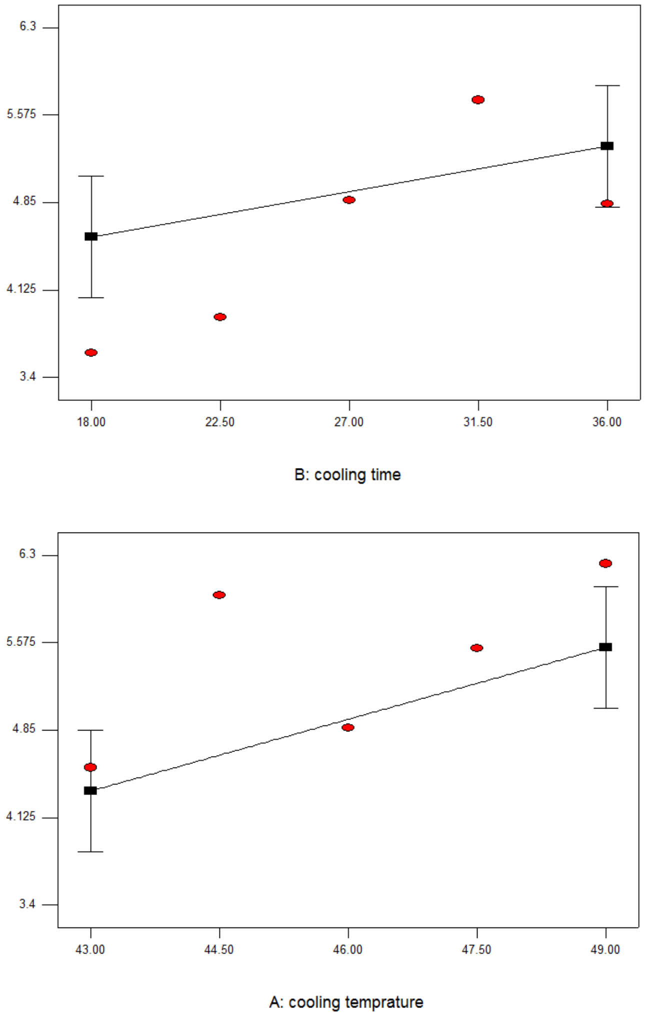

Figure 4. (a) The effect of cooling time on purity drop and (b) **E**ffect of cooling temperature on purity drop.

Optimization solution for D- massecuite boiling

The optimization was to get maximum purity drop, minimum nutch purity and minimum viscosity as much as possible. The Second response (nutch purity at boiling) was considered as an important response and more weight is given to it since it is the major determining factor of the final molasses purity. Six solutions are obtained. The solution with maximum desirability is selected as an optimum solution (with desirability of 58.8 %). Massecuite purity of 57.18^0, brix of 102^0 and seed volume of 2000 mL are selected as optimum parameters to obtain optimum purity drop of 21.41, nutch purity of 35.77 and massecuite relative viscosity of 244.332 Pa.s.

Table 4. Fit summary for massecuite viscosity.

S.No.	Source	*SD*	*R*^{2}	Adjusted *R*^{2}	Predicted *R*^{2}	Press	Remarks
1	Linear	47.68	0.6037	0.5123	0.5346	34707.30	Suggested
2	2FI	54.29	0.6048	0.3677	0.4830	38549.92	
3	Quadratic	61.25	0.6478	0.1950	0.3848	045878.45	
4	Cubic	80.51	0.6523	-0.3907		+	Aliased

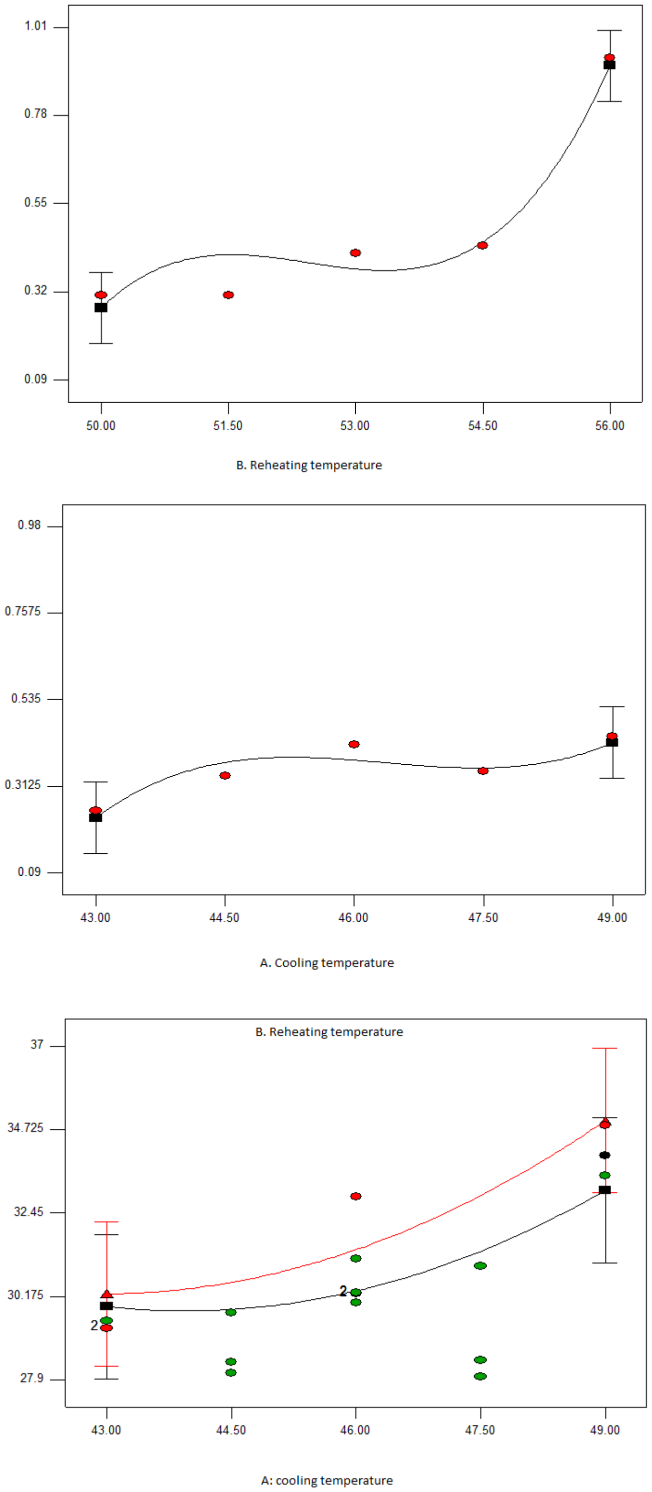

Figure 5. (a) Effect of reheater temperature on purity rise on reheater, (b) Effect of cooling temprature on purity rise across reheater (c) Response surface Plots Analysis for nutch purity after reheater.

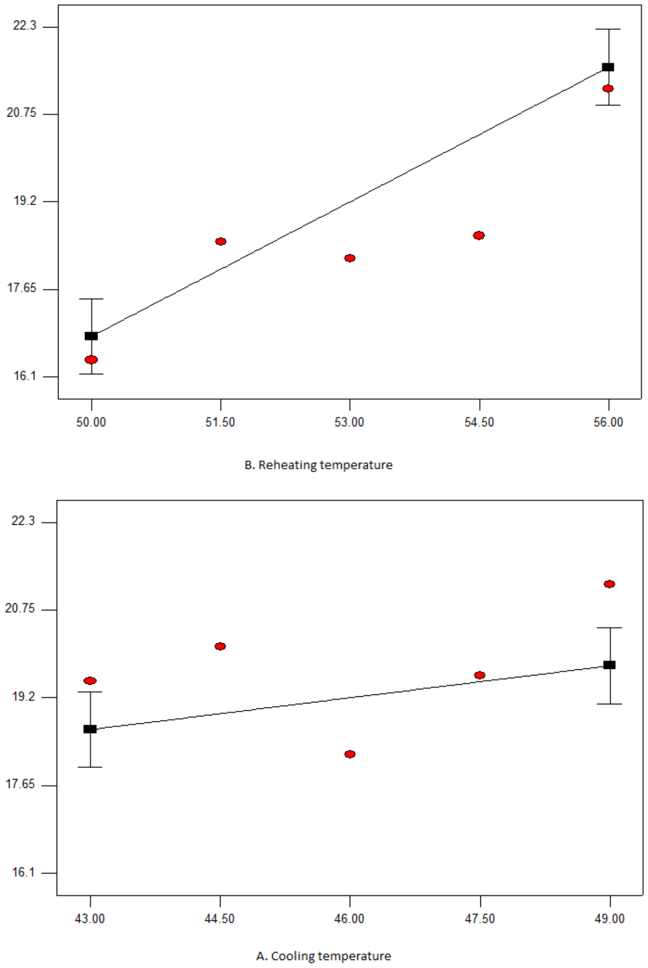

Figure 6. (a) Effect of water% massecuite on purity rise and (b) Effect of water percentage massecuite on DFW magma purity

D-Massecuite cooling optimization

Study of purity drop across continuous crystallizer was conducted by using nutsch analysis at different cooling temperature and time, in order to observe the trend of purity drop with temperature and cooling time, and to determine the optimum values. Cooling temperature is varied by changing the flow rate of cooling water to cooling discs and cooling time is varied by changing the massecuite flow rate to the crystallizer under study. Laboratory analyses were done for different factors level combinations as per the design.

Approach to this experiment

There are two batteries of crystallizers in Metahara sugar factory. One set of crystallizer (1st battery) was used for the study while the 2nd battery was working under accustomed condition. Before starting of the experiment, massecuite and cooling water flow were adjusted at different rates by manipulating the valves on the discharge lines in order to get the desired massecuite cooling temperature at desired cooling time. After several trials, the predetermined values were obtained at different valves openings. The valve opening positions and the water pressure on the cooling water discharge line were noted corresponding to the massecuite cooling temperature and cooling time. The cooling time was calculated from the known volume of the crystallizers and flow capacity of centrifugal machine in terms of current load.

Data analysis for massecuite cooling optimization

Data were modeled by multiple regression analysis and the statistical significance of the terms was examined by analysis of variance for each response. The statistical analysis of the data is performed using Design Expert Software (Stat-Ease). The adequacy of regression model was checked by R^2, Adj R^2, Pred R^2, Adeq Precision and F-test.[6] The significance of F value was judged at 95 % confidence level. The Model F-value of 3.26 implies there is a 6.88 % chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A and B are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve in model, which presented in Table 5.

Table 5. Post ANOVA test for purity drop D- masscuite cooling.

S.No.	Parameter	Value
1	SD	0.76
2	Mean	4.94
3	C.V. %	15.29
4	Press	11.24
5	R^2	0.3178
6	Adj R^2	0.2203
7	Pred R^2	0.0403
8	Adeq precision	6.124

The Pred R^2 of 0.0403 is in reasonable agreement with the Adj R^2 of 0.2203. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Our ratio of 6.124 indicates an adequate signal. This model can be used to navigate the design space. *SD* stands for standard deviation.

Model equations for purity drop on massecuite cooling

Equation in terms of coded factor:

$$\text{Purity drop} = 4.94+0.6 \times A +0.38 \times B \qquad (5)$$

Equation in terms of actual factor:

$$P_D = -5.32033 +0.19856 \times A + 0.0418 \times B \qquad (6)$$

where,

A = cooling temperature
B = cooling time

Response surfacep analysis of purity drop on massecuite cooling

Purity drop on massecuite cooling is shown in Fig. 4a and b, the purity drop increases with decrease in cooling temperature and increase in cooling time. The lower the temperature, the lower the solubility of sucrose in the solution and hence less sucrose remain in solution, more sucrose from the solution deposited to the crystal surface.

Optimization solution for D-massecuite cooling

The optimization was to get maximum purity drop at minimum cooling time and maximum cooling temperature as much as possible. Best results are obtained at cooling temperature of 49 ^{0}C and cooling time of 18 h. At these optimum parameters, the purity drop is 5.16129 units with a desirability level of 84.5 %.

Analysis of optimization experiment on D-massecuite reheating.

Response 1 - Purity Rise across reheater

Model equation for D-massecuite reheating optimization

Equation in terms of coded factors:

$$P_R = +0.38 - 0.051A - 0.062B + 0.21AB -0.051A^2 + 0.21B^2 - 0.097A^2B - 0.095AB^2 + 0.15A^3 + 0.35B^2 \qquad (7)$$

Equation in terms of actual factors:

$$P_R = -1645.41788 + 6.65489 \times T_C + 89.57652 \times T_R - 0.57058 \times T_C^2 - 2.03920 \times T_R^2 - 3.57835 \times 10^{-3} \times T_C^2 \times T_R - 3.50997 \times 10^{-3} \times T_C \times T_R^2 + 5.46755 \times 10^{-3} \times T_C^3 + 0.013991 \times T_R^3 \qquad (8)$$

where

P_R = Purity rise on reheater,
A= Coded value of cooling temperature,
B= Coded value of reheating temperature,
T_R= reheating temperature (°C),
T_C= Cooling temperature (°C),
N_P = Nutch purity after reheater.

Response 2 - Surface Plots Analysis for Purity Rise on Reheating

Effect of reheating temperature on purity rise across reheater : Purity rise across the reheater increases with increase in cooling as well as reheating temperatures.

The higher the gap between the cooling and reheating temperature, the higher is the purity rise.[11] This is due to the relatively longer time taken to bring the reheated temperature to the required value.

Model equation for nutch purity after reheater

Equ*ation in terms of coded factors*

$$N_P = 29.31 + 1.97A + 0.56B + 0.39AB + 1.16A^2 + 1.59B^2 \quad (9)$$

Equation in terms of actual factors

$$N_P = 861.65039 - 13.46743T_C - 20.47896R_T + 0.043268TC_{TR} + 0.1266T_C^2 + 0.17619T_R^2 \quad (10)$$

Response surface plots analysis for nutch purity after reheater

Nutch purity after reheating also increases with increase in both reheating and cooling temperature. Increase in temperature leads to dissolution of crystals in the massecuite and hence the purity of mother liquor. The result is representing in Fig. 5a, b and c.

Response - Massecuite Flow Rate (MFR) across reheater

Model equation development across reheater

Equation in terms of coded factor:

$$MFR = +19.20 + 0.56A + 2.38B \quad (11)$$

Equation in terms of actual factor:

$$MFR = -31.53825 + 0.18800T_C + 0.79422T_R \quad (12)$$

Response surface plots analysis for massecuite flow rate

The effect of cooling reheating temperature on massecuite flow rate is shown in Figure 6a and b. The massecuite flow rate increases with increase in temperature due to low viscosity at high temperatures. The figures reveal this fact and show that the effect of reheating temperature is more significant on the massecuite flow rate than cooling temperature. Flow rate sharply increases with increase in reheating temperature up to about 56 ˚C.

Optimization solution for Massecuite Reheating Experiment with maximum desirability is selected. One solution is obtained at desirability of 81.2 %. Minimum purity rise of 0.5346 units is obtained at optimum cooling temperature of 43 °C and reheating temperature of 50 °C.

D-massecuite centrifugal separation optimization

The amount of water was measured by online flow meter on the hot water line and the massecuite flow rate was calculated from the centrifugal machine load current. The load current has a direct relation with flow rate. The following data are generated for optimization across centrifugal machines.

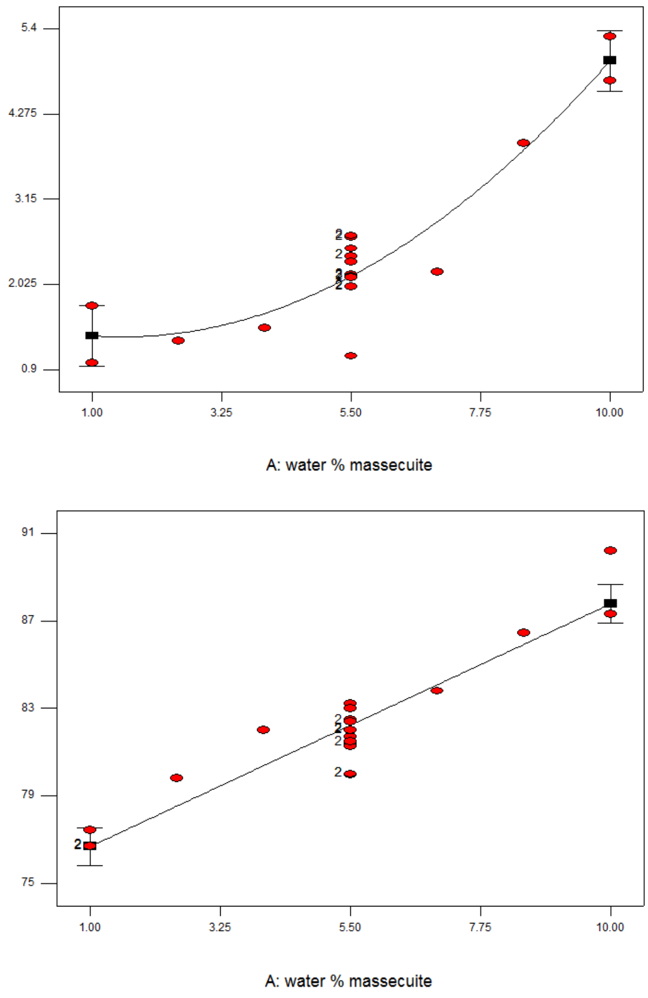

Figure 7. (a) Effect of water percentage massecuite on purity rise and (b)Effect of water percentage massecuite on DFW magma purity

(a) Analysis for optimization experiment on massecuite separation

The Model *F*-value of 57.74 implies the model is significant.There is only a 0.01 % chance that a Model *F*-Value this large could occur due to noise. Values of *Prob > F* less than 0.0500 indicate model terms are significant. In this case *A*, A^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model. The lack of fit *F*-value of 0.74 implies the lack of fit is not significant relative to the pure error. There is a 57.93 % chance that a lack of fit *F*-value this large could occur due to noise. Non-significant lack of fit is good, we want the model to fit.

Model equation for purity rise

Equation in terms of Coded Factors:

$$\text{Purity rise} = 2.14 + 1.82A + 1.03A^2 \quad (13)$$

Equation in terms of Actual Factors*:*

$$\text{Purity rise} = 1.44993 - 0.15377W + 0.050654W^2 \quad (14)$$

Response surface plots analysis for purity rise across centrifugal separation

Effect of water% massecuite on purity rise

There is a second order relationship between purity drop across centrifugal machine and the amount of spray water added, which is shown in Figure 7 (a).

DFW Magma Purity across centrifugal

The Model F-value of 111.43 implies the model is significant. There is only a 0.01 % chance that a Model F-Value, this large could occur due to noise. Values of *Prob > F* less than 0.0500 indicate model terms are significant. In this case A are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model. The Lack of Fit F-value of 1.57 implies the Lack of Fit is not significant relative to the pure error. There is a 23.73 % chance that a Lack of Fit *F*-value this large could occur due to noise. Non-significant lack of fit is good, we want the model to fit.

Model equation for DFW magma purity

Equation in terms of Coded Factors:

$$DFW\,pty = 82.23 + 5.55\,A \quad (17)$$

Equation in terms of Actual Factors:

$$DFW\,pty = +75.44733 + 1.2394W \quad (18)$$

Response surface plots analysis for DFW magma purity

The effect of water percentage massecuite on DFW magma purity is shown in Figure 7b. For optimization solutions, one solution with maximum desirability is selected by the software. The solution was obtained with desirability of 59.8 %. The optimum spray water is 7.65 % massecuite. At this spray water, the optimum purity rise and DFW magma purity are 3.23 and 84.889 units respectively.

The higher the purity rise, the higher is the loss of sucrose with final molasses. The lower the purity of DFW magma purity, the higher is recirculation of molasses (non-sucrose) back to the boiling house. Non-sucrose recirculation also needs equal attention since it reduces boiling house efficiency, increase steam consumption and reduce final product quality.

Conclusion

To sum, according to economical point of view that the process optimizations were compared with the factory's existing working norms. D- Massecuite boiling optimization has resulted in nutsch purity reduction of 0.28 units. Similarly, an increase in purity drop of 0.95 (from 4.21 to 5.16) across cooling crystallizers was obtained at optimum cooling time of 18 h and temperature to 49 °C for the existing crystallizer's capacity. The cooling experimental results have indicated that a purity drop of 5.25 units can be achieved if crystallizer capacity of MSF increased so as to give cooling time of 20.3 h and temperature of 49 °C. For the existing reheaters, the optimum reheating temperature was found to be 50 °C which gave a purity rise across reheaters of 0.530 against the value of 0.97 before optimization and the optimum massecuite flow rate of 16.25 t h^{-1}. From the centrifugal separation optimization result, the optimum spray water was found to be 7.65 %, with which massecuite giving a purity rise of 3.238 across centrifugal machines and DFW magma purity of 84.88. The overall effect of process optimization was a reduction in final molasses purity by 0.48 units (from 34.86 to 34.38) for the existing capacity of cooling crystallizer which leads to annual saving of 1428.84 tons sugar, equivalent to 18,574,920 Birr. Additional saving of 4,058,964 Birr per year is expected if enough crystallizer capacity is installed for MSF.

References

[1] Humbert, R.P., *The growing of sugar cane*. Elsevier, **2013**

[2] Heriot, T. H., *Manufacture of sugar from cane and beet. International Common United Methods of Standard Association (ICUMSA), A Methods Book*, Bartens the Sugar and Sweeteners Publishers, England, **2008**.

[3] Jiju, A., *Design of Experiments for Engineers and Scientists*, Elsevier **2014**.

[4] Kulkarni, D. P., *Cane Sugar Manufacturing* in India, The Sugar Technologists' Association of India, **2009**.

[5] Miller, K. F., and D. M. Hogarth. *Sucrose losses in low grade massecuite processing*. in International Society of Sugar Cane Technologists. Proceedings of the XXIV Congress, Brisbane, Australia, 17-21 September 2001. Volume 1., pp. 366-367. Australian Society of Sugar Cane Technologists, **2001**.

[6] Myers, R.H. and Montgomery, D.C., *Response surface methodology*, Willey, New York, **2001**

[7] Mosen, A., *Beet Sugar Handbook*, John Wiley & Sons. **2006**.

[8] Mullin, J. W., *Crystallization*, Butterworth-Heinemann, **2001**.

[9] Naidoo, G., Schoonees, B. M., and Schom, P. M., *SASTA Laboratory Manual including the Official Methods*, July 2005. The South African Sugar Technologists' Association, South African.**2005**

[10] Ninela, M., Rajoo, H., *Proc. S. Afr. Sugar Technol. Ass*., **2006**, *80*, 448-461.

[11] Rein, P.W., Smith, I.A., *Proc. S. Afr. Sugar Technol. Ass*., **1981**, *73*, 85-91.

Received: 23.11.2016

Accepted: 24.12.2016.