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MATHEMATICAL MODELING OF THE PROCESS EVAPORATION OF MULBERRY FRUITS JUICE

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When evaporating the juice of mulberry fruits, a differential equation was obtained for changing the amount of liquid over time, expressed as a material balance, converted to the liquid level in the separator of the evaporator, an expression for the density of the liquid, its flow rates at the inlet and outlet of the apparatus, the differential equation for changing the temperature of the liquid over time. Using the reference data of the state of water and steam, equations for the temperature, enthalpy of liquid and dry steam are obtained. A system of equations has been obtained - a mathematical model of the dynamics of the process of liquid evaporation in a single-vessel vacuum evaporator. Using the SIMULINK part of the MATLAB program, a computer model for solving equations was compiled. Some results of studies of the evaporation of mulberry juice on a five-case vacuum evaporator are given, the optimal number of stages of the complex is found.

Since the calculation of the process of evaporation of water vapor is associated with the thermodynamic parameters of the state of water, it is necessary to obtain equations for the dependence of the boiling point of water, the heat of vaporization of water, the enthalpy of steam, the enthalpy of water on pressure. Experimental data have been obtained for a long time, they are successfully used, however, there are no uniform empirical equations used by all researchers.

Using the capabilities of the MATLAB program, by statistical processing of tabular data, we obtain empirical equations in the form of polynomials for the state of water and water vapor, describing the real picture with an accuracy of 98% or more.

Keywords: heat balance, enthalpy, material balance, concentrate, computer model.

ПРОЦЕСТІ МАТЕМАТИКАЛЫҚ МОДЕЛЬДЕУ ТУТ ЖЕМІСІ ШЫРЫНЫН БУЛАНДЫРУ

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Тұт жемістерінің шырынын булану кезінде сұйықтық мөлшерін уақыт бойынша өзгертуге дифференциалдық теңдеу алынды, материалды баланс түрінде өрнектеледі, буландырғыштың сепараторындағы сұйықтық деңгейіне түрленеді, сұйықтықтың тығыздығының өрнегі. аппараттың кіріс және шығысындағы оның шығыны, сұйықтық температурасын уақыт бойынша өзгертуге арналған дифференциалдық теңдеу. Су мен бу күйінің анықтамалық мәліметтерін пайдалана отырып, температура, сұйық және құрғақ бу энтальпиясының теңдеулері алынады. Теңдеулер жүйесі алынды - бір ыдысты вакуумды буландырғыштағы сұйықтың булану процесінің динамикасының математикалық моделі. MATLAB бағдарламасының SIMULINK бөлігі арқылы теңдеулерді шешудің компьютерлік моделі құрастырылды. Бес корпусты вакуумды буландырғышта тұт шырынын булану зерттеулерінің кейбір нәтижелері келтірілген, кешеннің оңтайлы сатыларының саны табылған.

Су буының булану процесін есептеу су күйінің термодинамикалық параметрлерімен байланысты болғандықтан, судың қайнау температурасына, судың булану жылуына, бу энтальпиясына тәуелділік теңдеулерін алу қажет. , қысымдағы судың энтальпиясы. Эксперименттік мәліметтер ұзақ уақыт бойы алынған, олар сәтті қолданылуда, бірақ барлық зерттеушілер қолданатын біркелкі эмпирикалық теңдеулер жоқ.

MATLAB бағдарламасының мүмкіндіктерін пайдалана отырып, кестелік мәліметтерді статистикалық өңдеу арқылы нақты суретті 98% және одан жоғары дәлдікпен сипаттайтын су мен су буының күйі үшін көпмүшелік түріндегі эмпирикалық теңдеулерді аламыз.

Түйінді сөздер: жылу балансы, энтальпия, материал балансы, концентрат, компьютерлік модель.

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССА ВЫПАРИВАНИЯ СОКА ПЛОДОВ ТУТОВНИКА

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При выпаривании сока плодов тутовника получено дифференциальное уравнение изменения количества жидкости по времени, выраженное в виде материального баланса, преобразовано до уровня жидкости в сепараторе выпарного аппарата, выражение для плотности жидкости, её расходов на входе и выходе аппарата, дифференциальное уравнение изменения температуры жидкости по времени. Воспользуясь справочными данными состояния воды и водяного пара, получены уравнения для температуры, энтальпии жидкости и сухого пара. Получена система уравнений - математическая модель динамики процесса выпаривания жидкости в однокорпусном вакуум-выпарном аппарате. Используя часть SIMULINK программы MATLAB составлена компьютерная модель решения уравнений. Приведены некоторые результаты исследований выпаривания тутового сока на пятикорпусной вакуум-выпарной установке, найдено оптимальное количество ступеней комплекса.

Поскольку расчет процесса выпаривания паров воды связан с термодинамическими параметрами состояния воды необходимо получить уравнения зависимости температуры кипения воды, теплоты парообразования воды, энтальпии пара, энтальпии воды от давления. Экспериментальные данные получены давно, успешно используются, однако единых эмпири-ческих уравнений, используемых всеми исследователями не существуют.

Воспользуясь возможностями программы MATLAB, путем статистической обработки табличных данных, получим эмпирические уравнения в виде полиномов для состояния воды и водяного пара, описывающие реальную картину с точностью 98% и более.

Ключевые слова: тепловой баланс, энтальпия, материальный баланс, концентрат, компьютерная модель.

Introduction. A literary study of the process of evaporation of food solutions has shown the feasibility of their evaporation in multi-vessel vacuum evaporators. We have to solve the problem of modeling the process of evaporating clarified mulberry juice and choosing the number of plant buildings on the basis of computer research. To this end, we simulate the process of evaporating water from the composition of the juice in a single-vessel vacuum evaporator. Further, it is possible to carry out a gradual transition to two-, three-, four-, and five-case installations. Let us denote the input and output parameters of the process as follows [1, 2, 3, 5].

It is known that when modeling one stage of any process, the hydrodynamic structure of the flow is taken in the form of ideal mixing or ideal displacement. When compiling our model, the simulation object is taken as one cell of ideal mixing. At the next stage, when moving from one body to the entire installation, each body of the apparatus is taken as a separate cell of ideal mixing. They are combined accordingly and a cell model of countercurrent flows is adopted [4, 6, 7, 8, 9].

Methods and materials. The change in the amount of liquid over time is expressed by the equations of material balance, i.e. it depends on the difference between the flow rates of the incoming and outgoing liquids and the evaporated moisture [6, 9, 10,11]

$$\frac{dm}{d\tau} = G_s - G_f - G_2 \tag{1}$$

where m is the amount of liquid mixture in the body of the apparatus, [kg]; Gn - flow rate of juice entering the apparatus, G_k - flow rate of the liquid mixture leaving through the bottom of the apparatus, [kg / s]; G_2 is the flow rate of the evaporating liquid (secondary steam), [kg/s].

To express mass in terms of volume and density, we use the following equations:

$$m = V\rho = SH\rho \tag{2}$$

where V is the volume of liquid in the apparatus, [m^3]; ρ is the liquid density, [kg/m^3]; S is the cross-sectional area of the apparatus, [m^2];. H is the liquid level in the apparatus, [m];

Using formula (2), for the capacity of the body of the apparatus, the change in the liquid level in the apparatus is expressed by the following differential equation:

$$\frac{dH_f}{d\tau} = \frac{1}{S\rho}[G_s - G_f - G_2] \tag{3}$$

where H_s is the current liquid level in the separator of the evaporator, [m]; ρ is the density of the liquid mixture, [kg/m^3].

The value of the density of the liquid mixture is within the density of pure water and solids dissolved in water. Density can be calculated using the formula below

$$\rho = \rho_{fr} \cdot a_f + 1000 \cdot (1 - a_f) \tag{4}$$

P_{fr} - is the density of the pure product, [kg/m^3]; a_f - current concentration of solids in juice, [kg/kg]; 1000 - pure water density, [kg/m^3].

The flow rate of the liquid flowing from the apparatus has a functional dependence on the height of the liquid in the apparatus, i.e. the greater the hydrostatic pressure, the greater the fluid flow. If we consider this dependence in the simplest case to be proportional, then the equation for the flow rate takes the following form:

$$G_f = K_1 H_f \tag{5}$$

In fact, this dependence is not proportional, but has a more complex character. In addition, equation (3-4) does not take into account the viscosity of the evaporated liquid.

The flow rate of water vapor released from the mixture in one body of the apparatus is determined from the basic equation of the heat exchange process. The driving force of the process is the temperature difference.

$$G_2 = k_2(t_f - t^*) \tag{6}$$

where t* is the boiling point of the liquid in the apparatus case under vacuum (equilibrium temperature), [ºC].

Having determined the flow rate of the liquid entering the apparatus, the amount of solids entering together with the liquid, the flow rate of the liquid flowing from the apparatus, the flow rate of deaf steam heating to evaporate moisture, the flow rate of evaporated moisture, we can obtain an equation for determining the concentration of solids in the flowing liquid.

$$\frac{da_f}{d\tau} = \frac{1}{SH\rho}[G_s a_s - G_f a_f] \tag{7}$$

Using the heat balance, one can obtain a differential expression for the change in liquid temperature over time

$$\frac{da_f}{d\tau} = \frac{1}{SH\rho c}[G_s c t_s - G_f c t_f - G_2 i_{ss} + D i_s - D i_k] \tag{8}$$

where c is the heat capacity of the liquid mixture, [kJ/(kg ºC)]; i_s, i_k - enthalpy of steam supplied to the annular space of the apparatus and condensate, [kJ/(kg ºC)]; Ds, Dk is the flow rate of blind steam supplied to the annular space and condensate [kg/s].

Since the calculation of the process of evaporation of water vapor is associated with the thermodynamic parameters of the state of water, it is necessary to obtain equations for the dependence of the boiling point of water, the heat of vaporization of water, the enthalpy of steam, the enthalpy of water on pressure. Experimental data have been obtained for a long time, they are successfully used, however, there are no uniform empirical equations used by all researchers.

Using the capabilities of the MATLAB program, by statistical processing of the tabular data given in, we obtain empirical equations in the form of polynomials for the state of water and steam, describing the real picture with an accuracy of 98% or more.

The empirical dependence of the boiling point of a liquid on the pressure in the apparatus, obtained by processing tabular data, has the form:

$$t^* = -0.00059 \cdot p2 + 0.48 \cdot p + 51 \tag{9}$$

The empirical dependence of the heat of vaporization of water on the pressure in the apparatus, obtained by processing tabular data, has the form:

$$i' = -2.5 \cdot p2 + 2000 \cdot p + 210000 \tag{10}$$

The empirical dependence of the liquid enthalpy on the pressure in the apparatus, obtained by processing tabular data, has the form:

$$r = 1.4 \cdot p2 - 1200 \cdot p + 2400000 \tag{11}$$

The empirical dependence of the enthalpy of dry saturated steam on the pressure in the apparatus, obtained by processing tabular data, has the form:

$$i'' = -p2 + 800 \cdot p + 2600000 \tag{12}$$

Using the capabilities of the MATLAB program, we obtained empirical equations in the form of polynomials for the state of water and water vapor by statistical processing of tabular data. Such polynomials describe the real picture with an accuracy of 99.9% or more. These empirical equations are also included in the mathematical model of the mulberry juice evaporation process.

The system of equations (1-12) is a mathematical model of the dynamics of the liquid evaporation process in a single-vessel vacuum apparatus. Using the SIMULINK part of the MATLAB program, you can create a computer model for solving equations.

Having studied the process of moisture distillation in one-, two-, three-, four-, and five-case evaporator complexes, it is possible to compile a mathematical model of the economic indicators of the process.

The above equations are combined into a general system of equations (1-12), which is a mathematical description of the current single-vessel continuous vacuum evaporator plant. The mathematical model includes the equations of material and heat balances in the MVVE, as well as the empirical equations for the dependences of the boiling point, the heat of vaporization and the enthalpy of water, as well as the enthalpy of steam on the pressure in the apparatus. The problem is reduced to the study of the dynamic characteristics of changes in concentrations, juice temperature and the height of the liquid layer in the separator of a vacuum evaporator on a mathematical model [11, 12, 13].

The study of the mathematical model of the process of evaporation of the volatile component in the range of variations of the input parameters of the process and the analysis of the results obtained allows us to judge the dynamics of the evaporation process in a single-vessel apparatus. By accepting the output parameters of the process as the input of the subsequent vessel, it is possible to calculate the installation with any number of vessels.

$$\begin{cases} \dfrac{dH_f}{d\tau} = \dfrac{1}{S\rho}[G_s - G_f - G_2] \\ G_f = k_1 H_f \\ G_2 = k_2(t_f - t^*) \\ \dfrac{da_f}{d\tau} = \dfrac{1}{SH\rho}[G_s a_s - G_f a_f] \\ \dfrac{dt_s}{d\tau} = \dfrac{1}{SH\rho c}[G_s c t_s - G_f c t_f - C_2 i_{ss} + D i_s - D i_k] \\ \rho = f(a) = \rho_{fr} \cdot a_f + 1000 \cdot (1 - a_f) \\ m = V\rho = SH\rho \\ t^* = -0.00059 \cdot p2 + 0.48 \cdot p + 51 \\ i' = -2.5 \cdot p2 + 2000 \cdot p + 210000 \\ r = 1.4 \cdot p2 - 1200 \cdot p + 2400000 \\ i'' = -p2 + 800 \cdot p + 2600000 \end{cases} \tag{1-12}$$

To solve a system of equations, it is necessary to integrate its differential equations with respect to time. For example, in order to determine the height of the liquid column H from the equation, you must perform the following calculation:

$$H = \int_0^{\tau} \frac{dH}{d\tau} \tag{13}$$

This method is also used in solving equations (3-7) and (3-8), thereby determining the concentration of solids in the outflowing liquid ak and the temperature of the liquid mixture.

Results and discussion. The initial temperature of mulberry fruits at the entrance to the apparatus should not exceed tn=90°C. Residual pressure in the first building of the multi-case vacuum evaporator complex plant P = 61 kPa, in the second - 31 kPa, in the third and fourth - 8 kPa and the fifth - 5 kPa each. The flow rates of blind steam supplied to the steam jacket of each of the evaporators are predetermined and are, respectively, D(1)=0.93 kg/s;

- change in the concentration of solids at the outlet of the apparatus over time - the dynamics of the process (Fig. 1). Incoming juice concentration ar =22%. Within 4000 s, it reaches its maximum value and equals 48%. No further increase in concentration in the first vessel of the vacuum evaporator is observed. The conclusion is that in the first building of the vacuum evaporator, the residence time of the juice should be no more than 4000 s;

- change in the temperature of the juice at the exit - the dynamics of the process (Fig. 2). The temperature of the juice entering the apparatus decreases due to the evaporation of moisture. Within 70 s it reaches 87.8^{0}C, i.e. cooled by 2.2 ºC; Juice is supplied to the first building of the multi-vessel vacuum evaporator at the maximum attainable temperature (about 90 ºC) so that excessive cooling of the juice does not occur, because there are further stages of evaporation. Temperature losses are associated with the evaporation of moisture, they are replenished by heating the body of the apparatus with deaf steam;

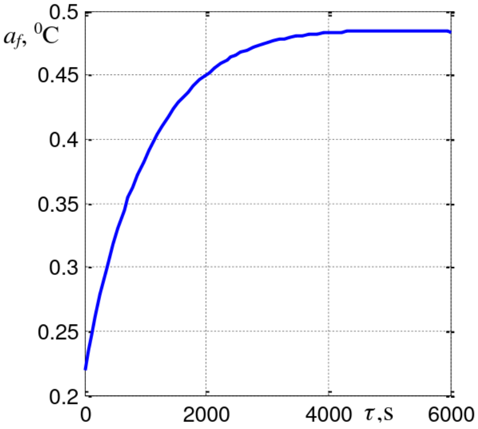

Fig.1 - Graph of the change in the concentration of solids at the outlet over time

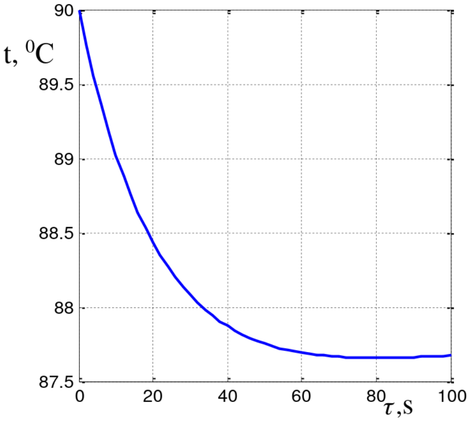

Fig.2 - Graph of the temperature of the liquid at the outlet over time

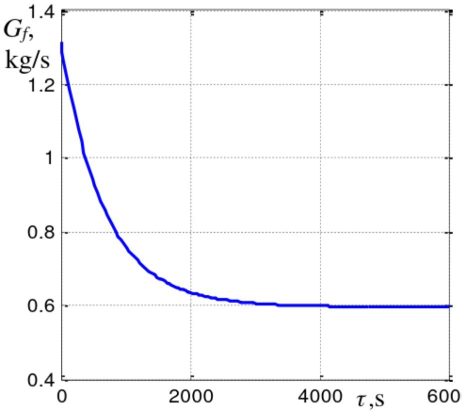

Fig.3 - Graph of change in fluid

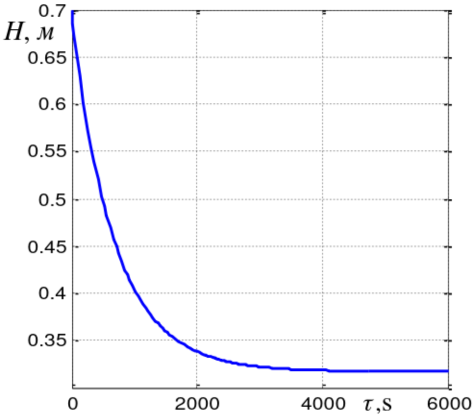

Fig.4 - Graph of the dependence of the height of the liquid in the apparatus on time

- change in juice consumption at the outlet of the evaporator over time - the dynamics of the process (Fig. 3). The flow rate of concentrated juice at the outlet of the apparatus must vary depending on the flow rate at the inlet of the evaporator and the concentration at the inlet and outlet, or the flow rate of the secondary steam evaporated from the evaporator. In the analyzed case, the liquid flow after a period of time of 3000 s decreases from 1,39 kg/s to 0,6 kg/s, then a constant (steady) mode of juice evaporation is established. In the case under study, the transition period is 4000 s. The curve is quadratic, the period of flow change from 1,39 [kg/s] to 0,6 [kg/s] is only 2000 s, but the decrease in flow lasts up to 4000 s;

- change in the height of the liquid in the apparatus H [m] over time, [s] (Fig. 4). The height of the liquid column in the apparatus is necessary to maintain the flow of processed juice through the lower branch pipe of the apparatus. In the case of an increase in height, the flow through the nozzle increases and vice versa, with a decrease in height, the height of the liquid column decreases [14, 15, 16].

The logical conclusion of mathematical modeling and the research procedure for the process of multi-vessel juice evaporation should be aimed at studying the economic indicators of the process. Below is a program for studying the process of concentrating in an VEC.

Mathematical model for the study of economic indicators of the process of evaporating juices in VEC

```
function Zevp = Zv ( Gk )
format short
Cva = 225000000;
En = 0.15;
Gk = 0.3
tau_sez = 2400;
A = Cva * En / ( Gk * tau_sez * 3600 )
Nmax = 5.5;
Ce = 64.2;
Zvak = Nmax * Ce / ( 3600 * Gk )
Cn = 420;
D = 0.93;
Zn = Cn * D / ( 1000 * Gk )
Zv = Cc*Gv
Zvip = A + Zn + Zvak +Zv
```

Figure 5 shows the dependence of the change in costs per unit of production [sum/kg] on the final productivity of the VEC Gk at Gn = 1,39 kg/s.

The program for displaying research results in the form of a graphical dependence

```
Gf = [0.2 0.25 0.3 0.35 0.4 0.45 0.5];
for i=1:7
Zvip (i) = Zv (Gk (i ));
 End
Plot (Gk, Zvip, '-o')
grid on
xlabel ('Gf, [kg/s]')
ylabel ('Zv, [sum/kg]')
Zevp = [  ];
```

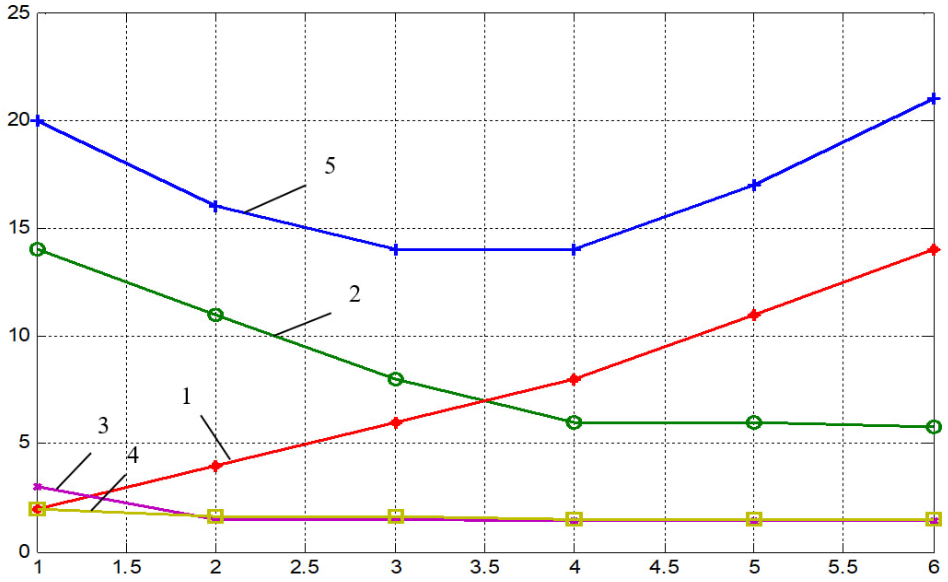

Fig.5 - Dependence of costs per unit of evaporated juice on the number of IDP cases
Number of devices VEC, ***n***

1-cost of apparatuses, 2-costs for heating apparatuses with deaf steam, 3-costs for creating a vacuum in the VEC, 4-costs for condensing secondary vapors with cold water, 5-curve for the sum of all costs for evaporation in the VEC.

In the range of final juice consumption Gevp from 0.2 to 0.5 kg/s, the cost of producing a unit of production decreases from 22 to 8.8 kg/s. This indicates that the greater the productivity of the apparatus, the lower the cost of producing a unit of output. In the range of our research, with an increase in productivity by 0.5/0.2=2.5 times, the cost per unit of output also decreases by 22/8.8 = 2.5 times. This suggests that the cost change curve Zv for productivity Gf is symmetrically proportional. The optimal value of costs per unit of production is selected based on the possibility of choosing the input parameters of the process and the design features of the devices of the VEC complex.

At the same time, from the curve of the total cost values for the production of silkworm raft concentrate (curve 5), it can be seen that the optimal number of VEC devices lies in the range of 3-4.

Conclusion. A mathematical model of the process of evaporating clarified mulberry juice in a single-vessel vacuum evaporator has been obtained, a way has been established for using the obtained mathematical model in multi-vessel vacuum evaporators, thereby mathematical modeling of the process of obtaining concentrates of fruit, berry and vegetable juices in the centrifugation system forces) - evaporation. The adequacy of the mathematical model of the system to the real process has been established on the example of concentrating the juice of mulberry fruits. The results of model studies are obtained and analyzed.

Mathematical modeling of the juice evaporation process allows you to determine the number of cases that provides the minimum energy costs for juice concentration, which is 3-4. The simulation results were used to compile a mathematical description of economic indicators and further optimize the evaporation process.

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