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DETERMINATION OF DEPENDENCE BETWEEN THERMOPHYSICAL PROPERTIES AND STRUCTURAL-AND-PHASE CHARACTERISTICS OF MOIST MATERIALS

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Abstract: Most of foods, raw materials and half-finished products are disperse systems. One of the most energy-consuming processes during foods production is drying. Intensive study of this process allows high-quality final products to be obtained at lower energy consumption. The aim of the research is to determine the interrelation between thermophysical properties and structural-and-phase characteristics of moist materials to establish optimum parameters for drying. A set of experiments has been made to find the influence of temperature on rheological properties of suspensions. A suspension of 40% chokeberry juice and ultradisperse starch from berry meal was used as the object of the research. Thermostatting was carried out in the range from 20 to 50°C with an increment of 10°C. The thermal conductivity coefficient for blocked samples with dimensions of 50×50×75 m^{-3} was determined by means of a continuous plate flat source. Samples were prepared using the plastic mass forming method at the pressure of 50 MPa and the moisture of mass of 15%, and then dried. The results show that yield stress increases with temperature because of coagulation structuring intensification. The material has the highest thermal conductivity at the least capillary moisture of W_{LCM} =14.2%, i.e. when a monomolecular layer of tightly bound water takes on the property of continuity through the material. The obtained results allow us to conclude that the use of volume phase characteristics makes it possible to improve the technique for determining thermophysical characteristics of dry and wet disperse systems to be improved, which in turn allows obtained results to be more accurate.

Keywords: Granulation, granules, powder, drying, phase characteristics

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INTRODUCTION

Dehydration is the main technological peculiarity when producing foods based on disperse systems. Water – together with smaller particles – forms suspensions and acts as a plasticizing agent during granule formation. Dehydration causes chemical, biochemical, rheological, mechanical and other changes in a material that in turn lead to mass and volume decreases, strength and lifetime increases, and etc. There are physicochemical, mechanical, thermal methods of dehydration [1]. The latter is more often being used to remove water from fine particle fractions.

A factor of drying is the partial pressure difference of vapour on the surface of the material being dried and in ambient medium [2]. The influence of operating parameters on the efficiency and time of drying, and the problems of product shrinkage and crack formation have been studied by such researchers as A.V. Lykov, A.S. Ginzburg, P.S. Kossovich, P.D. Lebedev, B.S. Sazhin, M.Yu. Lur'e, V.I. Mushtaev, B.N. Gak, O.S. Zaytsev [3].

The aim of the research is to determine the interrelation between thermophysical properties of moist materials and their structural-and-phase characteristics.

OBJECTS AND METHODS OF STUDY

In the theory of drying the object of the research are moist materials, their behavior during dehydration under different conditions and prediction of the process with time using drying sensitivity coefficients and crack formation criteria. These coefficients are calculated on the basis of mass balance using the weigh moisture content of materials. When drying free-disperse systems, e.g., wet berry meal, starch, and polysaccharide, it is enough to know mass balance of substances to describe drying. The case is different with structured disperse systems; apart from mass balance (sizes and geometrical form of particles are known preliminarily) total volume balance of mixture components should be used [4]. It is calculated according to the formula:

$$C_G + C_S + C_L = 1, \qquad (1)$$

where C_G, C_S and C_L are volume concentrations of gas, solid and liquid phases.

The equation is valid throughout drying independently of materials properties and process rate. When moisture completely is removed, a three-phase system becomes a two-phase one; the following formula is true:

$$C_G + C_S = 1. \tag{2}$$

The use of phase characteristics of disperse systems allows us to evaluate the efficiency of dehydration and the quality of dried foods. At present, the latter is the main criteria for evaluating the former. Quality evaluation is performed visually taking into account the presence of cracks and the degree of linear and volumetric shrinkage [5].

Solid-phase volume concentrations should be used as the criteria to determine the efficiency of dehydration both under static conditions and during material structure forming. At present, mass and heat balances and Ramzin i-d diagram are used when studying drying [6, 7]. This technique allows us to determine the temperature of a drying agent and change in dried material moisture content during the process. Drying of shaped materials requires controlling of such parameters of drying agent as rate, temperature, moisture and geometry of material; it is frequently difficult to do this using the moisture content as a controlling parameter, therefore, the use of volumetric characteristic of the object is possible to exclude errors.

There is a strong relation between structure and phase characteristics of disperse systems. For example, a new system with quite new properties (flowability, homogeneity of material, plastic and strength properties) will be obtained as a result of drying of a two-component “solid – liquid” system. Rheological, structural and mechanical properties of the system and its formability can be predicted if material moisture, porous substance properties (fine particle fraction with high specific surface) and properties of structure-forming framework are known. The amount of liquid component in the system predetermines strength and size of the formed crystallization structure; however, solid phase properties in the newly-formed disperse system do not influence the dependence between solid phase volume concentration and the material moisture content at $W \geq W_{LCM}$, where W is the moisture of material and W_{LCM} is the least capillary moisture [5]:

$$C_S = b \cdot W + a, \tag{3}$$

where *a* and *b* are constants determined empirically.

Drying can be considered as a reverse process of mass forming, i.e. a disperse system consisting of continuous and solid phases; however, Eq. (3) would be valid as well at various factors of changes in material structure during drying. To determine these changes the difference in the processes mentioned should be considered [8]. Assume that a two-component system consists of a structural framework and a porous substance. The latter is fine dispersed particles which bind major part of water and, thereby, form a suspension. Coarse dispersed particles form a framework of a molding compounds and are not able to bind much water. Water-binding mechanism with a fine dispersed fraction having small median sizes has been studied by the following researchers [6]: B.V. Deryagin, A.V. Dumansky, M.H. Carapet’yants, N.N. Kruglitsky, S.P. Nichiporenko, G.V. Kukolev and others. The system consists of liquid and dispersed phases, water-binding capacity of the latter directly depends on its physical and chemical properties, e. g., a large-size starch granule has a layer-like structure, and its top layers are formed mainly by molecules of branch structure known as amylopectin [9]. The decrease of water content inside the starch granule causes pressure increase. As a result X-shaped cracks are formed on its surface. Starch is able to absorb up to 21% of water but only 6% is bound. When temperature increases up to 50–60°C starch granules tend to swell; water penetrates into macromolecules causing hydrogen bonds breakage. Apart from thermal treatment, starch swelling can be achieved by introduction of solutions with high pH (on the order of 10). Jellies contain acids however their concentration causes pH to be 4–7. This is an accepted value in food industry and does not affect the structural framework of granules [10]. Powdered sugar has more water-absorbing ability than starch granules, sucrose crystals are losing their strength when moisture is about 8%. We can conclude that suspension properties of molding compounds or granules depend on sorption activity, wetting ability, swelling ability, ion exchange ability and colloidal and chemical properties. Is should be noted that swelling ability is a essential parameter for forming structure during drying, as water removal from the system leads to volume decrease; i.e., the process is opposite to swelling [1].

Shrinking and swelling of a system takes much time, therefore, the optimum time of drying should be established to prepare the molding compound. It is not easily to perform because of operating costs. Drying is the most expensive process in instant beverage production. The increase of drying rate has both advantages and disadvantages. One of the disadvantages is crack formation, which disrupts obtained product structure [9]. Apart from that, increased temperature leads to increased solubility of such components as lactose, sucrose or fructose that gives rise to the increase of the liquid phase volume that in turn adversely affects obtained granules strength. Consequently, such variables as property of dried material, operating parameters and technical and economic characteristics should be taken into account when determining optimum parameters of drying [11].

Traditional technology of instant beverage production includes drying dump granules. During the process the suspension is heated. A number of experiments have been studied to establish the effect of temperature on rheological properties of the suspension. A suspension of 40% chokeberry juice and ultradisperse starch from berry meal was used as the object of the research. Thermostatting was carried out in the range from 20 to 50°C with an increment of 10°C. Time and conditions of preparing suspension samples were strictly observed and were constant. Table 1 gives rheological parameters of the system as a function of temperature, where Θ is modulus of elasticity, η is internal friction and Ψ is sharing rate.

Table 1. Effect of temperature on rheological properties of suspension

Rheological parameters	Temperature, °C			
	20	30	40	50
Θ, dyne	270	290	340	470
η_1, poise	2.24	1.68	1.26	1.02
Ψ_1, s^{-1}	113	121	142	196

We can see that yield stress increases with temperature. That is because of coagulation structuring intensification. Viscosity value of the suspension changes twofold; similar situation is observed for water: the increase in temperature from 20 to 50°C reduces its viscosity from 0.001 Pa·s down to 0.00055 Pa·s. Solubility of sucrose in saturated solution of chokeberry juice rises by 25%, i.e., liquid phase volume increases. Taking into account changes in rheological parameters, it follows that plasticity rises sharply with temperature. In practice, we may observe it during the first stage of drying when granulate becomes softer. Dependences obtained can be true only for structured disperse systems that form the single pseudo phase.

Any material is capable of resistance to shrinking stress under certain conditions [12]:

(1) The material must contain minimal amount of capillary moving water before drying. This will help to produce higher homogeneity and less material shrinking, and prevent transfer of soluble substances into the liquid phase.

(2) Adhesive forces acting between structural framework particles must be equal to cohesion ones acting between particles of the suspension.

(3) Whey proteins or surfactants should be used to obtain particles of molecular size which, thus, conduce the balance between adhesive and cohesive forces during drying.

(4) Granulometric composition must insure particles to be packed tightly; this is achieved by structural framework and porous substance quantitative ratio.

(5) It is necessary to reduce suspension shrinking in order to increase hardness of obtained granules during drying and the solid-phase volume concentration. It can be achieved by introduction of a small quantity of modified starch or protein (up to 1.5%). Molecules penetrate into space between large grains, thus limiting mobility of large grains [13].

(6) Granulating should be performed at the drying temperature in order to decrease the volume of the liquid needed for coagulation to occur. Pellets formation process is attended by hydration; the amount of the liquid tends to be reduced, which provides hardness of granules.

Operating parameters of drying directly influence the crystallization rate of sucrose or lactose and the shrinkage of the material [14, 15, 16]. Drying regime, at which the decrease of the system volume is directly proportional to the increase of starch and meal volume during swelling, is the most optimum one. Shrinkage value depends on the drying rate. The higher operating parameters, the faster final shrinkage can be achieved. One should remember that shrinking will go on until capillary moving water is fully removed (even if volume shrinkage is stopped). Moreover, process rate effects distribution of temperature and moisture content across the material, especially for large cross-section granules. It implies irregular water distribution and shrinkage of layers during the process. Consequently, external layers reduce their volume, while internal ones keep their initial volume over time preventing granule shrinkage. It follows that tension forces act on the surface and compressing forces act inside. This leads to serious deformations and crack formation as a result. Professor A.F. Chizhsky has established the crack formation criterion based on the fact that an acting forces magnitude is proportional to the moisture difference between external and internal layers, product thickness being of no importance [17]:

$$\Delta W_{max} = W_{AV} - W_S, \qquad (4)$$

where ΔW_{max} is the maximum allowed moisture difference, %; W_{AV} is the average moisture of the sample, %; and W_S is the moisture on the sample surface, %.

For parabolic distribution of water, ΔW_{max} is equal (at constant rate of drying) to:

$$W_{max} = W_C - W_S\,, \qquad (5)$$

where W_C is the moisture in a central layer of the sample, %.

Academician A.V. Lykov suggested dimensionless similarity criteria [7]:

$$K = \frac{(W_{AV} - W_S)}{W_{in}}, \qquad (6)$$

$$K_i = \frac{2(W_C - W_S)}{W_{in}}, \qquad (7)$$

where K is the crack formation criterion, %; K_i is the Kirpichev's mass exchange criterion; W_{in} is the initial moisture of the material, %.

M.S. Belopol'sky has proved that sensitivity of disperse mass to drying can be described by two coefficients for soft-mud molding products. The first coefficient describes formation of cracks on the surface during surface layer shrinking, while the second one describes formation of internal cracks on the final stage of its shrinking. The values in the expression for determining the sensitivity coefficient of disperse materials to drying characterize structural-and-mechanical and thermophysical properties of the system that effect crack formation.

There are a number of difficulties in describing the process by using differential equations of heat-and-moisture transfer. Therefore, it is more convenient to use such similarity criteria of heat-and-mass transfer as Lykov (Lu), Posnov (Pn), Kirpichev (Ki), Vio (Bi), Kossovich (Ko), Fourier (Fo), Rebinder (Rb) criteria.

Lykov criterion is an analogue of the Lewis number and characterizes the relation between heat and mass transfer in disperse systems. Mass transfer goes on faster than heat transfer if Lu>1 [6]:

$$Lu = \frac{a_m}{a_q}, \tag{8}$$

where a_m is the water conductivity coefficient, m^2/s; a_q is the thermal diffusivity, m^2/s.

Posnov criterion determines the relative fall of moisture content inside the material caused by temperature difference. In other words, the change in water potential depending on that of temperature is estimated [4].

$$Pn = \frac{\delta_{\text{T}}\cdot\Delta t}{\Delta u}, \tag{9}$$

where δ_{T} is the thermal-gradient coefficient, kg/kg·deg; Δt is the temperature difference, deg; and Δu is the moisture content difference, kg/kg.

Kirpichev number characterizes the relation between intensity of internal and external moisture transfer [6]:

$$K_i = \frac{j_m\cdot l}{a_m\cdot\rho\cdot\Delta u}, \tag{10}$$

where j_m is the evaporation rate, kg/m^2·s); l is geometric dimension, m; and ρ is the liquid density, kg/m^3.

Vio criterion characterizes the ratio of heat input to the surface and heat output from the surface of the body to its inner layers due to thermal conductivity [7]:

$$B_i = \frac{\beta_m\cdot l}{a_m}, \tag{11}$$

where β_m is the mass exchange coefficient divided by the moisture content difference, m/s).

Kossovich criterion shows the ratio of specific heat spent on evaporation of all moisture removed to specific heat used to heat up the moist material [6]:

$$K_o = \frac{r\cdot\Delta u}{c_{\text{T}}\cdot\Delta t}, \tag{12}$$

where r is the specific heat of evaporation, kJ/kg; c_{T} is the specific heat capacity of the moist material, kJ/kg·deg.

Fourier criterion is a measure of heat saturation of the material and characterizes the process instability and governs change of moisture field (F_{om}) or temperature field (F_{oq}) in the material with time [6, 7]:

$$F_{om} = \frac{a_m\cdot\tau}{2l} \text{ or } F_{oq} = \frac{a_q\cdot\tau}{2l} \tag{13}$$

where τ is time, s.

Rebinder criterion is the main parameter of drying kinetics determining the ratio of heat needed to heat up wet material to heat needed to evaporate moisture for infinitely small period [7, 8]:

$$Rb = \frac{c}{r}\frac{dt}{du}, \tag{14}$$

where c is the specific heat capacity of dry material, kJ/kg·deg; u is the average material moisture content, kg/kg; and t is the average material temperature, deg.

Analysis of parameters mentioned above lets us distinguish four groups of factors that influence drying: properties of liquid (ρ, r), properties of the material being dried (c_{T}, c, β_{T}, a_m, a_q), geometry of the body being dried (l), and operating drying parameters (j_m, u, t, τ, Δu, Δt). Two last factors effect irregularity in temperature fields and moisture content distribution across the material: the higher these parameters between the surface of the material and its center in the cross section, the more difficult to ensure continuity of the structure. Liquid component properties in the system influence energy consumption for its evaporation. Properties of the material being dried are characterized by its thermophysical characteristics but thermal diffusivity is more informative [7]:

$$a_w = \frac{\lambda_w}{c_{pw}\cdot\rho_w}, \tag{15}$$

where a_w is the thermal diffusivity, m^2·s; c_{pw} is the wet material heat capacity at constant pressure, kJ/kg·deg; ρ_w is the wet material density, kg/m; λ_w is the wet material thermal conductivity coefficient, W/m·deg; $c_{pw}\cdot\rho_w$ is the volume heat capacity, kJ/m·deg.

The thermal diffusivity in terms of physics is diffusivity of heat. According to eq. (15) and Fourier equation, molecular heat conduction q may be represented:

$$q = -a_{\text{p}}\cdot\rho\nabla H, \tag{16}$$

where a_{p} is the thermal diffusivity divided by enthalpy, and ∇H is enthalpy gradient. Here, a_{P} is the diffusivity of enthalpy and $c_p\cdot\ \rho$ characterizes heat-storage capacity of volume unit of the material. It implies that heat capacity should be determined as the sum of all volume fractions included in the wet material:

$$\text{c}_w = \text{c}_s\cdot\text{C}_s + \text{c}_G\cdot\text{C}_G + \text{c}_L\cdot\text{C}_L, \tag{17}$$

where c_G, c_S and c_L are specific heat of gas, solid and liquid phases.

It can be concluded that the thermal conductivity may be calculated in terms of additivity rule and its magnitude does not depend on mass of the material. Kirsher in his researches used follow formulas to determine the thermal conductivity coefficient [3]:

– for heat transfer along layers:

$$\lambda_{mix} = \ 1 - P\ \lambda_S + P\lambda_L, \tag{18}$$

– for heat transfer across layers:

$$\lambda_{mix} = \frac{\lambda_S\cdot\lambda_L}{1-P\ \lambda_S+P\lambda_L}, \tag{19}$$

where P is the porosity of layer; λ_S, λ_L, λ_{mix} are thermal conductivity coefficients of solid, liquid phases and their mixture.

Such Russian scientists as K.S. Krasnov, V.A. Lotov, and B.S. Sazhin suggested various dependencies to determine the thermal conductivity coefficient for moist disperse materials. It should be noted, however, that all of them are empirical because they do not make allowance for volume phase composition compared to Kircher formula. The last takes into account volume concentrations of liquid and solid phases, nevertheless, the results may have some error. Consequently, the thermal conductivity coefficient of disperse materials should be calculated allowing for all phases volume presented in the system being subject to drying. According to the reference data, thermal conductivity of blocked food systems is within the range from 0.1 to 0.9 W/m·deg (these values for water and air are 0.58 and 0.023 W/m·deg, respectively). Volume fraction of each phase depends on their density, for example, low mass of gas phase has low density as well and occupies more volume in the system. Also gas phase has low thermal conductivity. It means that it will offer resistance to heat transfer during drying. Therefore, thermal conductivity directly depends on each phase volume concentration and their thermal resistance. Taking into account mentioned above, the thermal conductivity coefficient equation for disperse materials will take the following form:

$$\lambda_w = \frac{\mathrm{C}_S + \mathrm{C}_L \ / \ 1 - \mathrm{C}_S}{\frac{\mathrm{C}_S \cdot \alpha_1}{\lambda_{S1}} + \frac{\mathrm{C}_S \cdot \alpha_2}{\lambda_{S2}} + \frac{\mathrm{C}_S \cdot \alpha_3}{\lambda_{S3}} + \frac{\mathrm{C}_L}{\lambda_L} + \frac{\mathrm{C}_G}{\lambda_G}} \tag{20}$$

where λ_S, λ_L, λ_G, λ_w are thermal conductivity coefficients of solid, liquid, gas phases and disperse material; and α_1, α_2, α_3 are volume concentration factors of solid phase components. All of three phases are taken into consideration in the numerator, however, if $\mathrm{C}_L = 0$, it will include the ratio of solid and gas phases.

$$\alpha_1 + \alpha_2 + \alpha_3 = 1 \tag{21}$$

A number of experiments have made on a model mixture to determine the thermal conductivity coefficient to establish accuracy of eq. (20). Table 2 gives component composition of the mixture.

Table 2. Composition of studying mixture

Component	Content,%
Sugar	60
Starch	25
Chokeberry meal	15
Premixes	0.01 (above 100%)

The thermal conductivity coefficient for blocked samples with dimensions of 50 × 50 × 75 mm was determined by means of the continuous plate flat source Samples were prepared using the plastic mass forming method at the pressure of 50 MPa; the moisture of the mass was 15%. After pressing, samples were subject to air drying and then inside the drier at the constant temperature of 60°C; further, samples have been cooled in the exiccator up to 20°C for 24 hours. The thermal conductivity coefficient of the dry mixture was determined experimentally; its average value was 0.0696 W/m·deg. For the wet mixture, the thermal conductivity coefficient and the heat capacity factor were calculated using eq. (18), (19) on the basis of the data represented in Table 3 and obtained by calculation and experimentally.

According to the reference data, the heat capacity of solid, liquid and gas phases were taken 0.838, 4.19 and 1.005 kJ/kg·K, respectively. The results are given in Table 4. Moisture conduction was computed from the capillary absorption coefficient K_{ci}, m^2/s:

$$W = 0.344 \cdot 10^6 K_{ci} + 0.142, \tag{22}$$

$$\mathrm{C}_s = -0.52 \cdot K_{ci} + 0.74. \tag{23}$$

RESULTS AND DISCUSSION

We can see from Table 4 that the capillary absorption coefficient equals zero if the moisture of the mixture is less than the least capillary moisture $\mathrm{W}_{\mathrm{LCM}}$ (0.142). This water can be removed by drying and Lykov criterion can be found when capillary moving water emerges, implying that $\mathrm{W} > \mathrm{W}_{\mathrm{LCM}}$. If the moisture of the material is 19%, $K_{ci}=1$ due to the equilibrium rate of iso-concentration and isothermal surfaces. These conditions are optimal for drying. However, at W>0.19, Lu>1 implying that drying would proceed at constant rate and water diffusion rate would be higher than heat diffusion rate. Moreover, all energy supplied to the material is spent on water evaporation from the surface and energy movement from the center to the surface. It implies that when moving capillary water temperature in the center of the material would be much lower than drying temperature; the water movement process dominates. However, when capillary moving water would be removed, the temperature of the material would rise because of water evaporation from internal layers. Therefore, diffusivity dominates on this stage of drying. Figure 1 illustrates the relation between thermophysical properties and moisture content of the studied material.

Table 3. Calculated and experimental properties of studying mixture

W_i, rel.units	P_{press}, MPa	P_w, $\mathrm{kg/m^3}$	P_S, $\mathrm{kg/m^3}$	C_S	C_L	C_G	$\frac{\mathrm{C}_L + \mathrm{C}_G}{\mathrm{C}_S}$	S_v, $\mathrm{cm^2/cm^3}$	$\delta_{\text{envelope}} \times 10^{-7}$, m
0.178	18.50	2047	1738	0.690	0.309	0.001	0.449	8816	5.09
0.203	8.80	2003	1665	0.661	0.338	0.001	0.513	8446	6.07
0.228	4.45	1955	1592	0.632	0.363	0.005	0.582	8076	7.20
0.245	3.50	1919	1542	0.612	0.378	0.010	0.634	7822	8.10
0.281	1.71	1835	1433	0.569	0.403	0.028	0.757	7269	10.41
0.307	1.45	1775	1358	0.539	0.417	0.044	0.855	6889	12.41
0.325	0.96	1726	1303	0.517	0.423	0.060	0.934	6610	14.13
0.350	0.70	1652	1224	0.486	0.429	0.085	1.057	6209	17.02
0.369	0.50	1607	1174	0.466	0.433	0.101	1.145	5955	19.22

Table 4. Thermophysical properties of wet mixture

W_{abs}	p_w, kg/m^3	p_{dr}, kg/m^3	C_S	C_L	C_G	λ_w, W/m·deg	c_w, kJ/kg·deg	$a_w\times10^7$, m^2/s	$K_{ci}\times10^6$, m^2/s	Lu
0.051	1235	1156	0.630	0.079	0.290	0.140	1.150	0.206	–	–
0.082	1336	1205	0.650	0.131	0.220	0.208	1.313	0.253	–	–
0.100	1474	1304	0.690	0.170	0.140	0.376	1.510	0.369	–	–
0.121	1587	1373	0.718	0.214	0.068	0.758	1.566	0.676	–	–
0.142	1687	1328	0.740	0.260	–	1.883	1.709	1.466	0.000	0.00
0.158	1647	1368	0.716	0.279	0.005	2.028	1.774	1.550	0.046	0.30
0.181	1612	1304	0.690	0.308	0.002	1.999	1.870	1.475	0.113	0.76
0.198	1576	1250	0.670	0.327	0.003	1.822	1.934	1.324	0.162	1.22
0.218	1536	1190	0.644	0.347	0.009	1.453	2.002	1.041	0.221	2.12
0.236	1491	1130	0.620	0.361	0.019	1.102	2.051	0.789	0.273	3.46
0.252	1445	1074	0.597	0.372	0.031	0.844	2.090	0.607	0.319	5.25
0.275	1378	995	0.565	0.383	0.052	0.582	2.130	0.426	0.386	9.06
0,297	1306	916	0.533	0.391	0.076	0.415	2.161	0.312	0.450	14.42
0.319	1258	857	0.509	0.401	0.090	0.346	2.196	0.263	0.514	19.54
0.335	1182	785	0.480	0.397	0.123	0.249	2.188	0.200	0.561	28.05

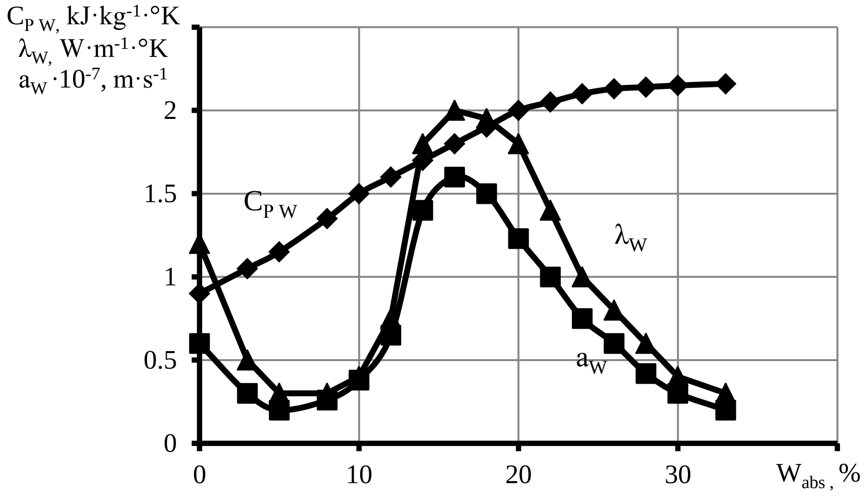

Fig. 1. Relation between thermophysical properties and moisture content of material.

According to Table 4, heat capacity of the studied mixture increases linearly up to its moisture optimal value (W = 0.24) and then heat capacity alters slightly, in spite of change in phase state of the material. This is because moisture content increases more intensively due to the fact that the liquid phase volume concentration alters more than that of solid phase since these phases have different density. Water has the highest heat capacity and with growing of hydration shells it would contribute increasing heat capacity until liquid layer thickness between particles reaches $1.5\cdot10^{-6}$ m. It should be noted that flow of the liquid takes on the property of continuity, and further increase of the liquid layer thickness has no significant effect on the heat-storage capacity of the material. Material with low moisture exhibits high thermal resistance because of gas phase presence; however, thermal conductivity of the material sharply rises up to 16% when moisture is 10–12%. For this moisture value, the thermal conductivity coefficient is higher than for all other phases. This is because of high thermal conductivity of wet materials. For the first time the phenomenon was found by M.S. Metsik: under the influence of force field in solid phase, water molecules are oriented so that the layer of tightly bound water in the form of ice-like crystalline framework is formed. We can presuppose that molecular layers of water do not exhibit significant thermal resistance because of Brownian motion absence. It follows from Fig. 1 that the material has the maximum thermal conductivity at the least capillary moisture W_{LCM} = 14.2%, i.e. when a monomolecular layer of tightly bound water takes on the property of continuity over volume of the material. For the studied mixture, we can obtain water molecule diameter at W_{LCM}-$\delta_{envelope}$ = $7\cdot10^{-7}$m using the equation for calculating the water layer thickness on the particle surface and the data from Table 4; its value is 0.276 nm. It implies that at W_{LCM} the particle surface is capable of retaining of 700/0.276 ≈ 2500 molecular layers of water. The value is relative since some water is held in capillary vessels by capillary forces but it gives general understanding of increase in the least capillary moisture which characterizes quantitative and qualitative changes in the disperse system on any stage of production process.

On the basis of findings obtained we can conclude that the use of volume phase characteristics allows the technique for determining thermophysical characteristics of dry and wet disperse systems to be improved, which in turn allows the obtained results to be more accurate. It may be used for more detailed understanding of thermal conductivity of wet materials to predict both changes in thermophysical properties and behavior of different materials during process taking into account Lykov criterion. Mentioning different materials, we mean materials including different phase contents.

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