межах 20 – 50 %. При зазначеній потужності, об'єм ефективної обробки складатиме близько 8000 см^3., при цьому час обробки для розігріву об'єму до температури інтенсивного вологовидалення складатиме до 300 с., після чого потужність генератора може дозуватись відповідно до обраного режиму обробки.

Зважаючи на надвисоку, порівняно з існуючими способами, швидкість нагріву, технологія використання енергії мікрохвильового електромагнітного поля для обробки потоку рослинної сировини безперечно знайде своє місце у сучасних технологічних процесах.

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EXPERIMENTAL STUDIES OF BOILING HEAT TRANSFER OF FOOD SOLUTIONS

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ЭКСПЕРЕМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ ТЕПЛООБМЕНА ПРИ КИПЕНИИ ПИЩЕВЫХ РАСТВОРОВ

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Abstract.Vacuum evaporation is widely used in the food technologies. The equipment for this process is well known and methods of calculation and design of vacuum evaporators are described in literature as well. However, in some cases the accuracy of existing methods is not enough. The problem of designing the new, more efficient apparatuses that work in regimes, which are not usual, needs to clarify some dependencies. It concerns the problem of boiling heat transfer coefficient determination for such solutes as food products because of the high or sometimes extremely high viscosity of many food staffs is. To take into account properties of products many authors use the Prandtl number. However, determination of these properties exact values is not always possible especially it concerns the viscosity of Non-Newtonian fluids, which are the most of food staff. For experimental verification of heat transfer coefficient values, an apple juice was chosen. At first, the theoretical value was obtained with Tolubinskiy dependency using. The vapor bulbs grows rate and surface tension coefficient were solved as for water. The dependencies between the heat transfer coefficient and heat flux for apple juice with concentration from 15 to 50 Brix were obtained as result. There are several different equations to calculate the properties of apple juice depending on temperature and concentration and several resulting dependencies that differ from each other were obtained. The comparison with the experimental data that was obtained by authors made possible to choose the right equations for apple juice viscosity determination when the heat transfer calculation error did not exceed 20% that is standard error for used dependency and for many others. To reduce this error on the base of obtained experimental data the correction coefficient was calculated. Therefore, the equation to calculate the heat transfer coefficient for boiling apple juice where maximum error did not exceed 5% was obtained. The experimental research was conducted under atmospheric pressure. To obtain the value of heat transfer coefficient in vacuum condition the Tolubinskiy dependency can be used or addition experiments should be conducted. It depends of required accuracy level.

Аннотация *В статье рассмотрена проблема определения коефициеннтив теплоотдачи при кипении концентрированных растворов пищевых продуктов. Проанализированы возможности использования для этого известных зависимостей, которые доступны в литературе и проведено сравнение полученных результатов с результатами экспериментальных исследований при кипении концентрированного яблочного сока, проведенных авторами.*

Keywords: boiling, heat exchange, evaporation, concentration, vacuum.
Ключевые слова: *кипение, теплообмен, выпаривание, концентрирование, вакуум.*

Introduction.

One of the energy-intensive sectors of the food industry of Ukraine is the heat treatment of food liquids and food concentrates. In Ukraine the production of concentrates annually evaporated about of 1-1.5 mln. ton of water, which in monetary equivalent is 300-400 mln. UAH. There are two typical problems of concentration processes: it is a high energy costs and loss of thermally labile component materials.

One of the methods in food production is the organization of evaporation of the initial solutions in a vacuum. The main problem is to disinfect the initial mass as much as possible and to preserve its organoleptic and sanitary-hygienic qualities. These conflicting requirements can be solved by organizing processes of concentration in a vacuum with short-term exposure to high temperatures and rapid cooling. Such technology requirements significantly complicate the engineering implementation, but are successfully solved using evaporation in vacuum evaporators and rapid cooling by natural means (ice water or cooled gases). This means that traditional technologies that implement such conflicting demands are burdened by a significant increase in energy use. Therefore, the study of effective ways to reduce energy costs, their optimization and practical application look like actual research areas in the field of food technology improving. A possible way of this can be an introduction of a heat pump to the traditional technology.

However, in the process of optimization of constructive and regime parameters of new designs of vacuum evaporators (VE) with heat pumps, the main goal was to determinate the heat transfer coefficient from the evaporator surface to the food product. Nowadays, the process of heat transfer during boiling of liquids has been studied sufficiently and the number of equations for determining the heat transfer coefficient is measured in tens [1]. The same array of experimental data on the coefficients of heat transfer during the boiling of various liquids is satisfactorily described by the empirical formulas in relation to the influence of surface tension, viscosity, evaporation heat, and other properties of the liquid, which is explained in [2] by the interdependence of various thermophysical properties of liquids. In [3], the most well-known dependencies which describe the process of heat transfer with sufficient reliability and theoretical justification at the boiling of liquids are presented and analyzed. There are also models in which the surface structure of the heater is taken into account by means of fractal dimensions [4]. It was noted in [5] that the absence of a closed mathematical description of the process and the abundance of factors influencing the heat transfer during boiling make the choice of generalized variables arbitrary. It is obvious that the choice of the dependence for determining the heat transfer coefficient should be determined by its reliability and convenience of practical use. In our case, it is necessary to take into account that boiling of not a pure liquid takes place, but a solution as many liquid food products. Despite the fact that there are many studies of the liquid mixtures boiling, the boiling of solutions of nonvolatile components has been paid attention only from the point of view of determining the vapor pressure over the surface of the solution. However, in spite of this, the reference books have quite complete information only on the boiling points of solutions of sugar and NaCl. For other food solutions, the information is incomplete and, in general, is of a private nature. Especially it concerns solutions with a high concentration of solids. A feature of many food solutions is their increased and often very high viscosity. However, according to Tolubinsky [6], the internal boiling characteristics of the solutions are determined by the properties of solvent, the Prandtl number (Pr) practically does not affect them, and the heat transfer during boiling of the solutions is generally characterized by the same laws as the heat exchange in the boiling of pure liquids. Therefore, there is no difficulty in using for the solutions the similarity equation (1).

$$\mathrm{Nu} = 75\mathrm{K}^{0.7}\,\mathrm{Pr}^{-0.2} \qquad (1)$$

$$\mathrm{Nu} = \frac{\alpha}{\lambda}\sqrt{\frac{\sigma}{g(\rho-\rho_v)}}$$

$$\mathrm{K} = \frac{q}{r\rho_v d_0 f}$$

where: Nu – Nusselt number, Pr – Prandtl number, α – heat transfer coefficient, λ – heat conductivity coefficient, σ – surface tension coefficient, g - acceleration of gravity, ρ – liquid density, ρ_v – vapor density, q – heat flux, r – latent heat of vaporization, d_0 – vapor bubble diameter, f – frequency of vapor babble formation.

Substituting in the equation 1 the properties of water and steam at a boiling point of 100 °C, we will obtain:

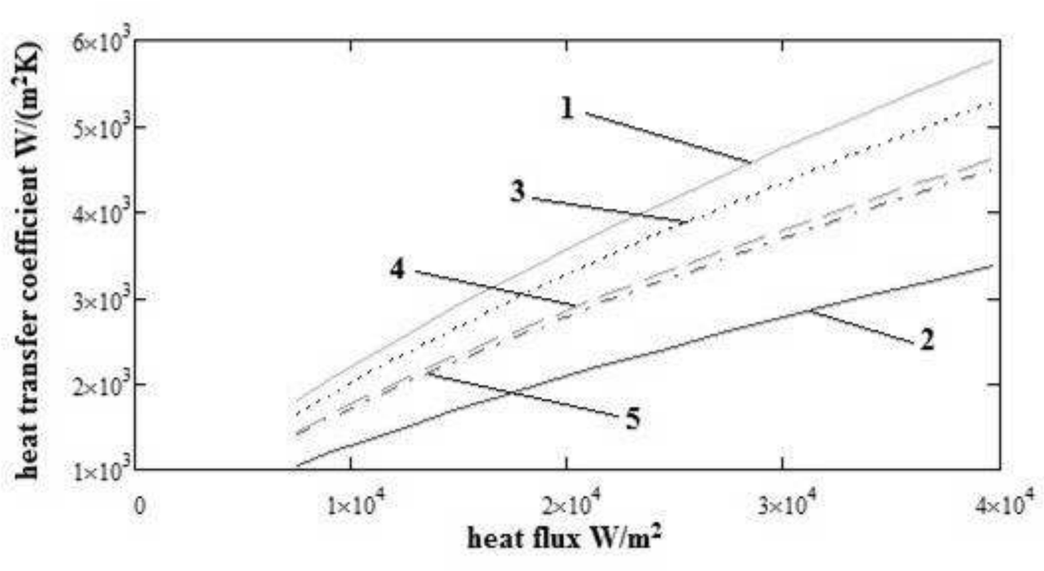
$$\alpha = 3.46 \times q^{0.7} \qquad (2)$$

It was also noted in [6] that the growth rate of vapor bubbles $\omega'' = d_0 f$ during boiling of aqueous solutions is determined by the properties of the solvent (water) and its vapor and depends very weakly on the properties of the solute, viscosity and Prandtl number of the solution. Therefore, the value of ω" upon boiling of aqueous solutions can practically be considered equal to ω" upon boiling of water. Thus, in order to use equation 1 for determining the heat transfer coefficients for the boiling of solutions, it is necessary to know their thermophysical properties and the magnitude of physic-chemical depression.

Determination of the heat transfer coefficient of food solutions according to the Tolubinsky formula.

Let us consider the possibility of using formula 1 to calculate the heat transfer coefficient of concentrating apple juice. As noted above, for this it is necessary to know the thermophysical characteristics of apple juice and its boiling temperature. The main source of the food products thermophysical properties data are the Chubik [7] and Ginzburg [8] handbooks. Apple juice is quite common and its properties are available in the reference books [7, 8], and apparently, there should be no problems in calculating the heat transfer coefficient. However, trying to determine the density of apple juice according to [7], we have seen the dependence of the juice density on the concentration of solids only at a temperature of 20 °C. A more general dependence of density from concentration and temperature for different juices is presented in [8]. The viscosity and thermal conductivity of apple juice with concentration of solids up to 50% can be also determined from the dependences from [7]. The heat capacity of apple juice at 15% of dry matter can be determined by [9]. With an increase in the concentration of dry substances, the heat capacity of the juice is expected to decrease, as shown in [9] for the specific heat of grape juice. The value of the coefficient of surface tension for apple juice in the literature was not found. The values of the coefficient of surface tension of pomegranate juice in the temperature range 10-90 °C and concentrations of 15-45% are presented in [10]. It is established that the coefficient of surface tension of juice σ decreases with increasing temperature and concentration. Analysis of the data from [10] shows that at low temperatures the coefficient of surface tension of the juice is less than the coefficient of surface tension of water. With increasing temperature, the value of the surface tension of the juice approaches the value of this coefficient for water, and at low concentrations, it exceeds it. The maximum difference in values did not exceed 6%. Because of this, it was decided to use the value of the coefficient of surface tension of water in calculations.

By substituting the values of the thermophysical properties of the juice in equation 1, we obtained the dependences of the heat transfer coefficient for the boiling of apple juice with a concentration of 10-50% at atmospheric pressure. The obtained dependences are shown in Fig. 1.



1-water, 2-juice at a concentration of 15%, 3-juice at a concentration of 25%, 4-juice at a concentration of 40%, 5-juice at a concentration of 50%

Fig.1. Dependence of the heat transfer coefficient of apple juice on the heat flux at atmospheric pressure, calculated according to the Tolubinsky formula;

In general form, these relationships can be represented by an equation of the form:

$$\alpha = Ac \times q^{0.7} \tag{3}$$

where Ac is a constant, depending on the properties of the juice and water vapor.

For atmospheric pressure, the dependence of Ac on the juice concentration is shown in Fig. 2.

As can be seen, the dependence of Ac on the concentration, shown in Fig. 2, has the form of a broken curve, which is due to the non-smooth crosslinking of the formulas for determining the viscosity of the juice at various concentrations. Especially noticeable is the jump with a change in viscosity from 15% to 20%. If we exclude from the calculation the dependence for viscosity, taken from [9] and use only the dependence for concentrated juices, we obtain a smoother curve.

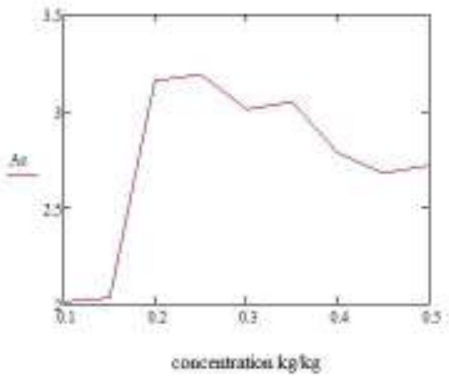
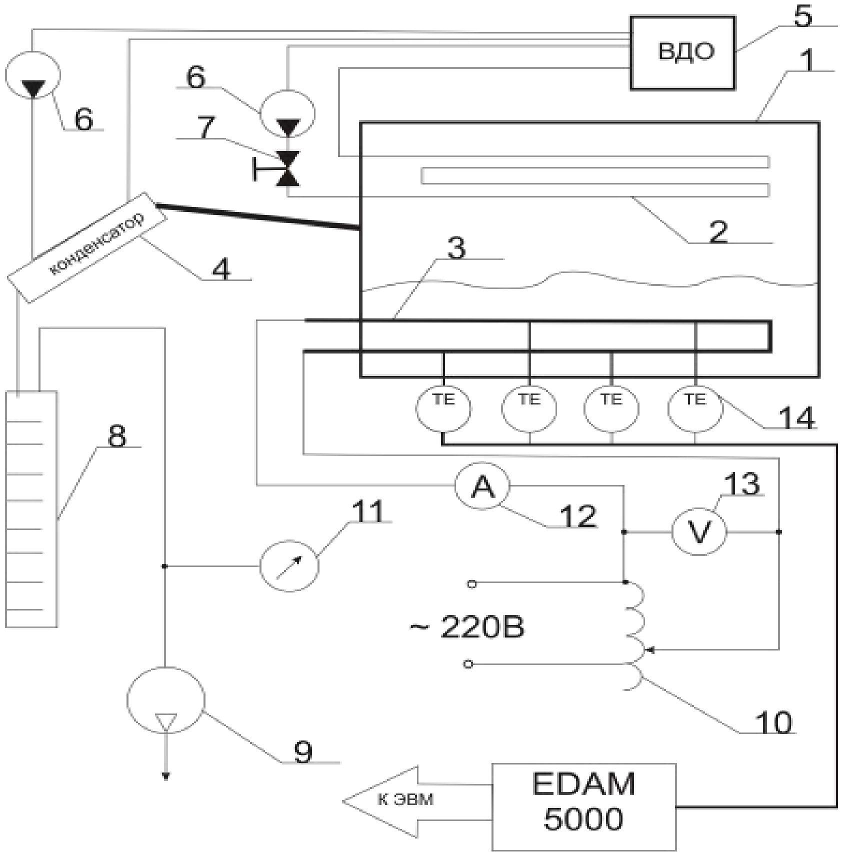


Fig. 2. Dependence of Ac on the concentration of juice

As can be seen from the graphs 1 and 2, the heat transfer coefficient at boiling of apple juice is less than its value at the boiling point of water and has a maximum at a concentration of dry matter in the juice of about 25%. The calculated values are doubtful, especially in the field of low concentrations of solids in juice due to the existing ambiguity in determining the properties of the juice. There is also no exact data on the rate of growth of vapor bubbles during boiling of apple juice, which can also affect the reliability of the calculated values. Check the degree of deviation of the calculated data from the actual values of the heat transfer coefficient by experiment.

Description of the experimental setup and experimental procedure.

To test the calculated heat transfer coefficients experimentally, a laboratory installation was created (Figure 3), the main element of which was the glass container 1. In the lower part of the container there is an electric heater 3, and in the upper part there is a tubular heat exchanger 2. In the heat exchanger 2, the pump 6 is supplied with cold water from the water cooling unit 5.



1 - volume, 2 - heat exchanger, 3 - electric heater, 4 - condenser, 5 - water cooling plant, 6 – circulating pump 7 - valve, 8 - measuring container, 9 - vacuum pump, 10 - LATR, 11 - manometer, 12 - ammeter , 13 - voltmeter, 14 - thermocouple.

Fig. 3. Scheme of the experimental setting.

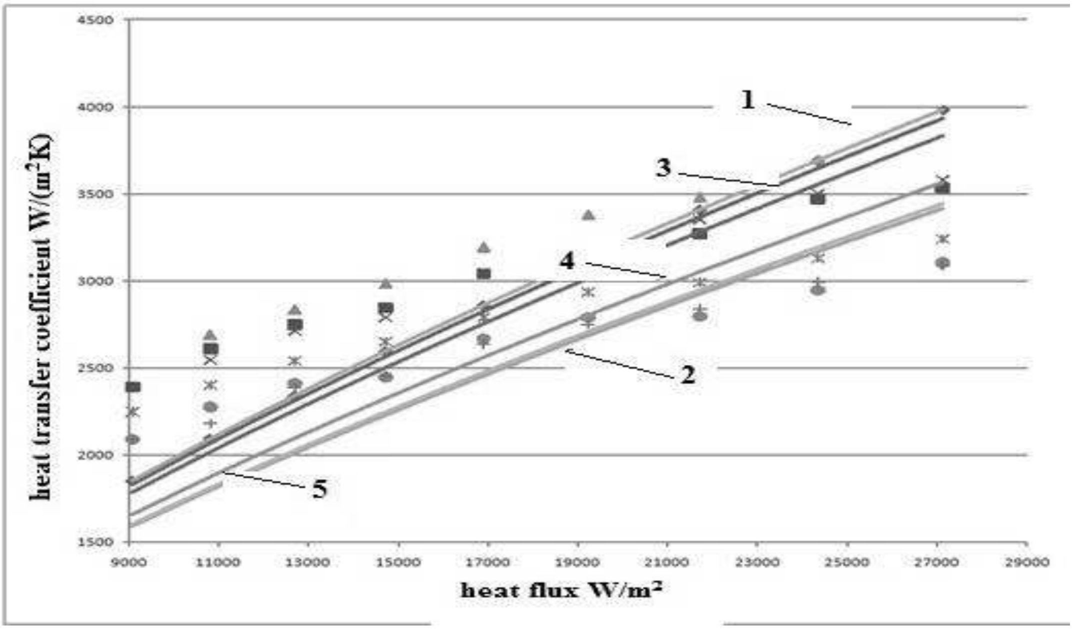
The heat transfer coefficient was defined as the ratio of the heat flux of the electric heater emanating from the unit surface to the liquid to the temperature difference between the surface of the heater and the liquid. To determine this temperature difference on the surface of the heater and in the liquid, there are thermocouples connected to the EDAM 5000 secondary converter, which transmits temperature values to the computer via a USB interface. The value of the heat flux was changed with the help of LATR. The onset of boiling was recorded visually and by stabilizing the temperature of the liquid. The setting. allows to carry out experiments both at atmospheric pressure and under vacuum. The instrumental error in determining the heat transfer coefficient does not exceed 6%.

For the experiments apple juice was used with an initial concentration of 12%. After carrying out the heat transfer coefficients and the temperature depression of this juice, the supply of cooling water to the heat exchanger 2 was closed by means of the valve 7, thereby stopping the condensation of the vapor inside the container. The secondary vapor was condensed in the condenser 4 and collected in a measuring container 8. Upon reaching the next preset juice concentration, the valve was opened, and the process was carried out. The changes were made in the range of concentration changes of 12-50% and the heat flux density of 6 - 47 kW/m^2.

Results of the experiments and comparison with calculations.

As a result of the experiment, the dependences of the heat transfer coefficient on the density of heat flux and concentration of apple juice at atmospheric pressure were obtained, presented in Fig. 4.

As can be seen, the experimental dependences of the heat transfer coefficient on the apple juice concentration have a maximum in the concentration range of 20-25%. Their character and the value of the maximum points coincide with the calculated dependences presented in Figures 2. A visual comparison of the experimental and calculated dependences is shown in Fig. 4. The graphs confirm the coincidence of the predicted influence of the concentration on the heat transfer coefficient. At the same time, there is some discrepancy between the numerical values of calculated and experimentally determined heat transfer coefficients. In the main in the range of heat flux densities from 12 to 50 kW/m^2, the relative divergence does not exceed 20%, which corresponds to the accuracy of calculations using formula (1). The principal increase the accuracy of the general formula is not advisable due to the fact that the effect on heat transfer during boiling "weak" factors (small impurities surface-active additives, impurities and the dissolved gases, specific microgeometry of boiling surface associated with the structure of the material, technology of preparation and surface treatment, the adsorption properties of the surface, its homogeneity, wet ability, etc.) are greater than the effect of "strong" factors such as the gravity intensity level field, vibration, organization of circulation and forced fluid flow, application of an electric field, the thermophysical properties of the material surface [11].



1-water, 2-juice at a concentration of 15%, 3-juice at a concentration of 25%, 4-juice at a concentration of 40%, 5-juice at a concentration of 50%

Fig. 4. Comparison of the calculated and experimental dependences of the heat transfer coefficient on the density of the heat flux at different concentrations of apple juice.

However, to optimize the evaporators the formula 3 can be used with an additional correction factor. This coefficient is obtained by dividing the values of the heat transfer coefficient obtained experimentally by the values calculated from formula 3. Then the modified equation for determining the heat transfer coefficient at boiling of apple juice has the form:

$$\alpha = K_K \times Ac \times q^{0.7} \tag{4}$$

where K_K is the correction coefficient.

Differences in K_K values for different concentrations of apple juice fluctuate within 5% relative to the average value. Consequently, these oscillations are within the error of the experiment.

Conclusions

As a result of the conducted studies, it was established that for the determination of the heat transfer coefficient at boiling of apple juice with a concentration of up to 50% at atmospheric pressure, using the Tolubinsky formula (1), the growth rates of steam bubbles and the surface tension coefficient determined for water at the appropriate temperature can be used. In order to obtain values of the heat transfer coefficient with greater accuracy, one can use partial dependencies, such as equation 4. It should also be taken into account that at atmospheric pressure the boiling point of the juice exceeds 100 ° C. According to [7] at such temperatures, the change in the viscosity of apple juice with increasing concentration to 50% is negligible. Under conditions of a deep vacuum, at boiling temperatures of 30-40 ° C, the viscosity change is already considerable and amounts to 800-1300% of the initial viscosity. Also, one should take into account the possible change in the coefficient of the surface tension of the juice in the region of high concentrations. Thus, it makes sense to determine experimentally the heat transfer coefficients at boiling of juice in the region of high concentrations (more than 50%) at boiling points of
60 -30 ° C.

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