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INNOVATIVE SUGARCRAFT: ALTERNATIVE TECHNOLOGIES AND IMPURITY CONTROL STRATEGIES FOR ELEVATING CRYSTALLIZATION EFFICIENCY IN THE SUGAR INDUSTRY

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Abstract: The sugar industry has traditionally relied on the periodic boiling of sugar massecuites for crystallization, but this method is limited by its instability and lack of efficient control. Researchers have sought to modernize this process through continuous crystallization, yet high costs and design defects have hindered the widespread adoption of this technology. In response, the authors propose a semi-continuous crystallization technology that achieves results comparable to continuous crystallization without significant changes in equipment. Three new technologies for crystallization of traditional periodic boiling are also presented, using mathematical modeling to analyze and compare results. The authors emphasize the importance of improving the efficiency of the crystallization process for reducing fuel consumption and increasing yield of finished product. The article also addresses the impact of impurities on crystallization and presents a criterion function for considering the qualitative composition of impurity in sugar processing. This study provides a comprehensive evaluation of the potentials for innovative crystallization technologies in the sugar industry and the importance of impurity control.

Keywords: sugar industry, crystallization, continuous crystallization, semi-continuous crystallization, impurity control, mathematical modeling, efficiency.

Introduction

The technology of sugar production is based on the use of very diverse and complex processes, technological equipment, physical and chemical transformations, thermal engineering and hydrodynamic transformations. For justification and development of new effective technologies of crystallization by authors the strategy of system approach, applied to relation to justification of process of mass crystallization, in particular, of isobaric evaporative crystallization of sucrose has been used. She has allowed them, as the main stage, to select the qualitative analysis of essence of various ways making a basic basis of technology of crystallization [1]. For studying of a problem and search of the new directions of creation of alternative technologies of crystallization authors proceeded from three aspects:

- semantic, i.e. preliminary analysis of aprioristic information on the known technological, physical and chemical, thermal and hydrodynamic features of process of crystallization of sucrose;
- the mathematical, i.e. qualitative analysis of the main kinetic regularities of course of the studied crystallization mode on the basis of methods of mathematical modeling;
- The experimental, i.e. quantitative and qualitative analysis of information on process and an object in dynamics.

The second and third aspects of system approach assume synthesis of structure of distribution of material streams and generalization of results of a research of process and an object in general. Realization of methodology of the system analysis has allowed authors to put forward a number of the new provisions concerning the theory and practice of industrial crystallization of sugar that will be shown below.

With distribution of computer facilities in all spheres of human activity before researchers' great opportunities for practical use of a mathematical apparatus of modeling for studying of kinetics and dynamics of course of technological processes have opened. Technical progress hasn't avoided also sugar industry.

Review of Literature

In literature and a work practice two technologies of isobaric evaporative crystallization of sucrose are well-known generally:

1. Traditional, classical technology of a periodic boiling sugar massecuite with all her improvements. But such shortcomings as periodic feeding boiling product, instability of the received parameters sugar massecuite, the grain formations connected with bad reproducibility of conditions and growth of crystals, inefficient control and management.
2. Continuous technology of crystallization of sucrose. The prospects of this technology as sucrose crystallization, is, perhaps, the only process which is implemented periodically can't deny. However, we will note that, on the one hand, she hasn't gained industrial distribution in Russia. On the other hand, with a certain degree of probability, it is possible to claim that hardly in the next years the vacuum apparatuses of continuous action will quickly replace all vacuum apparatuses of periodic action.

Materials and Methods

Mathematical modeling became the effective and rather widespread method applied during the developing and a research of technological processes and objects in recent years [2]. Mathematical modeling gives answers to many questions at a stage of a preliminary research of process and allows to define the optimum modes, production schedules and to select schemes of technological processes. It excludes unnecessary costs of labor and material resources of creation of irrational schemes and implementation of inefficient regulations. The mathematical model is extremely flexible means, and modeling gives the chance to investigate the course of technological process at desirable values of his parameters. Thanks to it the need for the difficult laboratory equipment decreases, allows avoiding essential financial expenses and ensures safety at operational tests of the created technological processes.

We will note that, on the one hand, it is difficult to realize experimental methods on the operating objects; on the other hand, information on new properties is necessary at a stage of their development and design. These problems are successfully solved with application of methods of mathematical modeling on the basis of a machine experiment which finds the increasing attention at researchers.

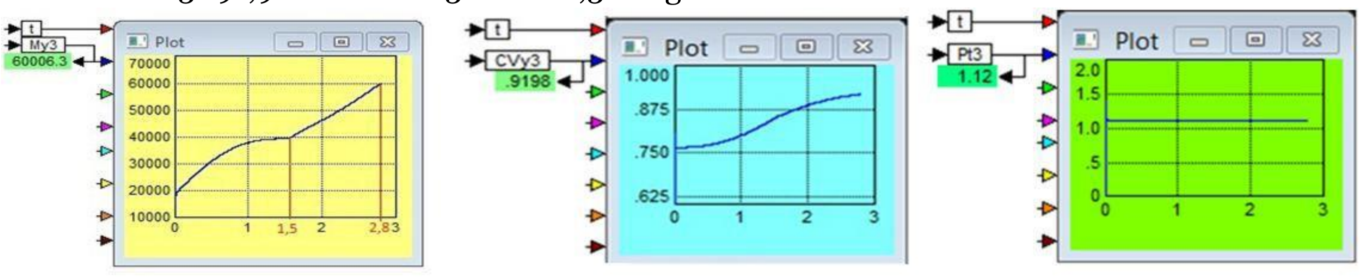
The mathematical description of process of isobaric evaporative crystallization of sucrose is submitted in work [3]. These equations have been the basis for creation of the mathematical model of the studied process functioning with the restrictions stated in the same work.

It is known that as an indicator of compliance of mathematical model to real process or an object (original) serves the criterion of adequacy. In this regard assessment of adequacy of model and the original has been carried out. For this purpose, on their entrances signals of various parameters, equal in size, in particular, temperature, pressure, various values of concentration and

supersaturation, and other parameters were given. As a result of assessment of compliance have come to a conclusion about adequacy of model and the original as the average divergence of signals didn't exceed the required magnitude that it is quite enough for studying of process of crystallization and justification of new technologies.
Tests of mathematical model have shown good coincidence of results not only on boiling duration for all studied crystallization cases, but also on all other technological, physical and chemical, thermal and hydrodynamic indicators that allows to draw a conclusion on universality of the developed mathematical model.
Starting the analysis of process of isobaric evaporative crystallization of sucrose, we will note that, on the one hand, it is known that with increase in duration of a season of production of sugar, hulls of evaporation plant are exposed to incrustation (tanning) that worsens heat exchange and causes decrease in concentration of syrup from the last hull to SVs < 65 %. On the other hand, there are known methods of evaporation to bring the syrup concentration to SVs > 80 % [4].
The comprehensive analysis with use of methods of mathematical modeling of technologies of crystallization from low and highly concentrated solutions has shown that in this case there is a problem of inefficient use of useful capacity of vacuum apparatuses [4]. It has turned out that if to carry out crystallization at constant supersaturation with use with SVs < 65 % and purity PS = 88 – 93 %, then massecuite reaches final concentration of SVf =92 % during descent with not full use of useful massecuite capacity of the vacuum apparatus. And, on the contrary, at revenues to a boiling of a product of high concentration, the vacuum apparatus it is overflowed ready massecuite. An exit from the situation – development of new technology of crystallization.
In this regard the technology of crystallization with use of syrups of two concentration has been developed. Her essence consists that at first crystallization is carried out, giving syrup of low concentration with SVs < 65 %, and then, in strictly certain time, begin to give syrup of high concentration with SVs > 65 % of the same purity, supporting at constant supersaturation during all cycle of growth of crystals.

Results

The special control algorithm which regardless of quality of a boiling product, technological, physical and chemical and heat technical indicators, allows to receive the required final concentration of SV_y =0,92±0,5 and weight massecuite My =60±0,5т has been developed for implementation of this way at the time of achievement by him of readiness for descent. The graphic representation of the course of change of technological parameters of process at use of the offered technology of crystallization is shown in the (Figure 1). From the Figure 1 it is visible that from 0 to 1,5 hour were carried out crystallization with addition of syrup of low concentration then have begun to give syrup of high concentration and by the time of 2,8 h the crystallizable product has reached SVu3=91,98 % and Mu3=60006,3 of kg.



a B c

Figure 1: Graphic interpretation of the offered method (a - mass massecuite (Mu3); в – concentration massecuite (CVu3); c – coefficient of supersaturation (Pt3). Lack of this method is need of installation of the additional evaporating apparatus for receiving syrup of high concentration of the same purity, as syrup of low concentration.

This shortcoming the technologies offered by us which are further development of the above described method are deprived. The technological essence of one of them is that crystallization carries out by use separately of syrup from evaporating station of concentration of SVs < 65 %, purity Ps, and then the concentrated klerovcy with SVkl > 65 %, purity P_{kl}. Management of process is made, as well as the last method, on specially developed algorithm.

Other technology of isobaric vaporizing crystallization of sugar with use of progressively increasing concentration of the pumpedup solution is offered and proved. The essence of this technology is that make continuous mixing of syrup of low concentration of SVs, purity Ps arriving from evaporating station from the concentrated klerovcy SVkl, purity Pkl. This mix of syrup and a klerovcy with the progressive growth of concentration of mix arrives on a boiling massecuite, control of which is exercised, as well as in the previous cases, on specially developed algorithm [5].

It is known that sucrose crystallization process in many respects depends on qualitative and quantitative composition of impurity (nonsugar) in initial raw materials. The composition of impurity (nonsugar) is influenced by such natural factors as seasonality of production, weather conditions and also element structure of the soil and fertilizers, a beet-growing zone from where sugar beet arrives for processing. The analysis of scientific and technical information on a case in point has shown that most sharply influence of structure of nonsugar is shown on solubility of sucrose and on their viscosity. In a general view criterion function of qualitative composition of impurity (nonsugar) can be expressed through two variables [4,5]:

Fns = f (Knas, Kμ)

where F_{ns} – criterion function of qualitative composition of impurity (nonsugar);

K_{nas} – the coefficient considering influence of composition of impurity (nonsugar) on solubility of sucrose;

K_{μ} - the coefficient considering influence of composition of these impurity (nonsugar) on viscosity of interstitial.

We will note what within the considered problem, takes place not only variety of the points of view, but also obvious contradictions in interpretation of separate scientific views on a problem of influence of qualitative and quantitative composition of impurity (nonsugar) as on separate technological and physical and chemical indicators, and on the course of processes of isobaric and polythermal crystallization of sucrose in general, including on duration of the considered processes [6]. The extreme variability of composition of impurity of various zones of a beet-growing from the above-stated factors is the reason of it.

Two equations given below have been the basis for definition of criterion function of qualitative composition of impurity:

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Knas = b + m · NS/VD + e– c·NS/VD K_{μ} = f (μ_m, t, Ns, Nns)

where: Knas – saturation coefficient;

"m", "b", "c" – integrated values of the coefficients characterizing qualitative composition of impurity (nonsugar) of this zone of a beet-growing;

K_{μ} – viscosity coefficient; t – solution temperature;

N_s and N_{ns} – concentration of sucrose and impurity (nonsugar) in the form of a mole fraction; NS/VD – concentration of impurity (notsugars); μ_m – viscosity of interstitial solution.

As a result of data processing across the Russian Federation it is revealed that "m" changes in the range of 0,1 – 0,5. According to "b" m + b ≅ 1 changes in the range of 0,9 – 0,5, and. The coefficient "c" changes in the range of 1,8 - 2,3. Integrated indicators of quality of "m" and "b" exert rather strong impact on solubility of technical solutions of sucrose while the coefficient of "c" has no significant effect.

The coefficient of the viscosity "K_μ", according to the known literary data, changes in the range of 0,6 – 0,8 though on given questions there are other data. He shows influence of composition of the same impurity of technical solution and has significant effect not only on duration of process of isobaric vaporizing crystallization of sucrose, but also on other characteristics of a crystallizable product.

We will note that above-mentioned coefficients exert especially strong impact on process of crystallization of solutions of low purity, the taking place especially at a boiling of the last massecuite and polythermal crystallization of sucrose. Undoubtedly, influence of these integrated coefficients should be considered in the analysis of industrial crystallization of sucrose, and the mathematical model developed by us successfully solves this problem.

Coming back to a problem of development of new technologies of isobaric evaporative crystallization of sucrose we will note that her justification is in detail presented in works enough [8,9]. We will remind that *the essence of this technology consists in elimination of a stage of concentrating of a boiling product to a labile state or her transfer on a separate step of evaporation, introduction to the vacuum apparatus of the ready crystal mass equal to initial set massecuite and creation of conditions of growth of crystals in a metastable zone of growth of crystals to readiness for descent during a full cycle of a boiling massecuite in periodically operating vacuum apparatuses on condition of the continuity of giving of a boiling product and maintenance of constant value of coefficient of supersaturation in a metastable zone of growth of crystals.*

We will note that this technology of crystallization of sucrose can be realized within the semi-continuous regime, according to classification of processes of chemical technology for a case if in the vacuum apparatus at continuous loading of a boiling product periodic unloading of a ready-made product is carried out [10].

If to apply this definition to justification of technology of isobaric evaporative crystallization of sucrose, then in relation to technology of semi-continuous crystallization three major stages are excluded from process:

1. Concentrating of a boiling product to a grain of crystals.
2. Formation of the centers of crystallization.
3. Growth of crystals to the size about 0,2÷0,3 mm.

In work possible options of implementation of technology of semi-continuous crystallization which are as follows are shown [9]:

1. Receiving sugar on a crystal basis same massecuite.
2. Crystallization with use artificially prepared "seed" massecuite by mixing of crystals with a liquid phase.
3. Crystallization with application, so-called "mother liquor".
4. Crystallization of sugar with transfer of a stage of liquor concentration to a labile state on a separate step of evaporation.

5. Crystallization with selection massecuite the previous or subsequent steps with their use as a crystal basis.
6. Other options on which the staff of "Technology of Sugary, Subtropical and Food-flavoring Products" department of MGUPP works now are possible.

Data of a machine experiment of isobaric vaporizing crystallization of sucrose of all product department of the sugar enterprise working in the regime of semi-continuous crystallization in comparison with standard technology of periodic crystallization are presented in (Table 1).

Feature of this version of the developed technology is that the proved technology is implemented at the same time at all steps of crystallization of sucrose, since the first step when instead of syrup use a crystal basis in the form of "seed" massecuite.

"Seed" (artificial) massecuite represents mix of crystals of sugar white, yellow or brown sugar and syrup. He is prepared in certain ratios of crystals of sugar and syrup of the set concentration, the size of crystals, distance between them and supersaturation of intercrystal solution. He pays off according to the special program developed for these purposes at our department.

Researched of Technology	**Measured indicators**											
	CVy3	DBm3	CVm3	Mcd3	Mkrob3	Mvi1	Mvi3	dkp	muy	mum	tyв	Nzo
Massecuite I (Standard)	0,92	0,768	0,832	64923	31433	4053 24924	20871	0,00040	11,22	0,433	3,10	3,15e11
Massecuite I (Proposed)	0,93	0,756	0,832	57939	34998	 17939	17939	0,00015	14,2	0,423	0,85	6,57e12
Massecuite II (Standard)	0,93	0,664	0,871	65846	27573	4497 25847	21355	0,00038	28,97	1,931	4,90	3,15e11
Massecuite II (Proposed)	0,94	0,597	0,874	46098	31548	 16098	16098	0,00021	66,68	1,913	3,49	2,19e12
Massecuite III (Standard)	0,94	0,600	0,896	66769	25403	4850 26767	21920	0,00037	91,02	8,369	6,19	3,15e11
Massecuite III (Proposed)	0,96	0,520	0,926	44649	27772	 15165	15165	0,00029	2,896	3,238	2,84	7,3e11
Standard:				197539	84409	77540					14,19	
Proposed:				148685	94319	39201					7,18	

Table 1: Crystallization massecuite results using the "seed" massecuite (Db = 0.83 Cv = 0.907, Pz = 1.1, dkp = 0, 0001m) in the selection of 1/3 (20 t) volume mass of massecuite on subsequent stages for 60 ton

	Measured indicators

Researched of Technology	CVy3	DBm3	CVm3	Mcd3	Mkrob3	Mvi1	Mvi3	dkp	muy	mum	Tyв	Nzo
Massecuite I (Standard)	0,92	0,7678	0,832	64923	31433	4053 24924	20871	0,00040	11,22	0,433	3,104	3,15e+11
Massecuite I (Proposed)	0,93	0,7517	0,8332	64915	34821	19916,8	19917	0,000165	15,00	0,439	1,09	4,93e+12
Massecuite II (Standard)	0,93	0,6639	0,8705	65846	27573	4497 25847	21350	0,000381	28,97	1,931	4,896	3,15e+11
Massecuite II (Proposed)	0,94	0,5965	0,8737	46098	31489	16097	16097	0,000230	64,63	1,937	3,683	1,6e+12
Massecuite III (Standard)	0,94	0,5997	0,896	66769	25403	4850 26770	21920	0,000371	91,02	8,369	6,185	3,15e+11
Massecuite III (Proposed)	0,96	0,5199	0,9256	44649	27753	15145	15145	0,000318	3,26	2,897	3,219	5,47e+11
Standard:				197539	84409	77540		0,00115			14,19	
Proposed:				155662	94062	41160		0,00071			7,99	

Table 2: Crystallization massecuite results using the "seed" massecuite (Db = 0.83 Cv = 0.907, Pz = 1.1, dkp = 0, 0001m) in the selection of 1/4 (15 ton) volume mass of massecuite on subsequent stages for 60 ton

After set "seed" massecuite growth of crystals in a metastable zone at continuous supply of syrup before achievement of limit begins massecuite in the vacuum apparatus then 1/4 parts ready massecuite in the vacuum apparatus of the second step of crystallization make selection. Remained 3/4 parts massecuite lower in the reception mixer or continue boiling in the same vacuum apparatus up to the full volume.

On the selected 1/4 part the first massecuite boiling the second massecuite, giving the corresponding runoff formed after centrifugation massecuite the first step. At achievement massecuite the second step of readiness for descent select 1/4part ready massecuite again and direct to a boiling massecuite to the third step. Remained 3/4 parts massecuite the second step, as well as

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in a case with massecuite the first step, lower in the reception mixer or continue boiling to the full volume.

At the second step which is selected 1/4 parts massecuite boiling massecuite the third step, giving the corresponding runoff formed after centrifugation massecuite the second step. At achievement massecuite to the third step of readiness it is directed to the cascade of crystallizers for cooling.

Technology of semi-continuous isobaric evaporative crystallization of sucrose, to some extent it is possible to compare to technology of continuous crystallization of sucrose as crystal mass consistently flows from the apparatus of the first step in the second, and then in the third step of crystallization and, finally, comes to the cascade of crystallizers on cooling. Thus, the finished cycle of Journal of Advancements in Food Technology
isobaric evaporative crystallization of all producted massecuite on a crystal basis with all positive effects which can be tracked is received, analyzing data of results of a machine experiment (Table 1). For comparison results of modeling of process of isobaric evaporative crystallization of standard technology of periodic crystallization of all producted massecuite are given.

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From the given results it is visible that for massecuite on a crystal basis in comparison with standard technology of boiling:

1. The steam consumption on 49,4 % is cut.
2. The mass of the added syrup and runoff decreases by 24,7 %.
3. Time for 49,4 % is reduced.
4. The mass of the taken crystallized sugar for 10,6 % increases.
5. "Productivity" of crystallization department for 54,7 % increases.

(We will notice that "productivity" paid off how the relation of lump of the taken crystallized sugar I, II, III to the general time of crystallization of these massecuite).

Undoubtedly, for creators (designers) of the new equipment and practicians the research of influence of originally gained mass "seed" massecuite on process of isobaric evaporative crystallization is of interest to the vacuum apparatus of the same volume of 60 tons. Have for this purpose conducted an additional research of influence of this factor, modeling process of a boiling massecuite I, II, III crystallization on the standard and offered way with a constriction massecuite in quantity (k_{otb} = 1/4, 15 tons) with indicators $Pz=0,83$ $CV_z=0,907$ $\Pi_z=1,1$ and the size of crystals 0,0001m). Comparative results of a research are represented in (Table 3). From the above-stated results it is visible that for massecuite on a crystal basis at input of "seed" mass in quantity of K_{otb} = 1/4, 15 t, in comparison with a standard boiling massecuite:

1. The steam consumption on 46,9 % is cut.
2. The mass of the added syrup decreases by a boiling for 21,2 %.

3. Crystallization time for 43,7 % is reduced.
4. The mass of the taken crystallized sugar for 10,3 % increases.
5. "Productivity" of crystallization department for 49,5 % increases.

Параметры исследуемой технологии	Изменения в ходе исследования предлагаемой технологии с перетяжкой утфелей относительно типовой технологии уваривания, %	
	с kotb=1/3 (20 тонн)	с kotb=1/4 (15 тонн)
Mvi	- 49,4 %	- 46,9 %
Mcd3	- 24,7 %	- 21,2 %
t ув.	- 49,4 %	- 43,4 %
Mkrob3	**+ 10,6 %**	**+ 10,3 %**
Производительность	+54,7 %	+49,5 %

(where "-" it was reduced by %; "+" has increased by %)

Table 3: Results of studying of two options of technologies

Analyzing the results received during the machine experiment with selection of Kotb = 1/4 and 1/3 some advantage of technology of semi-continuous crystallization with selection with kotb=1/3 (20 tons) in comparison with kotb=1/4 (15 tons) is observed.

Conclusion

The modeling system developed information allows not only to determine duration of processes of isobaric evaporative crystallization of sucrose considering composition of impurity of various regions and zones of a beet-growing, but also influence of number, the size, a form of crystals, a consumption of steam and amount of the evaporated water. She can be recommended for justification, design and creation of new technologies of crystallization of carbohydrate-containing substances.

Especially it is necessary to emphasize that this system with success can be applied in scientific research, to justification of production schedules and forecasting. For a number of years, the developed system with success is used in MGUPP within educational process and for professional development of workers of the industry of all levels of readiness, including mass working professions and technical personnel of the enterprise. At the corresponding completion this system is applicable for other food branches of the national economy such as starch, confectionery and not only for these branches, application of modern control methods will be important at the same time.

Designation of Parameters

Mco – the initial mass of the loaded syrup, kg;
CVcd – solids of the added syrup, fraction;
DBcd – high quality of the added syrup, fraction; Db – high quality of seed mass, a fraction;
Myz– the set mass massecuite, kg;
My3 – final mass massecuite, kg;
CVyz – the set maintenance of SV massecuite, fraction;
CVy3 – the final maintenance of SV massecuite, fraction;
CVm3 – solids of interstitial solution, fraction;
Cv – concentration of seedmass, fraction;
Pz – coefficient of supersaturation, unit;

Mcd3 – the mass of the added syrup or runoff, kg;
Mkrob3 – the mass of the taken crystallized sugar, kg;
Mvi1 – the mass of the evaporated water, kg; Mvi3 – the mass of the evaporated water, kg; dkp – the size of a crystal of sucrose, m; muy – viscosity massecuite, Pa*s; mum – viscosity of interstitial solution, Pa*s; tuv – temperature of a boiling, °C;
Mvi ob– the lump of the evaporated water, kg; t ув ob – the general time of a boiling, h; kotb – selection coefficient massecuite, fraction;

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