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MATHEMATICAL MODELING OF FRUIT DRYING AND SYSTEM ANALYSIS OF THE PROCESS (ON THE EXAMPLE OF PERSIMMON)

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Abstract: *Vegetable raw materials, as an object of drying, are characterized by a large amount of water and a low content of dry substances. Vegetable raw materials have a capillary-porous structure.*

Food products contain both bound and free moisture at the same time. The removal of moisture from the material during drying depends on the total moisture content and the form of connection of moisture with the material. Adsorption and osmotic - bound moisture is retained at the interface of colloidal particles with the environment. Food products contain both bound and free moisture at the same time. The quantitative ratio between them depends on the nature of the product. But even in one product, this ratio can change during grinding, adding additives, heat treatment, and so on.

The energy expended to remove 1 kg/mol of water from the wet material depends on the temperature and relative humidity of the air. The higher the temperature and relative humidity of the air, the greater the binding energy of moisture.

Keywords: *drying, moisture, energy, temperature, humidity, adsorption, diffusion, solution.*

Annotatsiya: *O‘simlik xom ashyosi quritish ob’ekti sifatida suvning ko‘pligi va quruq moddalarning kamligi bilan ajralib turadi. O‘simlik xom ashyosi kapillyar-g‘ovak tuzilishga ega.*

Oziq-ovqat mahsulotlari bir vaqtning o‘zida ham bog‘langan, ham erkin namlikni o‘z ichiga oladi. Quritish vaqtida materialdan namlikni olib tashlash umumiy namlik miqdori va namlik va material o‘rtasidagi bog‘lanish shakliga bog‘liq. Adsorbsiya va osmotik - bog‘langan namlik kolloid zarrachalar va atrof-muhit o‘rtasidagi interfeysda saqlanadi. Oziq-ovqat mahsulotlari ham bog‘langan, ham erkin namlikni o‘z ichiga oladi. Ularning miqdoriy munosabati mahsulotning xususiyatiga bog‘liq. Ammo bitta mahsulotda ham bu nisbat silliqlash, qo‘shimchalar qo‘shish, issiqlik bilan ishlov berish va hokazolarda o‘zgarishi mumkin.

Ho‘l materialdan 1 kg/mol suvni olib tashlash uchun sarflangan energiya havoning harorati va nisbiy namligiga bog‘liq. Havoning harorati va nisbiy namligi qanchalik yuqori bo‘lsa, namlikni bog‘lash energiyasi shunchalik katta bo‘ladi.

Tayanch iboralar: *quritish, namlik, energiya, harorat, namlik, adsorbsiya, diffuziya, eritma.*

Аннотация: *Растительное сырье, как объект сушки, характеризуется большим количеством воды и малым содержанием сухих веществ. Растительное сырье имеет капиллярно-пористую структуру.*

В пищевых продуктах одновременно содержатся, как связанная, так и свободная влага. Удаление влаги из материала при сушке зависит от общего содержания влаги и формы связи влаги с материалом. Адсорбционная и осмотическая - связанная влага удерживается у поверхности раздела коллоидных частиц с окружающей средой. Пищевые продукты содержат одновременно как связанную, так и свободную влагу. Количественное соотношение между ними зависит от природы продукта. Но даже в одном продукте это соотношение может меняться при измельчении, добавлении добавок, термической обработке и так далее.

Энергия, затраченная на удаление 1 кг/моль воды из влажного материала зависеть от температуры и относительной влажности воздуха. Чем выше температуры и относительной влажности воздуха тем больше энергия связи влаги.

Ключевые слова: *сушка, влага, энергия, температура, влажность, адсорбция, диффузия, раствор.*

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Introduction

Food products undergo various microbiological, biochemical and enzymatic changes during storage, which lead to their spoilage. One of the means of suppressing the growth of microorganisms and enzymatic activity is the removal of moisture by natural or artificial drying [1].

The minimum moisture content at which bacteria develop is 25-30%, mold fungi – 10-15%. When drying, humidity is most often brought to 8-20%, i.e. to a level that prevents the development of microorganisms. Vegetable raw materials, as an object of drying, are characterized by a large amount of water and a low content of dry substances. The bulk of the water is in free form and only about 5% is bound to cellular colloids and is firmly held. This explains the ease of drying fruit and vegetable raw materials to a humidity of 12-14% and makes it difficult to remove residual moisture [2].

Vegetable raw materials have a capillary-porous structure. Its chemical composition is represented by carbohydrates, proteins, lipids. Biologically active substances that determine the taste and biological value of raw materials are contained in small quantities: polyphenols, vitamins, organic acids, minerals. These components are most susceptible to adverse changes during the preparation of the material for drying, as well as during the drying process itself, which leads to a decrease in the biological value of the finished product [3].

Hydrophilic substances in the cell are in the form of aqueous solutions–emulsions and colloidal solutions. The water in the cell is the medium in which all reactions take place. It is distributed unevenly. The amount of water is contained least in the integumentary and seeds. Therefore, the purified, prepared for drying raw materials contain more water than the original.

Basically, plant cells contain: cellulose, hemicellulose, pectin substances, proteins, polyphenolic substances, organic acids, vitamins, minerals. Thus, vegetable raw materials are a complex structural object of drying and dehydration without loss of nutritional qualities is a very difficult task [4].

Material and Methods

Wet food products subjected to drying consist of a solid dry frame, water, a small amount of air and vapors. The process of removing moisture is accompanied by changes in the physico-chemical parameters of the product, its thermophysical characteristics and structural and mechanical properties [5].

Water is the main component of plant cells, it accounts for 75 to 90%. Free moisture is not bound to the molecules of the substance, it can move freely from cell to cell. It is used to nourish and maintain the vital activity of the cell. This is the main amount of moisture [6].

Bound moisture is formed as a result of interaction with the molecules of a substance and is characterized by the following physico-chemical properties. By its properties, bound moisture approaches an elastic solid [7].

Food products contain both bound and free moisture at the same time. The quantitative ratio between them depends on the nature of the product. But even in one product, this ratio can change during grinding, adding additives, heat treatment, and so on.

The removal of moisture from the material during drying depends on the total moisture content and the form of connection of moisture with the material. The connection of moisture with the material is characterized by the value of the free energy of isothermal dehydration – the work required to remove 1 mole of water at a constant temperature without changing the composition of the substance at a given moisture content. The energy expended to remove 1 kg/mol of water from the wet material is determined by equation (1):

$$A = -R \cdot T \cdot \ln\varphi \qquad (1)$$

here: A – is the binding energy of moisture, J/mol;

R – is the universal gas constant, 8.3114 J/(mol·K);

T – is the temperature, °C;

F – is the relative humidity of the air.

Table 1

№	**Relative humidity of the air, %**	**lnφ**	**Moisture binding energy, J/mol**		
			At a temperature of, °C		
			30	50	70
1	10	2,30	573,67	956,308	1336,65
2	20	2,99	745,77	1243,20	1737,64
3	30	3,40	840,02	1400,31	1957,25
4	40	3,69	920,36	1534,24	2144,44
5	50	3,91	975,23	1625,71	2272,29
6	60	4,09	1020,13	1700,56	2376,90
7	70	4,25	1060,04	1767,09	2469,89
8	80	4,38	1092,46	1821,13	2545,43
9	90	4,50	1122,39	1871,02	2615,17
10	100	4,61	1149,83	1916,77	2679,10

If there is free moisture in the material, A = 0. As moisture is removed, the strength of its bond with the material increases and the binding energy A increases. The lower moisture content of the material, the greater value of the binding energy.

Results and Discussion

Chemically bound moisture is divided into water bound in the form of hydroxyl ions and water enclosed in crystallohydrates. Crystallohydrate moisture enters the crystal structure and its removal is possible only during calcination. This moisture is characterized by the number of water molecules that are part of the crystal. The chemical bond is the strongest, chemically bound moisture is practically not removed during drying and does not affect the drying process. The binding energy of chemical moisture is the highest ($1\text{-}100\cdot10^5$ J/mol).

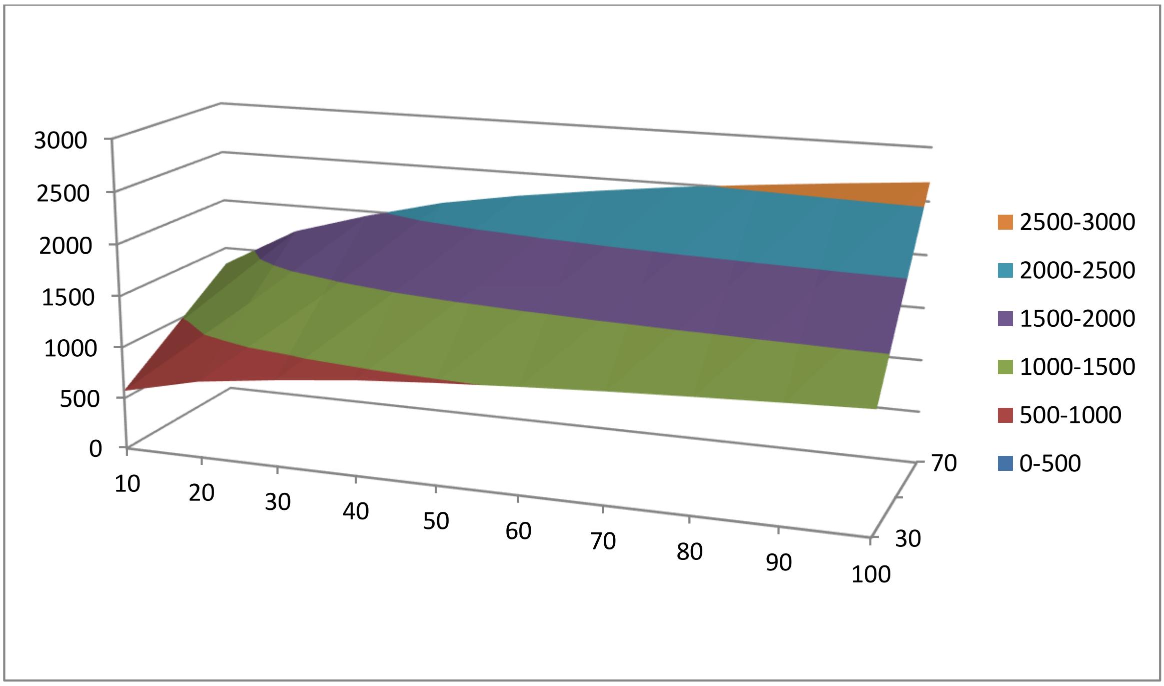

Fig.1. Graph of the dependence of the energy spent on the removal of 1 kg/mol of water depending on the temperature and humidity of the air

Adsorption and osmotic - bound moisture is retained at the interface of colloidal particles with the environment, due to the molecular force interaction of the micelle surface and hydrophilic centers of proteins, carbohydrates and lipids. Most plant products are hydrophilic colloids with high molecular weight, high degree of dispersion (particle size 10^{-7}-10^{-9} m), a large interface, and this leads to the appearance of significant surface energy. Under the influence of excess energy on the inner and outer surface of the material, air and water vapor molecules are absorbed from the surrounding space. This phenomenon is called adsorption. In addition, the usual dissolution of moisture with penetration into the substance may occur on the surface. This phenomenon is called absorption. Or there may be a chemical interaction between moisture and surface substances. This phenomenon is called chemisorption. All these processes are collectively called sorption [8].

The high solvent capacity of water is explained by the dipole nature of its molecules and their ability to form hydrogen bonds. The properties of aqueous solutions depend on the forces of interaction between water molecules and solutes. Osmosis is the process of solvent diffusion through a semipermeable membrane under the action of kinetic energy of molecules. And the shells of the compounds included in the product are semi-permeable. The diffusion of the solvent (water) occurs from an area with a higher partial pressure (lower concentration of the solution) towards a lower partial pressure (higher concentration of the solution). As a result of this process, osmotic pressure arises – a force that causes the diffusion of molecules.

For solutions, the osmotic pressure (P_{osm}) is equal to:

$$P_{osm.} = C\cdot R\cdot T \qquad (2)$$

here: C – is the molar concentration of the solution;

R – is the universal gas constant, J/(mol·K);

T – temperature, ^{o}C.

Table 2

№	Molar concentration of the solution, %	Osmotic pressure, Ps		
		At a temperature of, °C		
		30	50	70
1	10	2494,2	4157	5819,8
2	20	4988,4	8314	11639,6
3	30	7482,6	12471	17459,4
4	40	9976,8	16628	23279,2
5	50	12471	20785	29099
6	60	14965,2	24942	34918,8
7	70	17459,4	29099	40738,6
8	80	19953,6	33256	46558,4
9	90	22447,8	37413	52378,2
10	100	24942	41570	58198

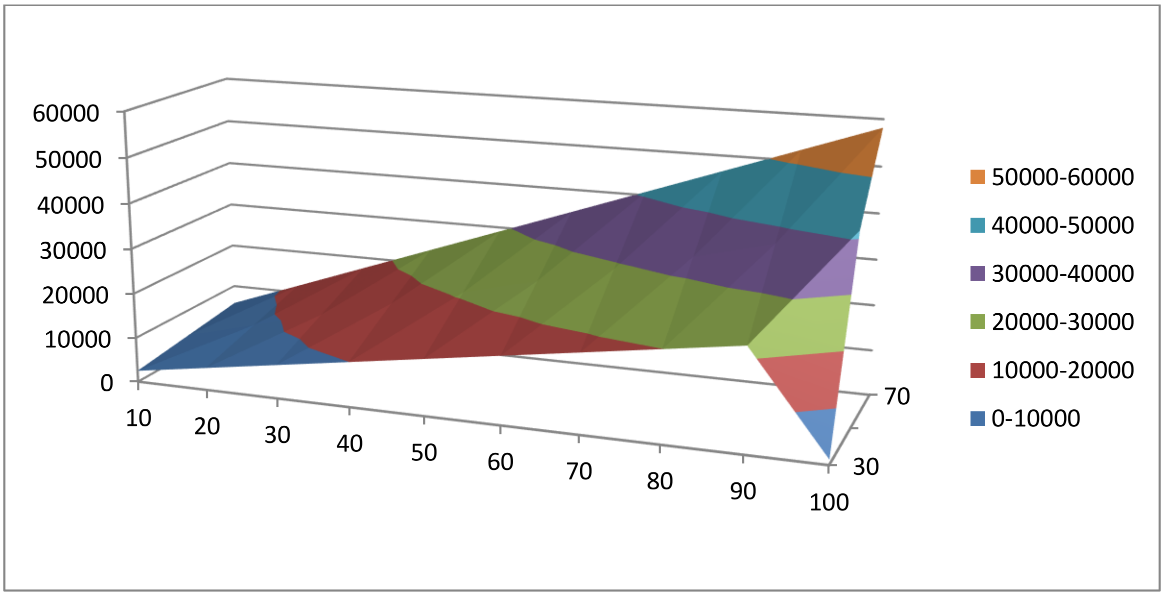

Fig.2. Graph osmotic pressure as a function of temperature and molar concentration of the solution

As a result, the water in the cell is in a state of turgor (bound by osmotic forces). Since the cell membranes are elastic, they can withstand such stress. This condition creates a support for tissues. Therefore, the quality of many fruits and vegetables depends on the state of their turgor. With an excess of moisture, the turgor increases, this can lead to cracking of fruits and vegetables. When there is a lack of moisture, plasmolysis occurs – the cytoplasmic membrane shrinks and separates from the cell membrane [9].

Osmotic bound moisture is located inside the cells as if in a semipermeable pouch, does not differ from ordinary water, moves inside the material during drying without phase transformation in the form of a liquid. The process of removing this moisture from the cells is similar and opposite to its osmotic penetration into the cells.

The binding energy of osmotically bound moisture is determined by equation (3):

$$A = - R \cdot T \cdot \ln n_0 \qquad (3)$$

here: n_0 – molar fraction of water in solution ($n_0 = 1 - n_1$);

n_1 – molar fraction of the solute.

Table 3

№	Molar fraction of water in solution, %	ln n_0	Osmotic bound moisture binding energy, J/mol		
			At a temperature of, °C		
			30	50	70
1	*2*	*3*	*4*	*5*	*6*
1	10	2,30	573,67	956,308	1336,65
2	20	2,99	745,77	1243,20	1737,64
3	30	3,40	840,02	1400,31	1957,25
4	40	3,69	920,36	1534,24	2144,44

5	50	3,91	975,23	1625,71	2272,29
6	60	4,09	1020,13	1700,56	2376,90
7	70	4,25	1060,04	1767,09	2469,89
8	80	4,38	1092,46	1821,13	2545,43
9	90	4,50	1122,39	1871,02	2615,17
10.	100	4,61	1149,83	1916,77	2679,10

Mechanically bound moisture is the weakest, retained by filling macro- and microcapillaries. Plant tissues have, depending on the size of the pores, a micro- or macro-capillary structure. Therefore, this moisture is also called capillary-bound.

Capillaries with a smaller radius have a lower surface pressure than wider ones, so the water in them rises to a greater height. During the drying process, water from the macrocapillaries moves to smaller ones and evaporates from there. At the same time, the moisture level in large capillaries decreases, and in small ones it remains constant [10].

Water contained in microcapillaries differs from free water by lower viscosity and surface tension and greater heat capacity. The freezing point of such moisture is less than 0°C. The binding energy in microcapillaries is determined by equation (4):

$$A = 2 \cdot \sigma \cdot V_0 / r \qquad (4)$$

here: σ - is the surface tension at the boundary of water with a vapor-air mixture, at a temperature of 20 °C is equal to 7,4 10^{-3} N/m;

V_0 – specific volume at temperature 20 °C equal to 1000kg/m^3;

r – capillary radius, m

Capillary radius, m 10^{-3}	0,5	0,4	0,3	0,2	0,1
Binding energy in microcapillaries, J/mol	29,6	37,0	49,3	74,0	148,0

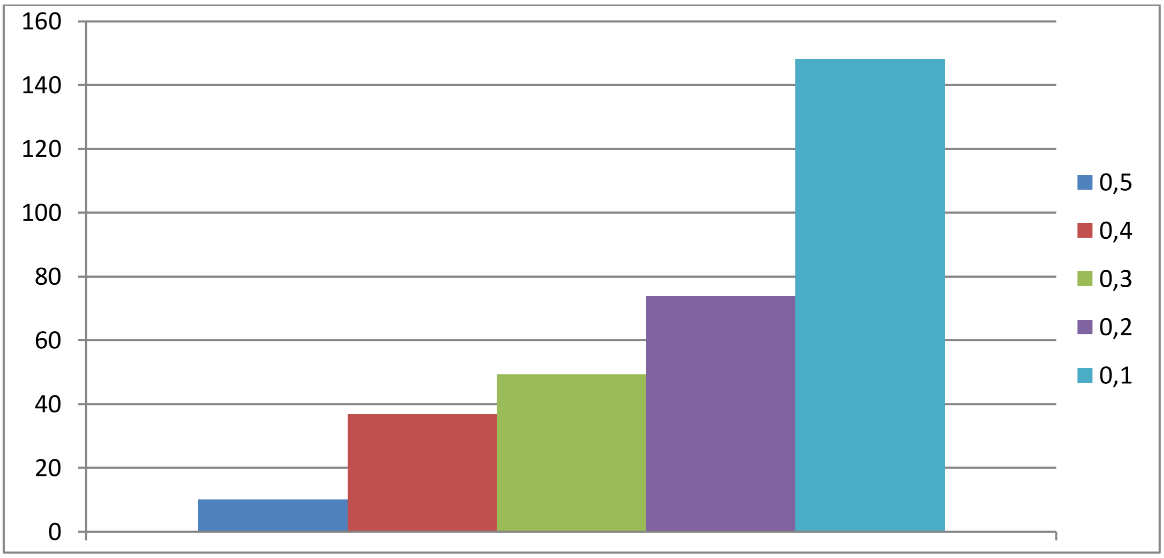

Fig.3. Graph of the dependence of the binding energy in microcapillaries on the radius of the capillary

This equation indicates an increase in the binding energy with a decrease in the radius of the capillaries. Mechanically bound moisture practically does not differ from the properties of free water, it can be considered as free moisture, which is easily removed during drying in the first place.

Conclusion

1. Water is the main component of plant cells, it accounts for 75 to 90%, the rest of the substances is 10 to 25%. Humidity is denoted by the letter W and is determined by the following formula;

$$W = M_{water}/(M_{water}+M_{things})$$

here: M_{water} - water mass;

M_{things} - mass of the substance (except water).

2. The energy expended to remove 1 kg/mol of water from the wet material depends on the temperature and relative humidity of the air. The higher the temperature and relative humidity of the air, the greater the binding energy of moisture.

3. If there is free moisture in the material, A = 0. As moisture is removed, the strength of its bond with the material increases and the binding energy A increases. The lower the moisture content of the material, the greater the value of the binding energy.

4. Under the influence of excess energy on the inner and outer surface of the material, air and water vapor molecules are absorbed from the surrounding space. This humidity is called the equilibrium moisture content and is denoted by W_p.

5. The diffusion of the solvent (water) occurs from an area with a higher partial pressure (lower concentration of the solution) towards a lower partial pressure (higher concentration of the solution). As a result of this process, osmotic pressure arises – a force that causes the diffusion of molecules.

6. Osmotic bound moisture is located inside the cells as if in a semipermeable pouch, does not differ from ordinary water, moves inside the material during drying without phase transformation in the form of a liquid. The process of removing this moisture from the cells is similar and opposite to its osmotic penetration into the cells.

7. Water in microcapillaries differs from free water by lower viscosity and surface tension and greater heat capacity. The freezing point of such moisture is less than 0^{o}C.

8. Mechanically bound moisture practically does not differ from the properties of free water, it can be considered as free moisture, which is easily removed during drying in the first place.

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IMPROVEMENT OF CONVECTIVE DRYING EQUIPMENT

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Abstract. *Drying of agricultural raw materials is an energy-consuming but integral process. Therefore, increasing the efficiency of drying and improving the quality indicators of dried material at minimum material and energy costs is relevant for producers of agricultural products. By present time numerous researches on improvement of constructions and processes of work of dryers providing satisfactory parameters of energy saving have been carried out. In some scientific materials it is shown that the use of generative gas and straw as fuel allows to reduce energy costs for the drying process in the fluidised bed dryer by 10-30%, the quality of seeds was not taken into account.*

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