Increasing the Efficiency of Massecuite Boiling Using Modeling and Optimization Techniques

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***Abstract*— This paper examines the process of sucrose crystallization during vacuum pan boiling and demonstrates the possibility of improving the A-massecuite boiling process using modeling and optimization techniques.**

Keywords*— sucrose crystallization modeling; massecuite boiling optimization; A-massecuite; optimization criteria; parametric model of controlled object; general criterion; process flow distribution; target function of process optimization; target function extremum; optimality criterion

I. Analysis of the Massecuite Boiling Process and the Method for Increasing Its Efficiency

An in-depth analysis of the massecuite boiling process requires considering it as a complex, multi-parameter process, with due consideration of the technological characteristics of the A-boiling stage.

Several studies have been conducted for this purpose, which resulted in developing a mathematical model of sucrose crystallization [1, 2].

A model of A-massecuite boiling in a vacuum pan was developed to precisely define the rational conditions of this process stage. The model was based on the following assumptions: Sucrose concentration in the initial solution remains identical throughout the process, and crystallization seeding sites are evenly distributed throughout the entire solution volume [5].

The developed quantitative model of the massecuite boiling process can be used to evaluate the efficiency of processes of granulated sugar production in vacuum pans within a single process cycle. The analysis of the data obtained from modeling revealed a number of mathematical dependencies. The obtained results were used as a basis for the optimization of the process.

The optimization of a production process consists in ensuring its maximum efficiency under certain process conditions. To this end, a specific optimality criterion is chosen at the very beginning of the optimization process, which is a qualitative or quantitative indicator of the maximum effect of an optimization decision used for comparing alternative optimization solutions and choosing the best one.

The chosen optimization solution is used for composing a target function, which represents the dependence of the chosen optimization criterion from specific parameters. A suitable optimization technique is chosen depending on the type of the target function, the nature of the applied constraints and the mathematical model used to describe the analyzed process. In our case, the optimization of the massecuite boiling process consisted in finding the optimum process parameter values, at which the target function reaches its extremum within the given constraints.

Since the previous studies in this area involve defining the optimum process conditions for the A-massecuite boiling stage, the authors chose the corresponding optimization criterion that reflects the variance of the qualitative and quantitative indicators of this process [4]. The ultimate goal of the A-massecuite boiling process is to ensure maximum sugar yield regardless of raw material quality. Therefore, this indicator is one of the most important optimization criteria for the process under consideration.

II. Massecuite Boiling Process Model

The following two optimality criteria were chosen to solve the problem of optimizing sucrose crystallization during A-massecuite boiling: the volume of sucrose diffusing at crystal surfaces (V), and the duration of crystallization (τ).

The parametric model of the controlled object (A-massecuite boiling process) is shown in Figure 1.

The following characteristics were used as model parameters:

$\overline{X}$ — input parameter vector:

$\overline{X}$ (Psyr, SLsyr, SCsyr, PmeltB, SLmeltB, SCmeltB, PmeltC, SLmeltC, SCmeltC),

where Psyr, PmeltB and PmeltC are the purities of syrup, B-sugar melt and C-sugar melt, respectively,

SLsyr, SLmeltB and SLmeltC are the solid contents in syrup, B-sugar melt and C-sugar melt, respectively,

SCsyr, SCmeltB and SCmeltC are the sucrose contents in syrup, B-sugar melt and C-sugar melt, respectively;

$\overline{Y}$ — output parameter vector:

$\overline{Y}$ (Psug, SLsug, SCsug, PrunA, SLrunA, SCrunA, PrunB, SLrunB, SCrunB),

where Psug, PrunA and PrunB are the purities of granulated sugar, A-runoff and B-runoff, respectively,

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SLsug, SLrunA and SLrunB are the solid contents in granulated sugar, A-runoff and B-runoff, respectively,

SCsug, SCrunA and SCrunB are the sucrose contents in granulated sugar, A-runoff and B-runoff, respectively;

$\overline{U}$ — governing parameter vector:

$\overline{U}$ (D, SCsup, SCsat, W, J, V, λ, k, t),

where SCsat is the concentration of the saturated sucrose solution,

SCsup is the concentration of the supersaturated sucrose solution,

D is the diffusion coefficient,

t is the time,

k is degree of sucrose supersaturation,

λ is the coefficient characterizing the average distance between sucrose particles,

J is the volumetric amount of sucrose reaching a crystal surface per unit time, J = 3SCsat(k−1)exp(−3Fo),

where Fo = Dt/h2 is the Fourier number,

V is the volume of sucrose diffusing at crystal surfaces in a given time t, V = SCsat·(k−1)h·s[1−exp(−3 Fo)],

W is the specific volume of sucrose crystallized from the solution phase, W = 6SCsat(k−1)λ[1−exp(−3Fo)]/(1+λ), where λ = h/d, and

h is the distance between crystals.

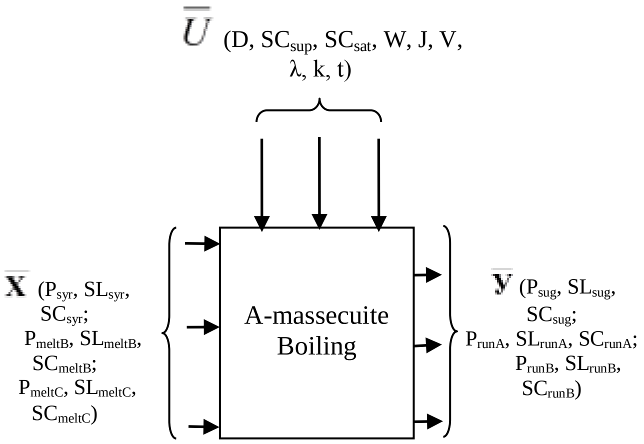

Fig. 1. Parametric model of the controlled object (A-massecuite boiling process)

III. Analysis of the Massecuite Boiling Process as an Object of Optimization

Using one of the methods for reducing multiple criteria to a single general one, the authors obtained the general criterion that depends on the main process parameters and evaluated the importance of these parameters.

Before defining and solving the problem of multi-parameter optimization, it was necessary to conduct a research that would allow making a conclusion on the existence of an optimum. For this purpose, the authors plotted graphs that express the dependence of the output value on two given input parameters, with all others remaining constant. An example of such a graph is shown in Fig. 2.

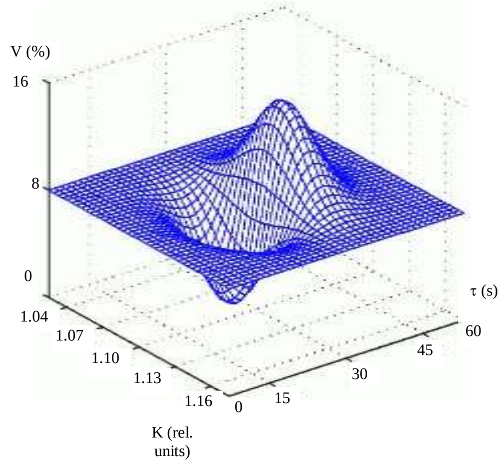

Fig. 2. Dependence of the volume of sucrose crystallized on crystal surfaces (V, %) on the time of crystallization (τ, s) and the degree of supersaturation (K, rel. units), with all other parameters remaining constant.

The analysis of the graphs shows that, if the crystallization time (τ, s) and sucrose concentration (cn, %) are taken as the governing parameters, the maximum volume of sucrose crystallized on crystal surfaces (V, %) will be V = 12% (τ = 47 s, cn = 87%) [3]. If the crystallization time (τ, s) and supersaturation degree (K, rel. units) are taken as the governing parameters, the maximum volume of sucrose crystallized on crystal surfaces (V, %) will be V = 11% (τ = 35 s, K = 1.1). If the supersaturation degree (K, rel. units) and sucrose concentration (cn, %) are taken as the governing parameters, the maximum volume of sucrose crystallized on crystal surfaces (V, %) will be V = 14% (cn = 88%, K = 1.11).

As can be seen from the above analysis, even in case of an n-dimensional governing parameter space, where n = 3 (only a three-dimensional space can be represented graphically), different combinations and variations of the chosen governing parameters result in different extremum values. In our case, the governing parameter space (D, SCsat, SCsup, T, λ, h, k) has n = 7, and therefore, obtaining the optimum values for the above parameters, which ensure the maximum efficiency of the A-massecuite crystallization process, requires solving a multi-parameter optimization problem.

IV. Formulating and Solving the Problem of Massecuite Boiling Process Optimization

The general criterion of the following the form was taken as the target function for solving the optimization problem at hand:

$$L = \frac{V}{t} \to \max_{\bar{x} \in Z}, \quad (5)$$

where $\bar{x}$ is the vector of governing parameters,

$$\bar{x} \in \{c_n, c_H, k, t, D, \lambda, J, W, V, t\},$$

V = SCsat·(k−1)h·s[1−exp(−3 Fo)],
t = Fo·h2/D.

The target function (5) can be expressed through the main parameters of the process under consideration:

$$L = \frac{c_н(\kappa - 1) \cdot S \cdot (1 - e^{-3 \cdot F_0}) \cdot D}{h \cdot F_0} \to \max_{\bar{x} \in Z}. \quad (6)$$

$$Z \in \begin{cases} 84\% \le c_П \le 90\% \\ 73\% \le c_Н \le 84\% \\ 1{,}06 \le k \le 1{,}15 \\ 10^{-4}\,м \le h \le 3 \cdot 10^{-4}\,м \\ 72^0\,C \le T \le 78^0\,C \\ 1{,}0 \cdot 10^{-4} \le D \le 4{,}5 \cdot 10^{-4} \\ 0{,}4 \le \lambda = f(h, D) \le 3 \\ 0{,}001\% \le J = f(c_П, c_Н, D, F_0(D,t,h), T, h) \le 46{,}67\% \\ 7{,}86\% \le W = f(c_Н, \lambda(h,D), F_0, h, S) \le 46{,}65\% \end{cases}, \quad (7)$$

where Z is the constraint region, which contains in a transformed form the conditions for finding the target function's extremum.

The optimality criterion L is, therefore, the maximum volume of sucrose crystallized on crystal surfaces (V) at the minimum crystallization time (t).

Thus, solving the problem of sucrose crystallization process optimization requires finding the values of the optimization parameters $\bar{x} \in \{c_n, c_н, k, t, D, \lambda, J, W\}$, at which the general optimality criterion L reaches its maximum within the constraints imposed on region Z.

In this case, the mathematical formulation of the optimization problem at hand is a non-linear programming problem, which can be solved using one of the methods developed for solving problems of this class, in particular, the method of Lagrange multipliers [6].

EUREKA statistics and optimization suite was used to this problem.

As a result, the values of the sucrose crystallization process parameters were obtained, at which the chosen general criterion reaches its optimum.

If the original process conditions change, the optimum process parameters need to be recalculated.

Using the proposed optimization solution allows increasing the granulated sugar output of a single vacuum pan by 1 to 2 tons as compared to the conventional production process.

V. Conclusions and Recommendations

1. An auto-analytic algorithmic database of scientific studies was created to facilitate a comprehensive study of the massecuite boiling process. This system was used for mathematical modeling of the analyzed process, its subsequent optimization, and conducting the necessary computer-based experiments.
2. The analysis of previous studies showed that changing massecuite boiling process conditions results in an increased sucrose loss. Therefore, it is necessary to create the process conditions that ensure a decrease in sucrose loss. The analyzed studies show that the same process design not always yields the maximum output.
3. The study at hand demonstrated the existence of the range of permissible process parameter values that allow optimizing the yield of the massecuite boiling process, while decreasing the sugar loss.
4. Previous studies showed that changing the main parameters of the massecuite boiling process in this system affects its efficiency. Therefore, applying the proposed process optimization algorithm to this process system allows finding the optimum solution.

Thus, the authors recommend recalculating the proposed optimization function for any changes in the conditions of the massecuite boiling process to ensure its maximum efficiency.

Modern computing devices can perform such calculations within minutes, which allows using the proposed system for real-time process optimization.

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