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BOILING AND CRYSTALLIZATION IN THREE-PHASE TWO-COMPONENTS SOLUTION

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КИПІННЯ І КРИСТАЛІЗАЦІЯ У ТРИФАЗНОМУДВОКОМПОНЕНТНОМУРОЗЧИНІ

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КИПЕНИЕ И КРИСТАЛЛИЗАЦИЯ В ТРЕХФАЗНОМ ДВУХКОМПОНЕНТНОМ РАСТВОРЕ

Abstract. Following general laws of heat-mass exchange in multiphase systems, common tendencies of vapor bubble and crystal dynamics and growth in a solution were studied with the assumptions that the solution medium consisted of two chemically neutral components - water and sucrose –and include three phases: liquid, solid and gaseous. Conservation equations and equations for interphase interactions are formulated with taking into account specific properties of the aqueous solution of sucrose. Assumptions on which a theory of multiphase heterogeneous systems is based are presented. Dynamic behavior of the three-phase two-component medium in an axial-symmetric channel is described with the help of one-dimensional flow model. It is shown that at low sucrose concentration and initial overheating of the solution in the channelvapor bubbles increase though sugar crystals dissolve. At higher concentrations and inessential overheating, both bubbles and crystals can increase. Thus, it is possible to specify conditions under which crystallization could occurred in the solution.

Keywords: bubble, crystal, solution, boiling, multiphase system

Introduction

Today, understanding of the heat-massexchange processes in the multicomponent and multiphase systems is a question of the day because of intensive development of new and upgrading of existing technological practicesfor preparingdifferent products by food, chemical or metallurgical industries. In this article, some common tendencies of vapor bubble and crystal dynamics and growth in the two-component sucrose solution are considered basing on the laws of heat-mass exchange in the multiphase systems.

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Formulation of the problem and basic equations

The assumption is that the mediumunder the study consists of two chemically neutral components - water and sucrose (sucrose solution) - and includes three phases: liquid (solution), solid (sugarcrystals) and gaseous (watervapour bubbles). Using the Nigmatullin methodology [1], some basic equations can be written down forthe component motion and heat-and-mass exchangewith the help of one-dimensional model and with taking into account the fact that exchange by mass and thermal flowsexists between liquid and solid phases and liquid and gaseous phases:

$$u_c \frac{dn_c}{dx} = -\frac{du_c}{dx} n_c, \tag{1}$$

$$u_p \frac{dn_p}{dx} = -\frac{du_p}{dx} n_p, \tag{2}$$

$$j_c = \frac{4}{3}\pi u_c \frac{dM_c}{dx}, \tag{3}$$

$$j_p = \frac{4}{3}\pi u_p \frac{dM_p}{dx}, \tag{4}$$

$$\rho_r \alpha_r \frac{du_r}{dx} = -\rho_r u_r \frac{d\alpha_r}{dx} - n_c j_c - n_p j_p, \tag{5}$$

$$\alpha_c = \frac{4}{3}\pi r_c^3 n_c, \quad \alpha_p = \frac{4}{3}\pi r_p^3 n_p, \quad \alpha_r = 1 - \alpha_c - \alpha_p, \tag{6}$$

$$\begin{gathered}(\rho_r + 2\rho_c) u_c \frac{du_c}{dx} = 3\rho_r u_r \frac{du_r}{dx} + \frac{3}{4}\rho_r c_{\mu c} \frac{|W_{rc}|}{r_r} W_{rc} + \\ + 3\rho_r u_r \frac{dr_c}{r_c dx} W_{rc} - 2(\rho_c - \rho_r) \ ,\end{gathered} \tag{7}$$

$$\begin{gathered}(\rho_r + 2\rho_p) u_p \frac{du_p}{dx} = 3\rho_r u_r \frac{du_r}{dx} + \frac{3}{4}\rho_r c_{\mu p} \frac{|W_{rp}|}{r_p} W_{rp} + \\ + 3\rho_r u_r \frac{dr_p}{r_p dx} W_{rp} - 2(\rho_p - \rho_r),\end{gathered} \tag{8}$$

$$\alpha_r\rho_r u_r \frac{du_r}{dx} + \alpha_c\rho_c u_c \frac{du_c}{dx} + \alpha_p\rho_p u_p \frac{du_p}{dx} = -\frac{dp_r}{dx} + \\ + n_c j_c W_{rc} + n_p j_p W_{rp} + 2\frac{\tau_T}{R_T} - \left(\alpha_r\rho_r + \alpha_c\rho_c + \alpha_p\rho_p\right) g \quad (9)$$

$$\alpha_r\rho_r u_r \frac{dc_w}{dx} = -n_c j_c \left(c_{wca} - c_w\right) - n_p j_p \left(c_{wpa} - c_w\right) - \\ - n_c g_{wca} - n_p g_{wpa} \quad , \quad (10)$$

$$\alpha_r\rho_r u_r \frac{dc_s}{dx} = -n_c j_c \left(c_{sca} - c_s\right) - n_p j_p \left(c_{spa} - c_s\right) - \\ - n_c g_{sca} - n_p g_{spa} \quad , \quad (11)$$

$$\alpha_r\rho_r u_r c_r^* \frac{dT_r}{dx} = -n_c j_c c_r^* (T_{ca} - T_r) - \\ - n_p j_p c_r^* (T_{pa} - T_r) - n_c \left[q_{ca} + j_c c_r^* (T_{ca} - T_r)\right] - \\ - n_p \left[q_{pa} + j_p c_r^* (T_{pa} - T_r)\right] - 2\frac{q_T}{R_t} \quad , \quad (12)$$

wherexis a longitudinalcoordinate; n_j is concentration in the heterogeneous phase; u_j is speed(index $j = r$isfor solution, $j = c$isfor crystal and$j = p$isfor bubble); ρ_j is density; r_j –is radius of the heterogeneous phase; α_j is volume fractions of the liquid, crystals and bubbles; j_j is massflowsonthe border between the heterogenous phases; p_r is pressure in the solution; $W_{rc} = u_r - u_c$; $W_{rp} = u_r - u_p$; $\tau = \mu_r \frac{\partial u}{\partial r}$ is friction stressofthesolution; c_i is componentsof the solution(i = w – water, i = s – sucrose); c_r^* is a coefficientofthe solutionthermalcapacity; c_{wca}, c_{wpa} are water concentration on the crystal and bubblesurfaces; c_{sca} , c_{spa} are sucrose concentrationon the respective surfaces; T_r is a solution volume temperature; T_{ca} is temperature on the crystal surface which is equal to temperature of crystallization; T_{pa} - temperature on the bubble surface which is equal to the boiling temperature; g_{ija} –diffusive flowof the *i*-component on the surface of the *j* heterogeneous phase; q_{ja} is a heat flow on the surface of the *j* heterogeneous phase; μ_r is effective viscosity of the solution; λ_r – is an effective coefficientofthe solutionheatconductivity, D_r is an effective diffusion coefficientof the solution; τ_T – is friction stress on the pipewall; q_T is aheat flow from the wall (q_T=0); R_T is the pipe radius. $M_c = \rho_c r_c^3$, $M_c = \rho_c r_c^3$, qT=0

In the system of equations (1) – (12), first two equations determine conservation of crystals and bubbles quantity in the medium; next three equations are mass conservation equations forthe solid, gas and liquid phases; the equation (6) determines volumetric fractions of this or that phase; expressions (7), (8) and (9) are the equations fordetermining the crystal, bubble and solution motion; the equations (10) and (11) describe component diffusion in the solution; andthe last equation (12) is an equation of the heat exchange in the solution. All parameters in this system are average by the channel area.

This system of the equations should be added by equationsfor calculating motion of the crystal and bubble surfaces (Nigmatullin [1]) and mass conservation for the phases and temperatures under the study (Eliseev[2]):

$$u_c \frac{dr_c}{dx} = \frac{u_c}{3\rho_r r_c^2} \frac{dM_c}{dx}, \tag{13}$$

$$(1-\varphi_{1i}) r_p u_p \frac{dw_a}{dx} = \Phi, \tag{14}$$

$$u_p \frac{dr_p}{dx} = w_a + \frac{u_p}{3\rho_r r_p^2} \frac{dM_p}{dx}, \tag{15}$$

$$c_c u_c \frac{dT_c}{dx} = -15\lambda_c \frac{r_c}{M_c}\left(1 - \frac{c_c}{15\lambda_c r_c} u_c \frac{dM_c}{dx}\right) \times \times (T_c - T_{ca}), \tag{16}$$

$$(c_p - R)\, u_p \frac{dT_p}{dx} = RT_p u_p \left(\frac{dM_p}{M_p dx} - 3\frac{dr_p}{r_p dx}\right) - -15\lambda_p \frac{r_p}{M_p}\left(1 - \frac{c_p}{15\lambda_p r_p} u_p \frac{dM_p}{dx}\right)(T_p - T_{pa}), \tag{17}$$

Where $\Phi = \frac{p_p - p_r - 2\sigma/r_p}{\rho_r} - 4\frac{\mu_r}{\rho_r}\frac{w_p}{r_p} - (1-\varphi_2)\frac{3}{2}w_p^2 + \frac{1}{4}(1-\varphi_3)W_{rp}^2$; φ_i–are coefficients from the Nigmatullinequation [1]; and $\sigma$is a coefficient of the surface tension.

Besides, in order to make this system of equations complete it is necessary to determine boundary conditions on the borders of heterogeneous mediums by the following equations:

$$u_c \frac{dM_c}{dx} = -3r_c^2 \frac{g_{sca}}{1-c_{sca}}, \tag{18}$$

$$u_p \frac{dM_p}{dx} = -3r_p^2 \frac{g_{wpa}}{1-c_{wpa}}, \tag{19}$$

$$u_c \frac{dM_c}{3r_c^2 dx} \Delta H_s = \left(q_{ca}^+ - q_{ca}^-\right), \tag{20}$$

$$u_p \frac{dM_p}{3r_p^2 dx} \Delta H_p = \left(q_{pa}^+ - q_{pa}^-\right), \tag{21}$$

where $\overline{q}_{ca} = 5\lambda_c \frac{T_c - T_{ca}}{r_c}, \overline{q}_{pa} = 5\lambda_p \frac{T_p - T_{pa}}{r_p}$ are inside heat flows (Eliseev,[2]), andoutside mass and heat flows can be written in the following way: $g_{ija} = \alpha_{mi}\left(c_{ija} - c_i\right)$, $q_{ja}^+ = \alpha_{Ti}\left(T_{ia} - T\right)$; $\alpha_{mi} = \frac{D_i Nu_{mi}}{2r_i}, \alpha_{Ti} = \frac{\lambda_r Nu_{Ti}}{2r_i}$ arecoefficients of mass and heat transfers (D_w=D_s=D_γ).

The Nusselt numbers for the crystals (Verigin [3]) and bubbles (Nigmatullin [1]) are assumed as:

$$Nu_{mc} = 2 + 1.28\left(Re_c \cdot Sc_r\right)^{1/3},$$

$$Nu_{Tc} = 2 + 1.28\left(Re_c \cdot Pr_r\right)^{1/3},$$

$$Nu_{mp} = 2 + 0.6 Re_{\text{p}}^{0.55} Sc_r^{1/3},$$

$$Nu_{Tp} = 2 + 0.6 Re_{\text{p}}^{0.55} Pr_r^{1/3},$$

where $Sc_r = \frac{\mu_r}{\rho_r D_r}, Pr_r = \frac{\mu_r c_r^*}{\lambda_r}$,

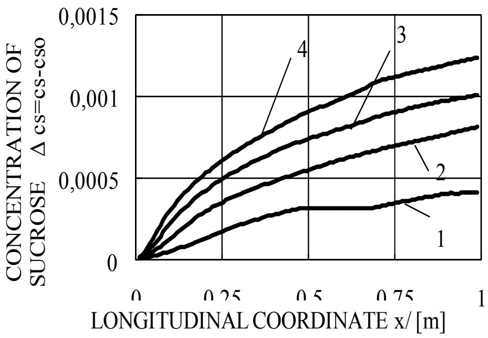
$$Re_c = \frac{2r_c\rho_r|u_r - u_c|}{\mu_r}, \quad Re_p = \frac{2r_p\rho_r|u_r - u_p|}{\mu_r}.$$

And, at last, this system of the equations should be added by the formulas which describe physical properties of the solution. These equations can be found inarticles ofPopov [4], Zubchenko [5], Guliy [6]. Besides, all necessary dependences taken from these works are presented in the Anfimova's article [7].

Discussion of the results

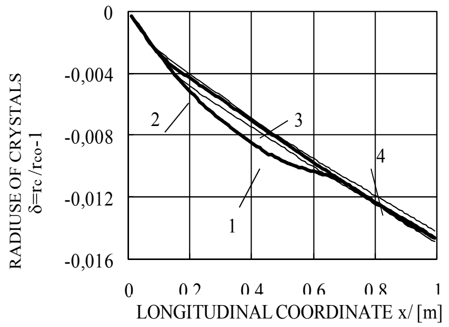
In order to make the calculation, certain values were fixed for the phase and temperature velocities and crystal and bubble concentrations in the initial pipe section. One more assumption was accepted: boiling centers (nucleuses of boiling) and crystallization centers (nucleuses of crystallization) are the bubbles and crystals themselves in the initial pipesection, and bubbles grow only in their centers (nucleuses), and crystals grow in the their centers (nucleuses), accordingly.

Two series of the calculations were performed which differed by sucrose concentrations, and their results are illustrated in the following six figures. The first three figures show curves which were obtained as a result of the calculations by the above equations for the case when sucrose concentration in the solution makes 0.8, and overheating of the solution is equal accordingly to 1 - 0.5°; 2 - 1.0°; 3 - 1.5°; 4 - 2.0° if compare with temperature of saturation. The Fig.1 shows curves of changed sucrose concentrations in the solution $\Delta c_s = c_s - c_{so}$ while the medium advances in the pipe.



1 – ΔT=0.5; 2 – 1; 3 – 1.5; 4 – 2

Figure 1: Change of concentration of sucrose in a solution at cs_o=0.8



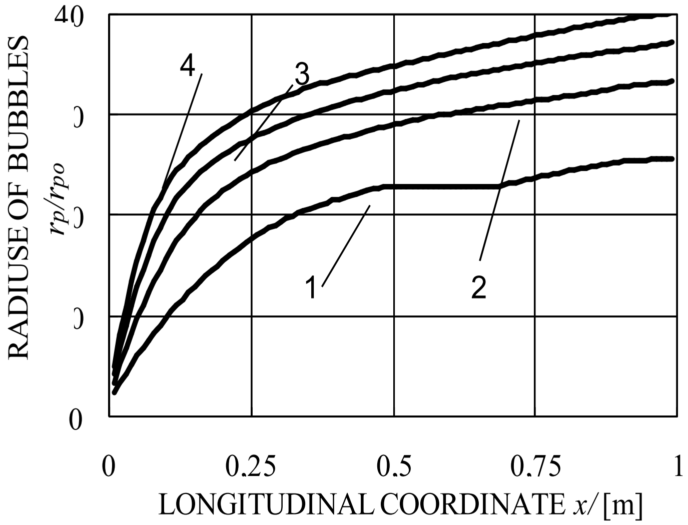
1 – ΔT=0.5; 2 – 1; 3 – 1.5; 4 – 2

Figure 2: Change of radiuses of crystals of sugar *n* the environment at c_{so}=0.8

Fig.3 demonstrates that increase of the bubble radius is intensive enough, and even insignificant overheating of the solution essentially impacts on the radius size of the rising bubbles.

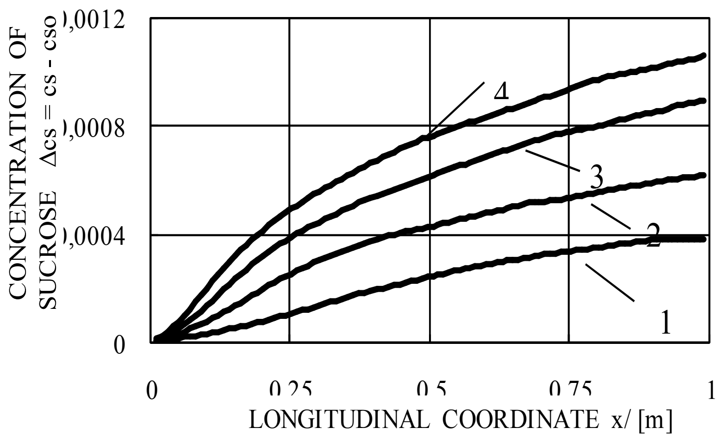
Second series of the calculations assumes that sucrose concentration is 0.9. As well as in the previous case, sucrose concentration in the solution grows (see Fig. 4), however, this growth is a little bit slower: the Fig. 4 shows no qualitative changes to Fig.1. At the same time, behaviour of sugar crystals differs: they grow (see Fig.5), however, the liquid overheating also only slightly changes the curves.

Thus, the process of the heat-mass exchange can be qualitatively different depending on initial sucrose concentration, and it is quite natural. However, interesting is the fact that boiling can be accompanied by different processes. In the first case it is accompanied by process of dissolution, in the second - by process of crystallization.



1 – ΔT=0.5; 2 – 1; 3 – 1.5; 4 – 2

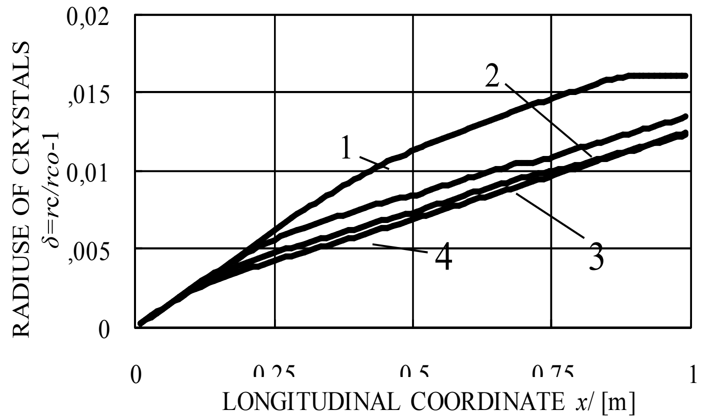
Figure 3: Changes of radiuses of bubbles pair in the environment at c_{so}=0.8



ΔT=0.5; 2 – 1; 3 – 1.5; 4 – 2

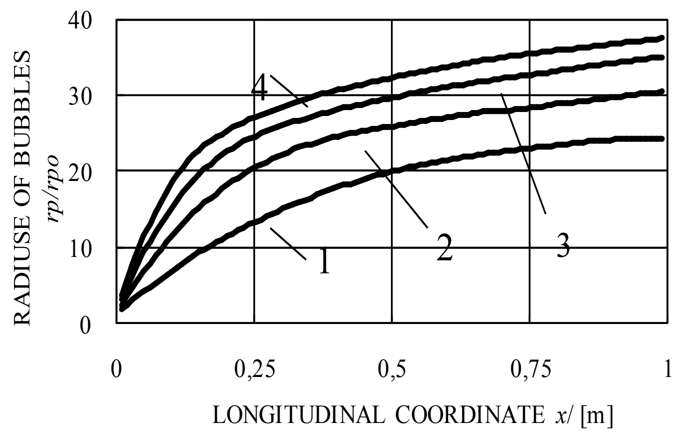
Figure 4: Change of concentration of sucrose in a solution at c_{so}=0.9

In the second series of calculations, crystallization should reduce sucrose concentration in the solution but instead the concentration becomes higher. Since the process of crystallization is rather slow the increase of the sucrose concentration is, of course, associated with the phase transition of water: an evidence of this fact is shown in the Fig.6: the bubbles increase in their size while advancing in the channel.Even at such low water concentration in the solution the water mass transition to the bubbles (phase transition) is greater all the same, than for the sucrose. These examples show that the processes can be developed in different ways depending on component concentration in the solution and the solution temperature. Here, difference between the component concentration in the solution and on the surface of the heterogeneous inclusion is of great importance, and these parameters are established and regulated by local conjugate heat and mass flows.



1 – ΔT=0.5; 2 – 1; 3 – 1.5; 4 – 2

Figure 5: Change of radiuses of crystals of sugar in the environment at c_{so}=0.9

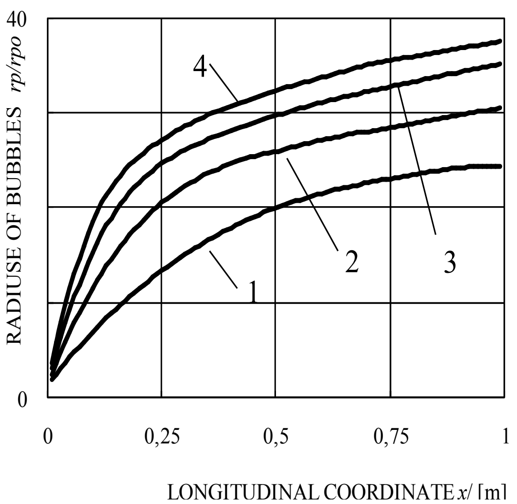


1 – ΔT=0.5; 2 – 1; 3 – 1.5; 4 – 2

Figure 6: Changes of radiuses of bubbles pair in the environment at c_{so}=0.9

As it is mentioned above, one of the most important assumption in the formulation of the problem is conformity between component phase transitions in the nuclei. In real process, this condition may not obligatory happen. Fig.7 shows curves$\Delta c_{spa}=c_{spa}-c_s$ (difference between sucrose concentrations on the surface of the vapour bubble and in the solution) and $\Delta c_{wca}=c_{wca}-c_w$(difference between water concentrations on the crystal surface and in the solution) for the case when the solution is overheated by 2°. This Figure shows that, at simultaneity of the boiling and crystallization processes (c_{so}=0.9), concentrations of another component are increased on the bubble and crystal surfaces.

At c_{so}=0.8, the sugar crystals are surrounded by area with the lower water concentration. At c_{so}=0.9, this concentration can exceed critical values and, as result, new nuclei can be formed.Thus, the calculations show that the increased concentrations of another component are formed on borders of the disperse phases that, probably, can result in formation of the component nuclei. For example, a high concentration of water can appear on the crystal surface, and in result of this water can transform into vapor on the crystal surface.



1 - Δc_{spa} ; 2 -Δc_{wca}; a – c_{so}=0.8; b – c_{so}=0.

Figure 7: Difference in concentration of sucrose and water on surfaces accordingly a bubble and a crystal at overheating a solution on 2 degrees

A similar phenomenon can be observed on the vapor-bubble surface where higher concentration of sucrose appears. Due to this high concentration, a nucleus of a sugar crystal can be formed around the bubble. Thus, some cross phase formations are quite possible. It is well known that heterogeneous inclusions in the overheated liquids are also the nucleation sites (centers of vapour formation).In the multicomponent mediums, mixed crystals (Kitaygorodskiy [8]) can be formed. This process is very much complicated and demands thorough experimental and theoretical researches.

Conclusions

Hereby, behavior of the three-phase two-component system was analyzed in this work on the basis of theory of heterogeneous media. Impact of initial overheat of the solution and initial concentration on the processes of sugar boiling, dissolution and crystallization is demonstrated on the example of sucrose dissolution in water. Analysis of the obtained dependences of the component concentration has shown that cross phase transition of the solution components is possible.

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Анотація.На основі загальних законів тепломасообміну в багатофазних системах розглянуті основні закономірності динаміки і зростання парових бульбашок і кристалів в розчині. Прийнято , що середовище складається з двох хімічно нейтральних компонентів: води і цукрози і трьох фаз: рідкої , твердої і газоподібної . Записані рівняння збереження і міжфазної взаємодії з урахуванням специфічних властивостей розчину. Вжито припущення , на яких базується теорія багатофазних гетерогенних систем . У рамках одновимірної моделі течії отримані рішення для динамічної поведінки трифазного, двохкомпонентного середовища в осесиметричному каналі. Показано , що при низьких концентраціях цукрози в каналі початковий перегрів рідини призводить до зростання парових бульбашок і до розчинення кристалів цукру. Для високих концентрацій при невеликих перегрівах можливі, як зростання бульбашок, так і зростання кристалів. Таким чином, можуть бути знайдені умови необхідні для кристалізації в розчині.

Ключові слова: міхур, кристал, кипіння, багатофазні системи

Аннотация .На основе общих законов тепломассообмена в многофазных системах рассмотрены основные закономерности динамики и роста паровых пузырьков и кристаллов в растворе. Принято, что среда состоит из двух химически нейтральных компонентов: воды и сахарозы и трех фаз: жидкой, твердой и газообразной. Записаны уравнения сохранения и межфазного взаимодействия с учетом специфических свойств раствора. Приняты предположения, на которых базируется теория многофазных гетерогенных систем. В рамках одномерной модели течения получены решения для динамического поведения трехфазной, двухкомпонентной среды в осесимметричном канале. Показано, что при низких концентрациях сахарозы в канале начальный перегрев жидкости приводит к росту паровых пузырьков и к растворению кристаллов сахара. Для высоких концентраций при небольших перегревах возможны, как рост пузырьков, так и рост кристаллов. Таким образом, могут быть найдены условия необходимые для кристаллизации в растворе.

Ключевые слова: пузырь, кристалл, кипение, многофазные системы

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ИССЛЕДОВАНИЕ ОСОБЕННОСТЕЙ ИЗМЕНЕНИЯ ПОКАЗАТЕЛЕЙ ТРУДА ГОРНЯКОВ ПРИ ВЫПОЛНЕНИИ РАЗЛИЧНЫХ ТЕХНОЛОГИЧЕСКИХ ОПЕРАЦИЙ

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ДОСЛІДЖЕННЯ ОСОБЛИВОСТЕЙ ЗМІНИ ПОКАЗНИКІВ ПРАЦІ ГІРНИКІВ ПІД ЧАС ВИКОНАННЯ РІЗНИХ ТЕХНОЛОГІЧНИХ ОПЕРАЦІЙ

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THE STUDY OF SPECIFIC CHANGES OF THE MINER'S WORK FACTORS WHILE THEY PERFORM DIFFERENT TECHNOLOGICAL OPERATIONS

Аннотация. Целью данной работы является определение особенностей изменения показателей труда горняков при выполнении различных технологических операций в условиях приближенных к шахтным. Методами исследований являются методы биомеханики, натурные наблюдения с фиксацией параметров при помощи специализированных стандартных приборов, обработка результатов исследований производится с помощью современных программно-вычислительных комплексов с использованием методов математической статистики. В результате установлено, что при использовании молодым рабочим респиратора во время погрузки горной массы объем выполненной работы уменьшается на 16%, а интенсивность затрачиваемой энергии уменьшается на 27%; при использовании опытным рабочим респиратора во время погрузки горной массы объем выполненной работы увеличивается на 10%, а интенсивность затрачиваемой энергии уменьшается на 11%. В среднем молодой рабочий несет меньше энергозатрат на выполнение всех рабочих операций, чем опытный. Также следует отметить, что средние энергозатраты при выполнении операций без респиратора превышают средние энергозатраты при выполнении операций с респиратором, исключение составляет спуск по лестнице и перенос груза как опытным, так и молодым рабочими.

Ключевые слова: физическая кондиция, квалификация рабочих, энергозатраты, интенсивность затрачиваемой энергии.

Для повышения эффективности процесса подземной добычи важным фактором является качество трудовых ресурсов. Повышение квалификации и физических кондиций рабочих приводит к увеличению концентрации производства, мощности и надежности применяемых средств механизации, опытного исполь-

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