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Mathematical Modeling of the Process of Preliminary Distillation of Vegetable Oil

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ABSTRACT: This article presents a mathematical model of a two-stage primary distillation process, and based on this model, a computer simulation has been developed. The distillation process was carried out using 4-meter-high equipment. Samples were taken at every 0.5 meters along the height, and the experimental results were analyzed. Additionally, the formation of a micellar film in the process and its thickness in relation to concentration were studied. According to the results obtained through the mathematical model, it was determined that the thinner the miscella film, the shorter the duration of the process and the higher its efficiency. Furthermore, the experiments analyzed the relationship between process duration and miscella concentration (12%, 15%, and 18%) under different working temperatures.

I. INTRODUCTION.

In recent years, the volume of food production in the world has been increasing. The volume of vegetable oil production was 625 million tons in 2022, 640 million tons in 2023, and 670 million tons in 2024. In January 2024, 7.4 thousand tons of vegetable oil were produced, while in January 2023 this figure was 6.5 thousand tons. This data means that the production of vegetable oils in 2024 increased significantly. In connection with the growth of the population, the demand for vegetable oil production capacity is also increasing. In order to supply the population with full-fledged high-quality vegetable oil, great attention is paid to scientific research aimed at improving processes, equipment and technologies for the production and processing of vegetable oils, and increasing energy efficiency based on modern achievements of science and technology. At the same time, it is of particular importance to improve existing technologies for the production of vegetable oils that meet modern standards at oil and fat enterprises in our republic, to fully utilize the working capacity of technological equipment, and to create new modern designs of devices[1,2,3].

II. MATERIALS AND METHODS.

In vertical tube evaporators, including the 120TD line's primary distiller, the vapor-liquid phase is the internal part of the boiling tubes. Here, as the liquid moves upward, several elementary processes can occur[4,5].

Initially, the miscella is heated to boiling temperature, where the mistletoe located near the wall heats up faster and small bubbles of steam are formed. A strong bubbling boil begins when the miscella reaches its boiling point[8,9]. If the process occurs at a high speed with the liquid moving further upwards, then the vapor bubbles coalesce and form a vapor stream. The mechanism of the process for the conditions existing during the primary distillation process was studied in the research work[6,7].

To determine the critical concentration, we find the maximum speed of the bubble using the following formula

$$\omega_n = \sqrt{\frac{d(\rho_j - \rho_n)g}{2\rho_j}} \tag{1}$$

In this: ρ_j, ρ_n – miscella and vapor density as appropriate; d – pipe inner diameter; g – free fall acceleration;

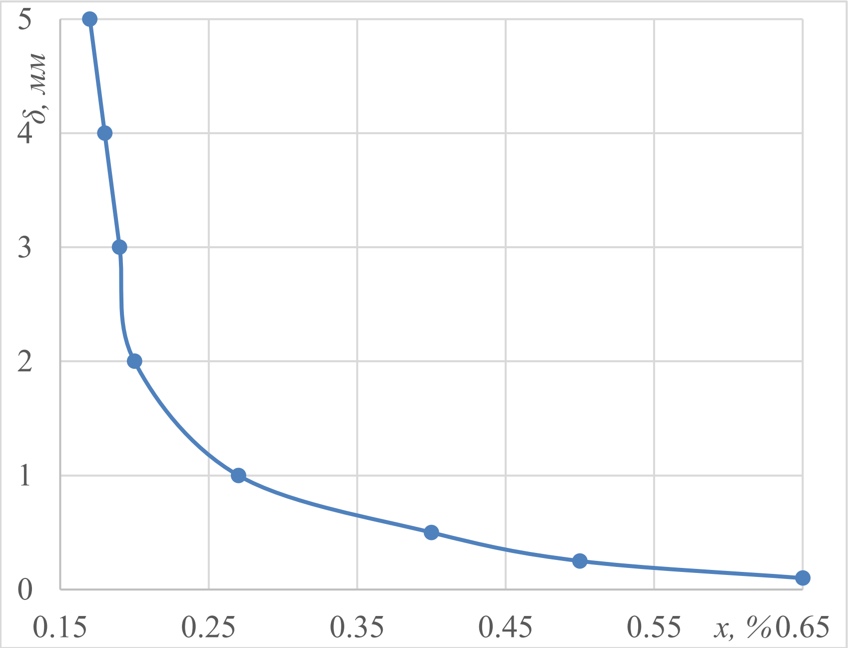

Fig.1 Dependence of the film thickness change on the concentration of miscella.

The amount of evaporated solvent is taken into account

$$G_{ur} = G_0(1 - \frac{a_n}{a}) \tag{2}$$

In this: G_{ur} - amount of evaporated solvent; G_0 - the amount of solution at the entrance to the pipe; a_n- initial concentration of miscella.

The linear velocity of steam flow is expressed as follows:

$$\omega_{para} = \frac{4G(a-a_n)}{\pi d^2 a \rho_n} \tag{3}$$

An equation representing the change in film thickness as a function of miscella concentration and initial consumption was obtained:

$$\frac{\lambda_n \rho_n G_0^2}{2\pi^2 a^2 (d-2\delta)} (\frac{4(a-a_n)}{\rho_n (d-2\delta)^2} - \frac{a_n}{\rho_j (d-\delta)\delta})^2 - \rho_j g - \lambda_j \frac{G_0^2 a_n^2}{\pi^2 a^2 \rho_j (d-\delta)\delta} = 0 \tag{4}$$

In this: G_0- initial fluid consumption, d- internal diameter of the boiling pipe, a_n- initial concentration.

Further upward movement of the liquid can occur by breaking the existing liquid film. Thus, the boiling of the liquid passes from the thin film layer regime to the vapor ring regime, which is undesirable because it leads to a sharp decrease in the heat transfer coefficient from the wall to the liquid.

When constructing a mathematical description of tube vaporizers, the vapor-liquid phase is usually divided into two parts: the liquid heating part and the boiling part.

For the heating part, a mathematical model of a tubular heat exchanger can be used.

In this case, the micella with an initial temperature of t_n is heated to the boiling temperature of t_k, in which case the hydrodynamic structure is assumed to be a fully squeezed model. In this case, the heat balance equation for the elementary zone is given by:

$$\frac{d(mct)}{d\tau} = G(c_2 t_2 - c_1 t_1)j + \alpha_2 dF(t_d - t_j)j \tag{5}$$

In this: c_1 - fluid heat capacity entering the elementary zone; c_2 - heat capacity of the fluid leaving the elemental zone; t_1 – initial fluid temperature; t_2 - liquid outlet temperature; ΔF - elementary zone heating surface; t_d - wall temperature; t_j - liquid temperature; G - fluid consumption.

It can be seen that the mathematical description of the vapor-liquid phase is linearly related to the inverse concentration (1⁄x) if the miscella boiling point is linearly related to the same quantity.

Considering that the first primary distiller of the three-stage distillation operates at atmospheric pressure and the miscella concentration increases from 15% to 60÷65%, the boiling point of cottonseed oil miscella is described by the equation by processing the experimental data:

$$t_{kip} = 93 - \frac{283}{a} \tag{6}$$

For this operating mode of the primary distiller, the cross-section of the boiling liquid is equal to 1/3 of the total cross-section of the vapor-liquid phase. In this case, the dynamics of the process in the first primary distiller is described by a simplified equation:

$$\frac{\partial(\frac{a_n}{a})}{\partial\tau} = 0.43\frac{\partial(\frac{a_n}{a})}{\partial h} - 0.000175(t_d - 93 + \frac{283}{a}) \tag{7}$$

This equation was calculated on a computer using the Matlab Simulink program. In this case, it was replaced by the height differential (Δh). A similar model for a four-cell model (H = 4; Δh - 0.5). The solution of the model for the four-cell model with a sharp wall temperature fluctuation (t_st=120->110°C) is shown in figure 1; the transition curves are obtained separately for each cell. The duration of the transition increases with the height of the boiling tube. The output curve corresponding to the height H = 4 m differs from the transition of the first-order aperiodic link. Using mathematical description (7), it is possible to obtain various combinations of a multi-cell model with a variable height of the elementary zone, which ensures the distribution of the liquid over the cross section of the boiling tube, as well as the heat transfer coefficient over the height of the boiling tube.

Using this mathematical model, the operation of the first-stage primary distiller of cottonseed oil miscella was studied. In this case, the following technological parameter values were adopted under the operating conditions of the primary distiller: heating steam pressure in the line 0.8 MPa; heating steam consumption 0.2÷0.6 kg/s; throughput coefficient k=0.3÷0.9.

The initial miscella concentration is 15%, the initial flow rate is 1.075 kg/s; the initial miscella temperature is assumed to be 65 °C.

The mathematical model of the primary distiller corresponding to this situation is represented by the following system of equations:

$$\begin{cases} \frac{\partial\left(\frac{x_n}{x}\right)}{\partial\tau} = 0.43\frac{\partial\left(\frac{x_n}{x}\right)}{\partial h} - 0000175\left(t_{st} - 93 + \frac{283}{x}\right) \\ \frac{dt_k}{d\tau} = 0.018\left(D_p - D_k\right) \\ D_k = 0.013\left(t_k - t_{jsr}\right) \\ D_P = K0.68 \\ \frac{dx_n}{d\tau} = 0.046(x_{vxn} - x_0) \\ \frac{dx_{vix}}{d\tau} = 0.01(x - x_{vix}) \end{cases} \tag{8}$$

Here, a corresponding simplification of the heating chamber model was performed by making appropriate substitutions.

III. RESULTS.

This mathematical model was implemented in the Matlab Silulink package. The change in miscella concentration over time with different initial concentrations was calculated using the mathematical model, and the transition curve is shown in Figure 2.

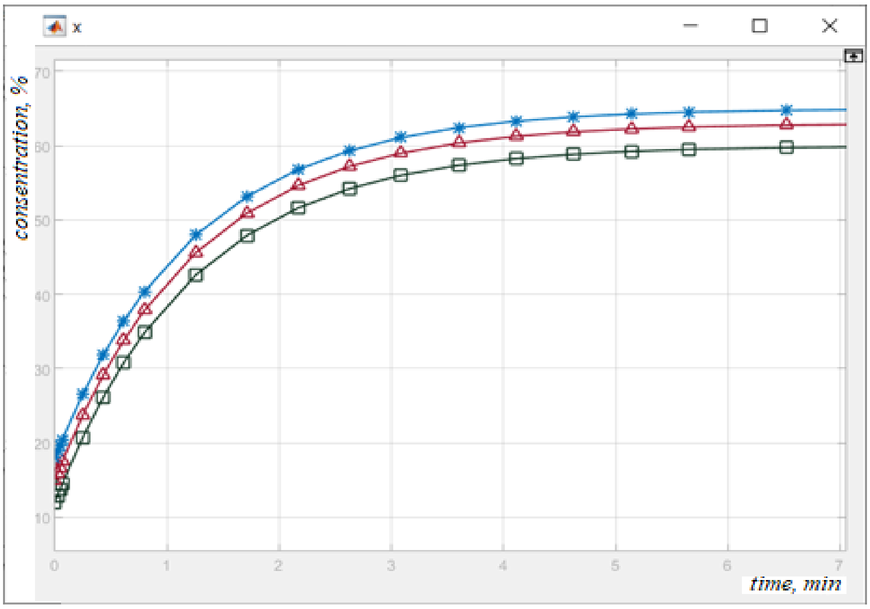

Fig.2 The change in the concentration of miscella with different initial concentrations over time.✳ 12%, △ 15 %, ⊟18 %.

Also, the temperature variation of miscella with different initial concentrations over time is presented in Figure 3. Figure 3.6 shows that in the initial period of the primary distillation process, the concentration of cottonseed oil miscella increases to 50% in a short time, and after a certain time, the concentration of cottonseed oil miscella stabilizes. The relative position of the curves in the figure shows a significant effect of the process temperature on the intensity of the change in miscella concentration.

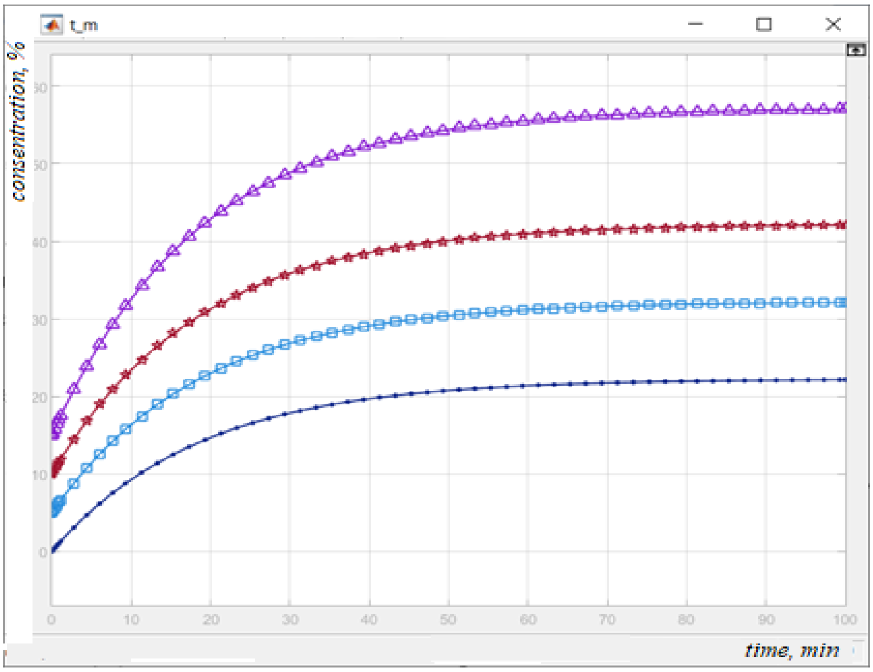

Fig.3 The temperature of miscella with different initial concentra-tions changes over time: △12-%, ☆ 15 %, ⊟18 %, • 20%.

IV. DISCUSSION

During the studies conducted on the computer model of the process, the changes in the solvent concentration in the liquid phases over time in each working zone of the primary distiller were considered. According to it, in the multi-stage distillation process, the concentration of the light volatile component in the liquid phase gradually decreases over time, from the first zone to the subsequent zones. At the same time, the concentration of the light volatile component in the vapor phase gradually increases.
Algorithmization of the technological process occurring in the primary distiller of the 120-TD line was carried out. A mathematical description of the vapor-liquid phase, characterizing the distribution of technological parameters, was obtained. The dynamics model of the pre-distillation process is implemented in the Matlab Simulink package. The dynamic characteristics of the primary distiller were studied and the correspondence of the proposed mathematical model to the real process of pre-distillation of cotton miscella was determined.

V. CONCLUSION.

Individual local processes occurring in the elements of the primary still of the 120-TD extraction line were studied. The main physico-chemical properties and thermal properties of miscella, oil and extracted gasoline were analyzed. The initial mathematical expressions were obtained in a form convenient for use in the mathematical model of the primary distillation process. Studies of mistletoe driving in primary still tubes have shown that this process has a small heating zone and small amount of bubble boiling. Mathematical descriptions for the critical concentration characterizing the transition from the bubble boiling regime to the film boiling regime and describing the change of the film thickness depending on the miscella concentration were made.

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