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# Study of the Kinetics of Vacuum Drying of Hard and Semihard Cheeses

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## Abstract

The chapter considers cheeses as an object of drying process. It describes the changes occurring in the cheese during the drying process. The results of experimental studies of cheese vacuum drying are presented as well. The kinetics of cheese vacuum drying is investigated. Such important indicator as the shrinkage losses of cheeses in the process of vacuum drying was studied. It has been established that cheese vacuum drying proceeds in two steps: at constant drying speed and at falling one. By graphic differentiation, the curves of the speed of cheese drying were constructed. It was determined by an analytical method that the moisture content of polymolecular adsorption for cheeses is 4–9%. The values of equilibrium moisture for cheese vacuum drying were established. The dependences of the coefficients of cheese shrinkage on the thickness of the drying layer, the shape, and size of grinding were obtained. When the thickness of the drying layer is from 10 to 30 mm, the coefficient of cheese shrinkage, depending on the shape and size of grinding, is from 3 to 14%. With an increase in the mass fraction of moisture in cheeses, the shrinkage coefficient increases as well.

**Keywords:** kinetics, vacuum drying, cheeses, temperature, shrinkage, moisture, drying the adjusted, heat, drying curves

## 1. Introduction

Considering cheese as an object of drying, it should be noted that the change in the cheese properties during the drying process depends on both the physicochemical properties, the structure, the binding forms of moisture in the material, and the thermophysical characteristics that take into account the features of mass and energy transfer.

The main structural elements of the cheese are the macrograins, the interlayer between the macrograins, the microvoids, and the micrograins. The basis of each macrograin structure is a protein network, in the cells of which numerous micrograins are interspersed in the form of fat drops, lipid drops, and crystalline formations.

The transition of fat from milk to cheese depends on many factors. Most of the fat balls are transferred (under all other conditions) to medium-sized fat and then to small and large fat [1, 2]. Milk fat is considered to be the most valuable component of milk, although in terms of the nutrition physiology, milk proteins are

superior in value to milk fat. Four factors determine the special significance of milk fat in milk and dairy products: economic value, nutritional value, taste, and physical properties of fat-containing dairy products caused by the presence of fat [2].

During maturation, all components of the cheese mass are exposed with profound changes; as a result of which, the proper consistency and drawing of this type of cheese are acquired [3].

Cheese humidity depends on the technological mode of production, temperature and duration of rennet clotting, temperature of the second heating stage, partial salting of the curd mass in the grain, and adding water during the second heating stage, as well as on the duration of the cheese grain processing. With a decrease in the clotting temperature and the temperature of the second heating stage, the moisture capacity of the curd and the water content in the finished product increase. As the temperature rises, the moisture content in the cheese decreases. Loss of moisture occurs at the stage of salting (osmotic transfer of water) and during the period of maturation (evaporation). The intensity of the microbiological and biochemical processes occurring in it depends on the value of the initial moisture content of the cheese (after pressing) [4].

According to the GOST (the RF standards and regulations) 7616-85, GOST 11041-88, and GOST R 52686-2003, the following dependence characterizes cheese: with an increase in the moisture mass fraction, the mass fraction of fat decreases. The mass fraction of fat and moisture of all objects of the current research is presented in **Table 1**.

For most solid and semihard cheeses, the mass fraction of fat in the dry matter is 45–50%, and the mass fraction of moisture is 40–44%.

The fat in the cheese is in the form of micrograins with a diameter of 10–15 microns. There are also larger inclusions of fat, the so-called fat drops, which are allocated evenly throughout the thickness of the cheese. Fat drops and lipid micrograins in cheese are milk fat destabilized in the process of cheese making and ripening. This judgment is justified, since at temperatures above 20°C, the fat in the cheese can be melted out of the cheese mass, which is the main obstacle in the thermal dehydration of the cheese.

Product name	Mass fraction (%)	
	Fat in the dry matter (no less than)	Moisture (no more than)
<b>Hard cheeses with a high temperature of the second heat stage</b>		
Sovetskiy	50	42
Swedish	50	42
Altaiskiy	50	42
Gorniy	50	40
Moscowskiy	50	42
<b>Semihard cheeses with a low temperature of the second heat stage</b>		
Dutch	45–50	43–44
Kostromskoy	45	44
Poshekhonskiy	45	42
Yaroslavskiy	45	44

**Table 1.**  
*Mass fraction of fat and moisture of the research objects.*



there is a valve for depressurizing the system and removing the moisture frozen on the evaporator upon completion of the drying process.

The vacuum in the system is maintained using a two-stage vacuum pump brand 2TW-1C. Evaporation of evaporated moisture and non-condensable gases occurs as follows: evaporated moisture from the product enters the desublimator through the pipeline, where it passes through the evaporator and freezes on its surface that portion of water vapor that is not frozen and the non-condensable gases are pumped out with a vacuum pump into the environment.

The content of the mass fraction of moisture in the cheeses before and after drying was determined by an accelerated method on a Chizhova device, by drying the weight of the product according to GOST 3626-73.

The content of the fat mass fraction in the cheeses before and after drying was determined by the Gerber acid method according to GOST 5867-90. The method is based on the separation of fat from milk and dairy products under the action of concentrated sulfuric acid and isoamyl alcohol, followed by centrifugation and measuring the amount of released fat in the graduated part of the fat meter.

Experiments on the study of the forms and the energy of the binding of moisture in semihard cheeses were carried out using non-isothermal analysis using a derivatograph. In the course of heating the sample of the samples under study, the change in mass, the rate of change in mass, and the rate of change in temperature of the product, obtained by thermogravimetry, were determined.

Thermophysical characteristics of cheeses were determined by the first buffer method of two temperature-time intervals.

### 3. Results of experimental studies

Moisture is one of the most important cheese components. The moisture content of cheeses affects the ripening process, the cheese structure, and its thermophysical properties. The quantitative content of various forms and the binding energy of moisture in cheeses were determined (Tables 2 and 3).

It should be clarified that the mass fraction of moisture in the cheese was, for Sovetskiy, 40%; Dutch, 44%; and Ozerniy, 48%. In the “Soviet” cheese, the highest content of bound moisture is set at 18.0%, “Dutch,” 13.0%; and “Ozerniy,” 10.0%. The Sovetskiy cheese shows the smallest amount of total moisture from the three considered cheeses, while it contains the greatest amount of bound moisture. The content of energy-intensive bonds in cheeses depends on the technology of their production and the duration of the ripening process. P.F. Krashenin and V.P. Tabachnikov established a general increase in the water-holding capacity along with the cheese maturation [5]. That is, the duration of ripening can be taken into account as a first approximation as a factor affecting

Types of cheese	Physicochemical bond		Physicomechanical bond	
	Adsorption-bound moisture		Osmotically bound moisture and microcapillary moisture	Wetting moisture and macrocapillary moisture
	Monomolecular	polymolecular		
Sovetskiy	7.0	11.0	12.0	10.0
Dutch	5.0	8.0	19.0	12.0
Ozerniy	4.0	6.0	21.0	17.0

**Table 2.**  
Quantitative content of various forms of moisture binding in cheese (%).

Form of the moisture binding with the matter	Types of cheese		
	Sovetskiy	Dutch	Ozernyyi
<b>Physicochemical bound</b>			
Monomolecular adsorption	4.20–2.70	3.90–2.50	3.40–2.50
Polymolecular adsorption	2.20–0.50	2,30–0,70	2.20–0.70
Osmotically bound	0.45–0.12	0.65–0.10	0.60–0.10
<b>Physicomechanical bound</b>			
Microcapillary	0.45–0.12	0.65–0.10	0.60–0.10
Wetting and macrocapillary	<0.10	<0.10	<0.10

**Table 3.**  
 Binding energy of moisture in cheese  $\cdot 10^{-5}$ , J/kg.

the amount of bound moisture in cheese: the longer the ripening process is, the more bound moisture is contained in the cheese. This dependence is quite aligned with our results.

Studies have shown that the energy characteristic of the bound moisture is different; when moving from free moisture (wetting and macrocapillaries) to bound moisture (mono- and polymolecular adsorption), the binding energy of moisture to the dry matter of the cheese increases significantly. Binding energy ( $10^{-5}$  J/kg) for wetting and macrocapillary moisture, it is <0.10, for osmotically bound moisture and moisture of microcapillaries 0.45–0.12, for polymolecular adsorption moisture 2.30–0.50, and for moisture monomolecular adsorption 4.20–2.50. Consequently, the moisture of the monomolecular and polymolecular adsorption due to the highest binding energy is the most strongly bounded. In this regard, it can be said that the moisture of monomolecular adsorption is the main hydration indicator of the product constituent parts and is important for the food restoration after drying.

It is known that while storage, dry food products absorb moisture from the ambient air until an equilibrium state occurs. The works of R.I. Ramanauskas are devoted to the study of the equilibrium moisture content of dairy products [6, 7].

We have conducted studies of the cheese hygroscopic characteristics (**Table 4**).

When the air relative humidity decreases, the equilibrium moisture of the product decreases too, while the binding energy of moisture with the dry part of the product increases.

**Table 5** shows data on the thermal characteristics of cheese. To determine the mode of drying for any product, including cheese, it is necessary to know both physicochemical parameters and thermophysical characteristics. The latter characteristics are necessary in the determination of regime parameters and technological ones as well. When choosing regime parameters (temperature, heat flux density, and residual pressure), it is important to take into account the product's heat capacity and thermal diffusivity in order to calculate the temperature distribution over the layer thickness and the rate of its change. In determining the technological parameters (thickness of the drying layer and the degree of grinding), the thermal conductivity should be observed, since the thickness of the layer of dried material depends on its size.

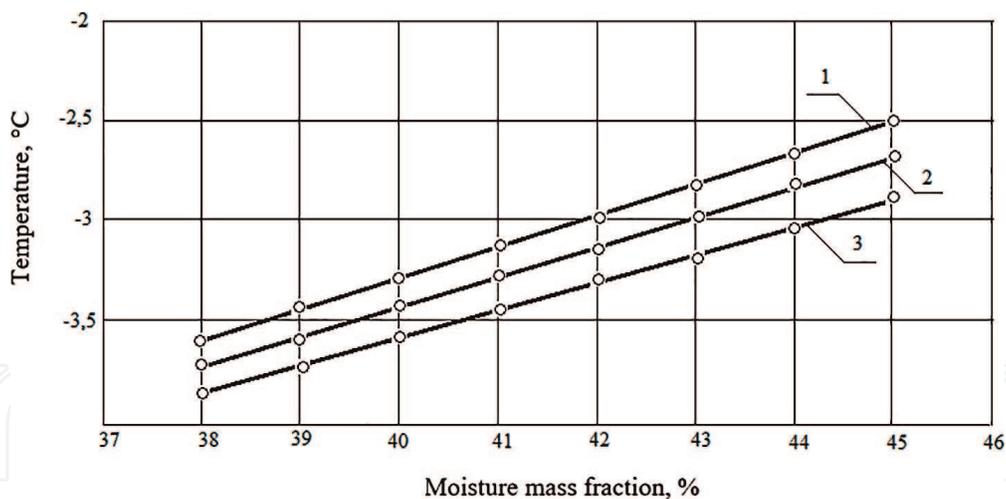
To determine the effect of moisture content in cheese on its cryoscopic temperature, samples of “Dutch,” “Kostromskoy,” and “Poshekhonskiy” cheese with a pH of 5.7 and a moisture content of 38–45% were used. **Figure 2** shows the dependences of the change in the cryoscopic temperature of semihard cheeses with a low second heating temperature on the mass fraction of moisture.

Relative air humidity (%)	10	20	30	40	50	60	70	80	90
<b>Sovetskiy cheese</b>									
Equilibrium humidity (%)	7.0	10.0	11.5	13.5	15.5	17.5	19.5	22.0	26.5
<b>Dutch cheese</b>									
Equilibrium humidity (%)	5.0	6.5	8.0	9.5	11.0	13.0	17.0	25.0	33.0
<b>Ozerniy cheese</b>									
Equilibrium humidity (%)	4.0	5.0	6.0	7.0	8.0	10.0	15.0	22.0	31.0

**Table 4.**  
Hygroscopic characteristics of cheeses.

Types of cheese	Thermophysical characteristics			
	Density (kg/m <sup>3</sup> )	Thermal conductivity (W/(m·K))	Heat capacity (J/(kg·K))	Thermal diffusivity (10 <sup>-6</sup> m <sup>2</sup> /c)
Sovetskiy	1070	0.34	2570	0.135
Dutch	1060	0.35	2530	0.133
Ozerniy	1040	0.35	2540	0.132

**Table 5.**  
Cheese thermophysical characteristics.



**Figure 2.**  
Dependence of the cryoscopic temperature of cheeses on the mass fraction of moisture: (1) “Dutch,” (2) Kostromskoy, and (3) “Poshekhonskiy.”

As a result of the research, the dependences between the cryoscopic temperature  $t_{kp}$  and the moisture content in hard cheeses with a low second heating temperature were revealed for:

“Dutch” cheese:

$$t_{kp} = 0,1595 \cdot B_c - 9,67 \quad (1)$$

“Kostromskoy” cheese:

$$t_{kp} = 0,1464 \cdot B_c - 9,28 \quad (2)$$

“Poshekhonskiy” cheese:

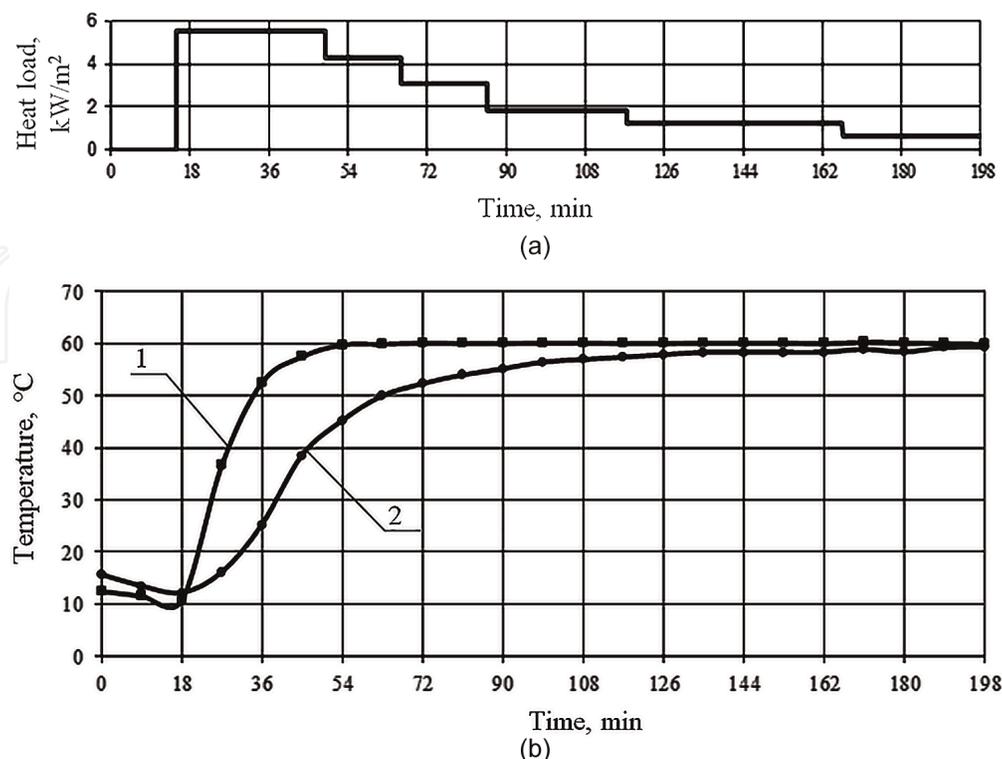
$$t_{kp} = 0,12 \cdot B_c - 8,38 \quad (3)$$

where  $B_c$  is the mass fraction of moisture in the cheese.

According to **Figure 2** and Eqs. (1)–(3), it follows that a change in moisture of 1% leads to a change in the cryoscopic temperature of the studied cheeses by 0.25°C.

The kinetics of the drying process is usually understood as a change in the average volume of the dried material humidity  $\varphi_c$  and temperature  $t$  over time  $\tau$ . The nature of the drying process is most accurately described by the drying curves (in the coordinates of the moisture mass fraction–time), the curves of the drying speed (in the coordinates of the drying speed–the moisture mass fraction), and temperature curves (in the coordinates of the material temperature–the humidity of the material). The work of drying units of different performances cannot be compared by changing the mass of material in the drying process. To do this, it is rational to use graphic figures of the change in moisture mass fraction of the material over time ( $\varphi - \tau$ )—drying curves.

The data for constructing the curves is usually obtained in the laboratory when the mass (weight) of the material sample and its temperature are recorded during the drying process. Drying is usually done with heated air at a constant rate. For vacuum drying, the constant mode is the material temperature, the residual pressure value. Naturally, the transfer of laboratory research data to production conditions (where drying is usually carried out under variable conditions) requires special adjustments. The change in the average volume moisture mass fraction over time  $\varphi_c = f(\tau)$  is graphically represented by a curve called the drying curve. In the general, the drying curve consists of several sections corresponding to different periods of drying [6]. **Figure 3** shows the curves of vacuum drying (heat load–time, temperature–time, mass fraction of moisture–time) for the “Swiss” cheese.



**Figure 3.** Drying curves for “Swiss” cheese. (a) Heat load. (b) Temperature on the surface and throughout the thickness: mode:  $t = 60^\circ\text{C}$ ,  $q = 5,52 \text{ kW/m}^2$ ,  $P = 2-3 \text{ kPa}$ , and  $h = 10 \text{ mm}$ . (1) On the surface. (2) Throughout the thickness.

Within 9–15 min, until the drying unit reached the required mode by residual pressure (2–3 kPa), heat is not supplied from the heaters (**Figure 3**), and the cheese temperature decreases from 17 to 15 to 12–10°C.

The temperature lowers due to the intense evaporation of moisture from the surface of the cheese. The decrease in the mass fraction of moisture while the unit is set to operate is 2–3%. Segment A–B corresponds to the time required for the unit to reach the required mode by residual pressure (2–3 kPa). Then comes the first drying period—a period of constant drying rate, a segment B–K1 on the curve of change in the mass fraction of moisture. The first period is characterized by a constant rate of decrease in the mass fraction of moisture (for equal periods of time, the same amount of moisture is removed).

The temperature of the cheese increases due to the supply of heat from the heaters. The cheese temperature during the first period reaches the desired value and is maintained at a predetermined level (**Figure 3**). By the end of the first period, the temperature leveling along the thicker layer of the dried cheese is observed. At the beginning of the first period, the heat load is equal to the maximum allowable value. When the cheese reaches the desired drying temperature, the heat load is reduced. Reducing the heat load is necessary to prevent the drying temperature of the cheese from exceeding the required value.

During the first period, the greatest amount of moisture is removed. In the first drying period, the moisture mass fraction of the “Swiss” cheese decreased by 24%; “Dutch,” 23%; and “Poshekhonskiy,” 34%. The duration of the first drying period is, for the “Swiss” cheese, 74 min; “Dutch,” 83 min; “Kostromskoy,” 92 min; and “Poshekhonskiy,” 80 min. The period of constant drying speed continues until the first critical moisture content reaches.

During the period of constant drying rate, the intensity of the process is determined only by the parameters of the drying agent and does not depend on the moisture content (mass fraction of moisture) and the physicochemical properties of the material. At a certain value of the moisture mass fraction, the rate of the moisture removal begins to decrease and the second period starts—the period of falling drying rate. The beginning of the second period corresponds to the critical moisture content of the material. During the second period, the moisture that is the most strongly bound to the product is removed. The evaporation rate decreases, the drying rate slows down, and the temperature levels throughout the product thicken.

In the period of the falling drying rate, the drying rate decreases with decreasing moisture content of the material. During this period, the bound moisture is removed, and a gradual decrease in the drying rate is explained by an increase in the binding energy of moisture with the material.

In the period of falling speed of drying, the mass fraction of moisture of the “Swiss” cheese decreases by 12%; “Dutch,” 15%; “Kostromskoy,” 24%; and “Poshekhonskiy,” 12%. The duration of the period of the falling speed of drying “Swiss” cheese is 108 min; “Dutch,” 100 min; “Kostromskoy,” 17 min; and “Poshekhonskiy,” 100 min.

Duration of the period of the falling drying speed can be divided into some segments corresponding to the first and second phases. By the second critical moment, the evaporation zone reaches the deep layers of the product. At this moment, movement of moisture occurs only in the form of steam, and mainly adsorption moisture evaporates.

At the end of the drying process, the drying curve (the curve of change in the mass fraction of moisture) asymptotically approaches the equilibrium moisture, and the equilibrium moisture value corresponds to this drying mode. When equilibrium moisture occurs, the drying process stops—the drying rate equals zero.

The first derivative of the function  $\varphi_c = f(\tau)$  calculates the drying rate, under which we understand the change in the material moisture content per unit time ( $d\varphi_c/d\tau$ , %/МИН). Curves of drying rates were drawn by the method of graphical differentiation according to drying curves (curves of change in the mass fraction of moisture): the drying rate at a given time is determined as the tangent of the tangent angle, drawn through the drying curve point that corresponds to a specific moisture mass fraction:

$$tg\psi = \frac{d\varphi}{d\tau}. \quad (4)$$

Maximum drying rate  $N$  during the period of constant drying rate:

$$tg\psi = \left( \frac{d\varphi}{d\tau} \right)_{МАКС} = N, \%/\text{ЧИЛИ}\%/\text{МИН}. \quad (5)$$

By the end of the process at equilibrium moisture, the drying rate is  $\frac{d\varphi}{d\tau} = 0$ .

At the beginning of the drying process, the unit goes to the desired mode for the residual pressure, and the drying rate increases from zero to the maximum value. The maximum value of the cheese drying rate for “Swiss” is 0.62%/min; “Dutch,” 0.71%/min; “Kostromskoy,” 0.88%/min; “Poshekhonskiy,” 0.78%/min; “Rizhskiy,” 0.92%/min; and “Russian,” 0.75%/min.

In the period of constant drying rate, the drying rate is equal to the maximum. During the constant period of drying, moisture is removed from the cheeses: “Swiss,” 18%; “Dutch,” 17%; “Kostromskoy,” 22%; “Poshekhonskiy,” 28%; “Rizhskiy,” 48%; and “Russian,” 32%.

Starting from the first critical point, a decrease in the drying rate begins. The nature of the curves in the period of the falling drying rate corresponds to colloidal capillary-porous bodies.

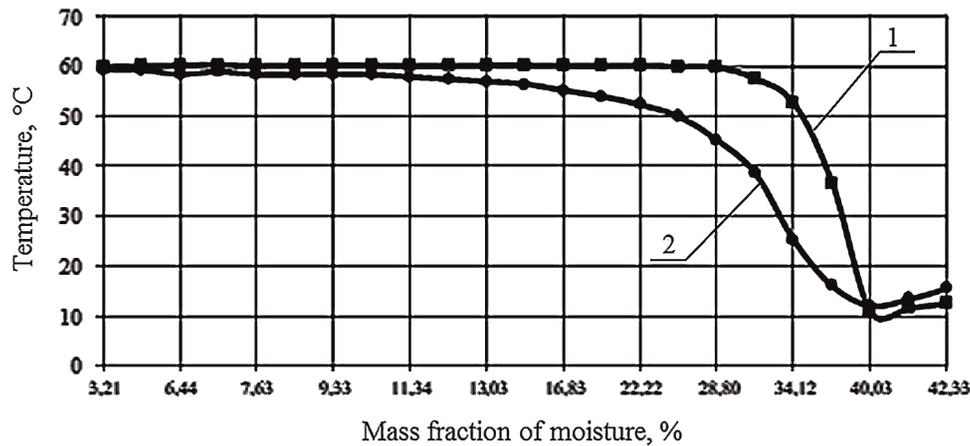
Critical humidity corresponds to the humidity limit when the mechanism of moisture movement in the material changes. This point marks the beginning of moisture removal by polymolecular adsorption.

The second critical point corresponds to the following mass fraction of moisture of cheese: “Swiss,” 10%; “Dutch,” 10%; “Kostromskoy,” 13%; “Poshekhonskiy,” 8%; “Rizhskiy,” 10%; and “Russian,” 9%. Moisture mass fraction of dry cheeses is 4–5%. The difference between the mass fraction of moisture at the second critical point and the mass fraction of moisture of dry cheeses is the moisture of polymolecular adsorption. That is, the mass fraction of moisture of polymolecular adsorption for cheeses is 4–9%.

Temperature curves  $t = f(\varphi_c)$  are very informative. Temperature curves for the first were introduced by A.V. Lykov; now, they are important for the analysis of the drying process. **Figure 4** shows the temperature curves characteristic of vacuum drying of Swiss cheese.

At the beginning of the drying process, the cheese temperature decreases as the heat from the heaters is not supplied. At the beginning of the first drying period, when the heaters are turned on, the surface temperature of the material rises, reaching the temperature of the wet-bulb thermometer. During this period, the most intense moisture return occurs, and practically all the heat imparted to the material is spent on the moisture evaporation. The temperature over the thicker layer of cheese is equalized by the end of the first drying period.

Starting from the first critical point, the rate of moisture evaporation decreases. When the humidity of the cheeses reaches the value of the equilibrium moisture, the drying process is completed. The equilibrium moisture content for



**Figure 4.**  
Temperature curves of vacuum drying of Swiss cheese: (1) on the surface and (2) in the thickness.

cheeses is, for “Swiss,” 5.21%; “Dutch,” 4.46%; “Kostromskoy,” 5.46%; and “Poshekhonskiy,” 4.26%.

It has been established that vacuum drying of cheeses proceeds in two periods: constant and falling drying rates. The drying curves of various types of cheeses in the coordinates were obtained and investigated (heat load-time, temperature-time, mass fraction of moisture-time). By graphic differentiation, the curves of drying rate of cheeses are constructed. By the analytical method, it was determined that the amount of moisture of polymolecular adsorption for cheeses is 4–9%. The temperature curves of the cheeses in the coordinates (temperature-mass fraction of moisture) were investigated. The values of equilibrium moisture for vacuum drying of cheeses are established.

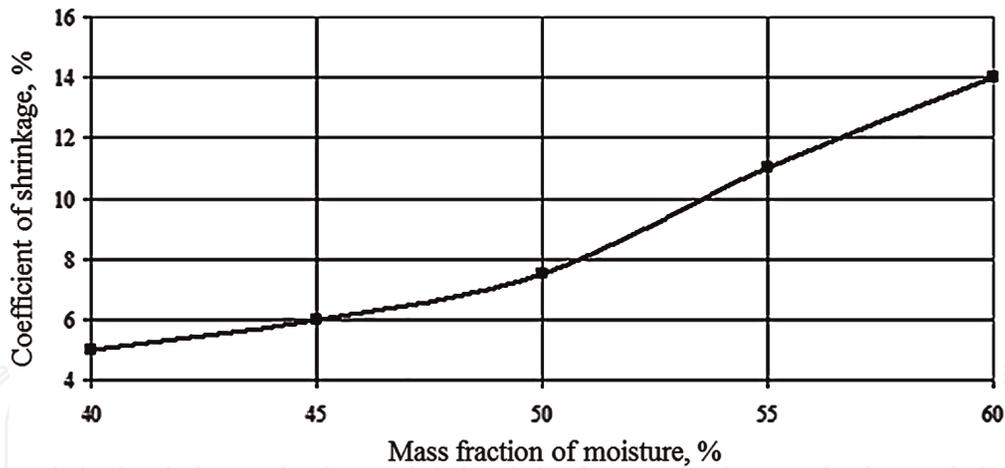
The size and volume of most materials are reduced during the drying process. This phenomenon is called material shrinkage [8–10]. For example, in convective drying, such materials as vegetables, fruits, and cereals shrink significantly, decreasing in volume by three to four times [11].

Most materials (peat, grain, leather, dough, bread, etc.) shrink throughout the drying process. However, a number of materials (clay, ceramic masses, and some other materials) shrink during a period of constant drying rate. In this case, the shrinkage is stopped at approximately critical moisture content, if the moisture content gradient inside the material is small. Other materials (wood, coal) shrink only in the period of falling drying rate, it begins approximately at a point of critical moisture content [12].

The least shrinkage results are shown by cheeses produced with a residual pressure of 2–3 kPa. It is established that an increase in the size of grinding and thickness of the drying layer of the “Dutch,” “Kostromskoy,” and “Poshekhonskiy” cheeses leads to an increase in shrinkage factors. At the drying material thickness from 10 to 30 mm, the shrinkage ratio is from 3 to 14%. When the thickness of the drying layer is 40 mm, the coefficient of shrinkage increases up to 15–24%. Drying the cheeses with the required operating and technological parameters causes minimal drops in the mass fraction of moisture, while particle shrinkage is minimal and takes place with preservation of shape.

**Figure 5** shows the dependence of the coefficient of cheese shrinkage on the initial mass fraction of moisture.

With an increase in the mass fraction of the cheese moisture, the shrinkage factors increase. The greatest increase in the coefficient of cheese shrinkage is observed when the mass fraction of moisture is more than 50%. With a change in the mass fraction of the cheese moisture from 40 to 50%, the shrinkage rate increases by 2.5%; from 50 to 60%—by 6.5%.



**Figure 5.**  
 The dependence of coefficients of cheeses shrinkage on the mass fraction of moisture.

**Figure 6** shows the dependence of the shrinkage factor on the initial mass fraction of the cheese moisture in the drying process. According to the curves presented in **Figure 5**, the following dependence is established: with an increase in the mass fraction of cheese moisture, the shrinkage rate increases. A similar dependence follows from the analysis of the curves presented in **Figure 6**. Shrinkage of cheeses in both periods of vacuum drying occurs evenly.

If the linear size of the material (length, width, height) is denoted with  $l$ , when the mass fraction of moisture is  $W$ , then it can be written as [13]

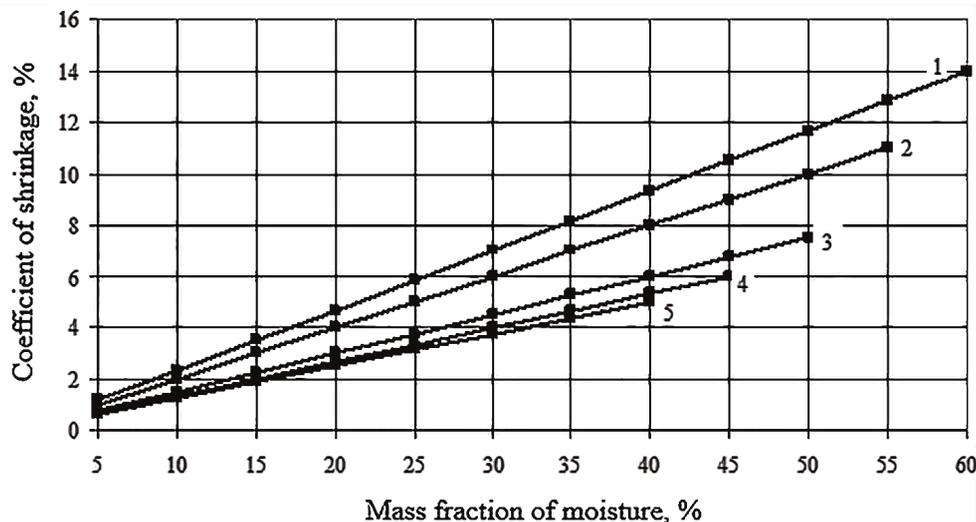
$$l = l_0 \cdot (1 + \beta_l \cdot W) \quad (6)$$

where  $l_0$  is the linear size of the absolutely dry material;

$\beta_l$  is a coefficient of linear shrinkage, characterizing shrinkage rate of 1%, i.e.,  
 $\beta_l = \frac{1}{l_0} \cdot \frac{dl}{dW}$ .

Formula (6) is valid for relatively small gradients of moisture content inside the material. With a large moisture content gradient, the surface layers of the material will shrink faster than the average ones. **Table 6** shows the moisture content of the “Sovietskiy” and “Dutch” cheese in a layer thickness of 20 mm.

The moisture content data on the thickness of the cheese layer was obtained at the required temperatures, thermal loads, and residual pressure of the vacuum drying of the cheeses. As the temperature increases, the heat load on the surface of the cheese



**Figure 6.**  
 The dependence of shrinkage coefficients of cheeses on the initial mass fraction of moisture.

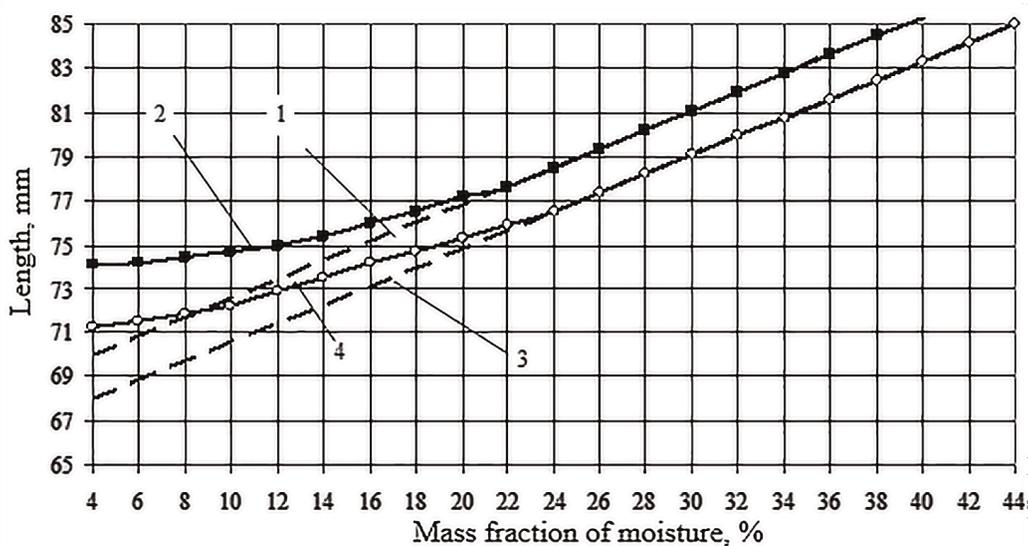
moisture content decreases rapidly, while in the thickness layers, it changes more slowly. Surface layers, which affect the size of the material, tend to decrease not in proportion to the average moisture content, but approximately in proportion to the moisture content on the surface. Therefore, starting from a certain moisture content (mass fraction of moisture), shrinkage is hardly observed (Figure 7).

The shrinkage curves of the cheeses, “Sovietskiy” (1) and “Dutch” (3), were obtained at the required drying temperature of 60°C. Shrinkage curves 2 and 4 were obtained at a temperature higher than the required one (80°C). When the drying temperature is high, the surface layers dry quickly. The central layers have an increased mass fraction of moisture. Shrinkage at elevated temperatures is less, but dry cheese has a large mass fraction of moisture.

With an increase in the drying temperature, the shrinkage coefficient decreases; this is explained by an increase in the gradient of the mass fraction of moisture inside the material. In the presence of a gradient of the mass fraction of moisture, the surface layers tend to shrink more compared to internal ones. However, the reduction of the surface layers is impeded by internal ones, the mass fraction of which is more moisture than the surface layers. As a result, the shrinkage of the surface layers is less than that which should correspond to the moisture removed from them. Consequently, an increase in the difference in the mass fraction of moisture between the inner and surface layers is accompanied by an increase in the difference between the actual shrinkage and the possible shrinkage corresponding to the amount of liquid to be removed.

Cheese	Moisture content (wet/dry material)			
	At the first critical point		At the second critical point	
	Surface layers	Thickness layer	Surface layers	Thickness layer
Sovietskiy	6–9	20–24	4–5	9–17
Dutch	6–8	19–22	4–5	7–12

**Table 6.**  
Moisture content of cheeses at the layer thickness of 20 mm.



**Figure 7.**  
Shrinkage curves of cheeses “Sovietskiy” (1 and 2) and “Dutch” (3 and 4): (1)  $t = 60^{\circ}\text{C}$ ;  $q = 5.52 \text{ kW/m}^2$ ;  $P = 2-3 \text{ kPa}$ ; (2)  $t = 80^{\circ}\text{C}$ ;  $q = 5.52 \text{ kW/m}^2$ ;  $P = 2-3 \text{ kPa}$ ; (3)  $t = 60^{\circ}\text{C}$ ;  $q = 7.36 \text{ kW/m}^2$ ;  $P = 2-3 \text{ kPa}$ ; (4)  $t = 80^{\circ}\text{C}$ ;  $q = 7.36 \text{ kW/m}^2$ ;  $P = 2-3 \text{ kPa}$ .

Thus, formula (6) is valid only with a small gradient of moisture content (mass fraction of moisture), when the mass fraction of moisture  $u$  at any point of the cheese is approximately equal to the average mass fraction of moisture  $W(u \sim W)$ . A more rigorous writing of the formula (4.6) was proposed by A.V. Lykov [14, 15]:

$$l = l_0 \cdot (1 + \beta_l \cdot W). \quad (7)$$

For most materials, the dependence between the volume of the body and its moisture content is linear:

$$V = V_0 \cdot (1 + \beta_V \cdot W), \quad (8)$$

where

$\beta_V$  is the coefficient of volumetric shrinkage, equal to the relative decrease in volume when moisture content changes on 1%,  $\beta_V = \frac{dV}{V_0 \cdot dW}$ .

$V_0$  is the volume of absolutely dry matter.

A.V. Lykov proposed to determine the coefficient  $\beta_V$  by two values  $V_1$  and  $V_2$  for the mass fraction of moisture and, for example, before and after drying. Consequently:

$$V_1 = V_0 \cdot (1 + \beta_V \cdot W_1), \quad (9)$$

$$V_2 = V_0 \cdot (1 + \beta_V \cdot W_2). \quad (10)$$

$V_0$  and  $\beta_V$  can be determined by these equations. Denoting relative shrinkage (with respect to the original volume) with  $\delta$ , it is as

then 
$$\delta = \frac{V_1 - V_2}{V_1}, \quad (11)$$

$$\beta_V = \frac{\delta}{(W_1 - W_2) - \delta \cdot W_1}. \quad (12)$$

**Table 7** shows the coefficients of volumetric shrinkage of cheeses.

If the linear sizes of the cheeses vary from the mass fraction of moisture according to the ratio (7), a simple relationship can be found between  $\beta_V$  and  $\beta_l$ , as well as between  $\beta_l$  and  $\beta_S$ .

The area of the sample material is equal to the product of the length  $l$  by the width  $L$ , that is:

$$S = l \cdot L = l_0 \cdot L_0 \cdot (1 + \beta_l \cdot W)^2 = S_0 \cdot (1 + \beta_l \cdot W)^2, \quad (13)$$

where  $S_0 = l_0 \cdot L_0$  is the area of absolutely dry material.

Cheese	Coefficient of volumetric shrinkage ( $\beta_V$ )
Sovietskiy	0.017–0.004
Dutch	0.006–0.003

**Table 7.**  
 The coefficients of volumetric shrinkage of cheeses.

In deriving Eq. (13), it is assumed that the material is isotropic and shrinkage along the length and width is the same. If  $(1 + \beta_l \cdot W)^2$  expanded in a row, the value of  $\beta_l^2 \cdot W^2$  is small compared to  $2 \cdot \beta_l \cdot W$ ; then, it can be written as

$$S = S_0 \cdot (1 + 2 \cdot \beta_l \cdot W) = S_0 \cdot (1 + \beta_S \cdot W), \quad (14)$$

where  $\beta_S = 2 \cdot \beta_l$  is the coefficient of shrinkage on the area; it equals to twice the linear shrinkage coefficient.

The coefficient of shrinkage on the area can be determined by the formula:

$$\beta_S = \frac{\delta_S}{(W_1 - W_2) - \delta_S \cdot W_1}, \quad (15)$$

where  $\delta_S = \frac{(S_2 - S_1)}{S_1}$  is the relative shrinkage on the area.

The dependence between the volume of the material and the moisture content is written as

$$V = V_0 \cdot (1 + \beta_V \cdot W)^3. \quad (16)$$

Thus, an approximate formula can be derived:

$$V = V_0 \cdot (1 + 3 \cdot \beta_V \cdot W) = V_0 \cdot (1 + \beta_V \cdot W), \quad (17)$$

where  $\beta_V = 3 \cdot \beta_l$  is the coefficient of volumetric shrinkage, equal to triple linear shrinkage coefficient.

Thus, the dependences of the coefficients of cheese shrinkage on the thickness of the drying layer and the shape and size of grinding are obtained. When the thickness of the drying layer is from 10 to 30 mm, the coefficient of cheese shrinkage is from 3 to 14%, depending on the shape and size of the grinding. With an increase in the mass fraction of the moisture of the cheeses, the shrinkage coefficient increases. It was determined that the shrinkage of cheeses in both periods of vacuum drying occurs uniformly. When the drying temperature rises above the required shrinkage ratio decrease, this is explained by the increase in the gradient of the mass fraction of moisture inside the material.

Shrinking of wet material with a uniform distribution of moisture content and temperature is a physical property of the material, when fluid is removed from it and does not cause any dangerous stresses. Only shrinkage of the material with an uneven distribution of moisture content causes a stress state, which can lead to the appearance of cracks and the complete destruction of the body structure. Therefore, the main obstacle to the rapid drying of many materials is their cracking. The cause of the cracking appearance (local destruction), as well as complete destruction (loss of the integrity of the structure), is the development of the volume-stressed state of the material being dried beyond the maximum allowable, due to the strength of the material.

This stress state is created by unacceptable shrinkage, which, in turn, appears as a result of an uneven distribution of moisture content and temperature inside the material [16, 17].

The method of studying shrinkage stresses does not exclude a phenomenological approach to the phenomenon of shrinkage of wet material under study. It is important to note that the capillary and wedging pressures of the liquid phase in a solid body are functions of moisture content. Therefore, the field of capillary contractions under isothermal conditions will be similar to the field of moisture content.

It follows that the uneven distribution of moisture content (moisture content field) is the main characteristic of the volume-stressed state of a moist body when it is dried.

A similar picture occurs when studying thermal stresses. The phenomenological approach consists in the fact that the body-stressed state of the body at heating is uniquely determined by an uneven temperature distribution (temperature field). The main cause of cracking in the drying process is the presence of moisture content and temperature fields with a significant difference in these values.

A.V. Lykov considered drying the material in the form of a plate. Evaporation occurs from two opposite sides (the remaining surfaces have moisture insulation, that is, the moisture content surface is one-dimensional), and the temperature is the same everywhere and constant (isothermal drying conditions in the first period). It has been determined that the maximum compressive stresses occur in the central plane ( $u_y = u_{\text{макс}}$ ) and the maximum tensile stresses appear on the surface ( $u_n = u_{\text{мин}} < \bar{u}$ ) when the linear strain modulus  $E$  remains unchanged.

During the period of constant drying rate, the moisture content is distributed according to the law of a parabola. This distribution does not occur immediately, but after a certain period of time. Then, the difference between the average moisture content  $\bar{u}$  and the moisture content on the surface  $u_n$  equals to

$$\bar{u} - u_n = \frac{2}{3} \cdot \Delta u = -\frac{R}{3} \cdot (\nabla u)_n, \quad (18)$$

where  $\Delta u_n = u_y - u_n$  is the moisture content difference between the central layers and surface.

$(\nabla u)_n$  is the moisture content gradient on the plate surface.

$2 \cdot R$  is the plate thickness.

The tensile stress on the surface of the plate is [18]

$$P_n = -\frac{2}{3} \cdot \frac{\beta_l \cdot E \cdot \Delta u}{(1 + \beta_l \cdot u_n) \cdot (1 - \mu)} = \frac{\beta_l \cdot E \cdot R}{3 \cdot (1 - \mu) \cdot (1 + \beta_l \cdot u_n)} \cdot (\nabla u)_n. \quad (19)$$

According to the formula, it follows that, if the value is  $\Delta u_n = u_y - u_n$ , the cracking of the drying material occurs when its strength is less than the value of  $P_n$ . Experiments on vacuum drying of raw materials confirm that cracking occurs at a certain value of  $(\Delta u)_{\text{макс}}$ .

Dry cheeses are an indispensable product for diet food, supply of remote areas, army, and expeditions. In addition, the product is necessary for the production of modern nutrient mixtures for a given purpose (dry breakfasts, mixtures of medical nutrition). Dry cheese can be used as a base for various foods and sauces. Cheese-based sauces can be used instead of mayonnaise, which can significantly expand the possibilities of their use in cooking. After reconstitution, the dry cheese is vacuum dried and has the consistency of melted cheese.

The obtained research results can be successfully applied in the food industry not only to cheeses but also to other products. They are of theoretical and practical value and can be used by technologists, researchers, and food industry workers in the development of relevant technological processes.

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