# KINETICS OF THE VACUUM DRYING OF CHEESES

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**Abstract**: Cheeses are analyzed as vacuum drying objects. An experimental vacuum drier and its elements are schematized. The operating principle of the experimental setup is described. Moisture is demonstrated to be among the most important components of cheese. The physicochemical composition of cheeses is considered. The forms and energy of moisture binding in cheese are discussed. The hygroscopic and thermophysical properties of cheeses are reported. The kinetics of the vacuum drying of cheeses has been investigated. The vacuum drying of cheeses includes two stages: the drying rate is constant at the first stage and decreases at the second stage. The temperature curves of cheeses have been plotted in the temperature–moisture weight fraction coordinates. Drying curves in the heat load–time, temperature–time, and moisture weight fraction–time coordinates have been obtained and analyzed for various cheeses. Cheese drying rate curves have been constructed by graphical differentiation. The maximum cheese drying rates have been determined. Equilibrium moisture content values for cheese drying have been found. The cheese shrinkage ratio has been correlated with the thickness of the cheese bed being dried and with the shape and size of cheese pieces. Cheese shrinkage at both stages of vacuum drying proceeds uniformly. Raising the drying temperature above the prescribed temperature reduces the shrinkage ratio.

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

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## INTRODUCTION

When considering cheese as a vacuum drying object, note that the variation of the properties of cheese during drying depends on the physicochemical properties, structure, and binding forms of moisture in the material and on the thermophysical characteristics of the cheese, including specific features of mass and energy transfer. The basic structural elements of cheese are macrograins, interlayers between macrograins, microvoids, and micrograins. The main element of each macrograin is a protein network, whose cells contain numerous included micrograins as fat drops, lipoid drops, and crystals.

The passage of fat from milk into cheese depends on many factors. Other conditions being equal, medium-size fat globules primarily pass into cheese, followed by small and large ones [1, 2]. Milk fat is viewed as the most valuable constituent of milk, even though milk proteins are still more valuable from the standpoint of nutrition physiology. The following four factors contribute to the particular significance of milk fat in milk and dairy products: economic attractiveness, nutritional value, taste, and the physical properties of dairy products that are due to the presence of fat [3].

During cheese ripening, all cheese components undergo profound changes and, as a result, the given cheese brand acquires its characteristic texture and pattern [4].

The moisture content of cheese depends on processing conditions, namely, renneting temperature and time, second-heating temperature, partial salting of cheese curds, water addition in the second heating, and cheese curds processing time. As the curdling temperature and second-heating temperature are decreased, the moisture capacity of the cheese curds and the water content of the finished product increase. As the temperature is raised, the water content of the cheese decreases. Moisture is lost at the salting stage due to osmotic water transfer and at the ripening stage via evaporation. The intensity of the microbiological and biochemical processes occurring in a cheese depends on the initial moisture content of the cheese after pressing [4, 5].

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

Fat in cheese is mainly in the form of micrograins 10–15 μm in diameter. There are also larger fat inclusions, which are referred to as fat drops and are uniformly distributed throughout the cheese bulk. The fat drops and lipoid micrograins in cheese are milk fat destabilized during cheese making and ripening. This is true because, above 20°C, cheese fat can melt out of cheese curd, and this is the main obstacle in thermal cheese dehydration.

## OBJECTS AND METHODS OF THE STUDY

The objects of our study were the Sovetskii, Shveitsarskii, Altaiskii, Gornyi, Moskovskii, Gollandskii, Kostromskoi, Poshekhonskii, Yaroslavskii, and Ozernyi brands of cheese. The study was carried out using standard, commonly accepted, and modified physicochemical, rheological, microbiological, and biochemical methods.

The drying techniques and drier designs employed in cheese making are very diverse. First of all, any drier design should ensure uniform heating and drying of the product and reliable control of its temperature and moisture content. The driers should have a sufficiently high output capacity, but at the same time they should be economical in terms of heat and electricity requirements and should be metal-intensive to the least possible extent. Present-day driers should be multipurpose, capable of drying various materials [6, 7].

Only a few types and sizes of driers are manufactured at present. Many of the various driers operated by cheese makers are single-copy models designed by the manufacturer itself or, much more frequently, by a branch research institute or education institution, and many have been purchased from foreign companies.

Drier designers should take into consideration that drying is a unit operation involved in manufacturing, so the design of the apparatus should ensure establishing optimal processing conditions and obtaining a high-quality dry product. Although each product as an object of drying has its specific properties, for organizing full-scale drier production at machine-building plants it is rational to develop versatile apparatuses intended for a group of similar materials and fitted with up-to-date automated monitoring and process control systems [8–10].

When selecting a rational drier design and drying method, one should be guided by the following requirements:

– high quality indexes of the product (reconstitutability, unaffected odor);
– minimum heat, steam, air, and electric power consumption per kilogram of moisture evaporated or per ton of finished product;
– high process intensity minimizing the dimensions of the apparatus (in terms of the amount of water removed from 1 $m^3$ of the apparatus volume or 1 $m^2$ of the working area);
– maximum possible automatability and mechanizability of the drying process.

In all cases, it is necessary to thoroughly study the effects of the main parameters of the drying agent and the material to be dried on the dehydration process. In particular, it is necessary to understand whether it is possible to increase the drying temperature, the air flow rate, and the relative humidity of the air and to use oscillating drying modes, combined heat supply and drying methods, and feedstock pretreatment. It is also necessary to take care of the chemical composition of the finished product (retention of vitamins, proteins, and fat) [11–14].

Taking the aforesaid into account, we designed the cheese vacuum drying unit schematized in Fig. 1.

This drying unit is versatile and can be employed in the drying of practically any feedstock of vegetable and animal origins. The drying chamber *2*, shown in Fig. 2, is a horizontal cylinder with a wall thickness of 15 mm, an inner diameter of 290 mm, and a length of 530 mm.

The chamber is heat-insulated from the outside to prevent heat dissipation to the environment. The heat-insulating material is sheet Termafleks, whose heat transfer coefficient is below 0.034 W/($m^2$ K) at 25°C (RF State Standard GOST 7076-99). One end of the chamber is convex; it is made from steel, like the cylindrical part of the chamber, and welded to the latter. The second end is removable, made from a 40-mm-thick organic glass sheet.

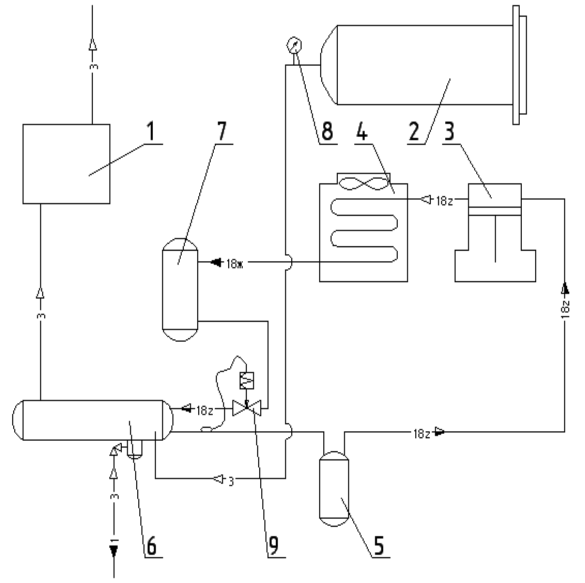


**Fig. 1.** Schematic of the experimental vacuum drier: (*1*) vacuum pump, (*2*) vacuum drying chamber, (*3*) compressor, (*4*) condenser, (*5*) liquid separator, (*6*) desublimator, (*7*) receiver, (*8*) vacuum gage, and (*9*) thermal expansion valve.

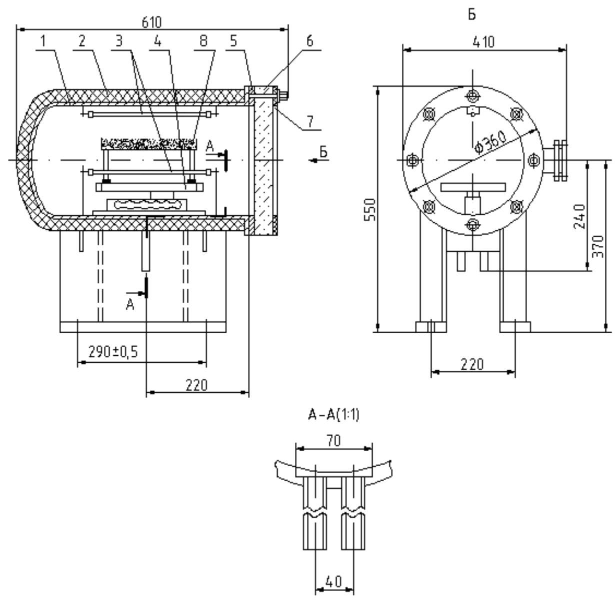


**Fig. 2.** Drying chamber: (*1*) body, (*2*) heat insulation, (*3*) heaters, (*4*) balance, (*5*) vacuum-tight rubber, (*6*) organic glass, (*7*) sealing ring, and (*8*) product.

The heat supply system should ensure uniform heating of the product being dried. The heaters should allow the applied power to be regulated and should have a low thermal inertia. The sources of heat in the unit are two KGT 220-1000 infrared lamps *3*, each having a power of 1 kW. The IR heaters are in the upper and lower parts of the chamber, 50–70 mm away from the pan on which product *8* is placed.

The design of the vacuum chamber allows the distance between the product pan and the heaters to be varied. The product bed is heated by IR radiation pulses to the preset temperature. A specific feature of the IR lamps is their low thermal inertia. This feature enables one to fairly precisely maintain the necessary temperature during vacuum drying. In the lower part of the drying chamber, there is a pipeline connecting the chamber with a desublimator. The desublimator is a shell-and-coil, in-tube boiling, heat exchanger serving as the evaporator in the refrigeration unit shown in Fig. 3.

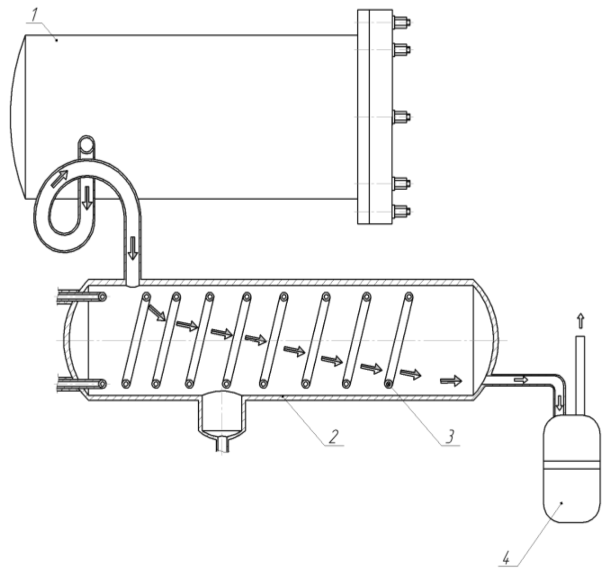



**Fig. 3.** Schematic of the desublimator: (*1*) vacuum chamber, (*2*) desublimator, (*3*) evaporator coil, and (*4*) vacuum pump.

The desublimator is intended for removing, from the vacuum chamber, the water vapor released by the product being dried. The cold surface of the coil condenses the moisture removed from the product, intensifying the drying process by generating a water vapor partial pressure drop between the drying chamber and the condenser. This difference between the partial pressures makes the vapor move from the product to the evaporator surface. Throughout the drying process, the moisture evaporated from the product freezes progressively on the coil surface. In the lower part of the desublimator, there is a valve for unsealing the system and for removing the ice that will have frozen on the evaporator surface by the completion of the drying process.

The vacuum in the system is maintained with a 2TW-1C two-stage vacuum pump. The evaporated moisture and noncondensable gases are removed in the following way: the moisture evaporated from the product moves through a pipeline to the desublimator, where it passes through the evaporator and freezes on its surface; the unfrozen water vapor and noncondensable gases are pumped out by the vacuum pump and are discharged into the environment.

A block diagram of the control and measurement system of the vacuum drying unit is presented in Fig. 4.

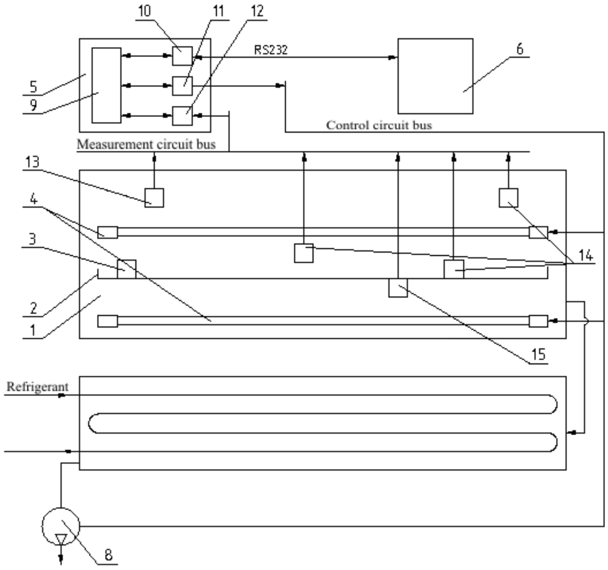



**Fig. 4.** Block diagram of the experimental bench: (*1*) vacuum chamber, (*2*) pan, (*3*) material being dried, (*4*) IR heaters, (*5*) interface block, (*6*) PC, (*7*) condenser, (*8*) vacuum pump, (*9*) microcontroller, (*10*) PC interface, (*11*) executor control unit, (*12*) analog-to-digital converter, (*13*) pressure sensor, (*14*) temperature sensor, and (*15*) load cell.

The drying parameters and algorithm are set by the researcher from the console of PC 6 and are input in the interface block 5 through an RS 232 serial port. The interface block 5 consists of a microcontroller 9 controlling the operation of the measurement unit, a data exchange interface 10 between the microcontroller and the PC, an executor control circuit 11, and an analog-to-digital converter circuit 12. The signal from the executor control block 11 is directed through a control bus to the heaters 4 and vacuum pump 8 for maintaining the preset temperature, heat load, and residual pressure.

The weight of the material being dried is monitored using an electronic load cell (strain gage) 15 mounted inside the drying chamber, and the residual pressure in the system is measured with a pressure sensor 13. The temperature sensors 14 are used to monitor the temperature inside the chamber, in the cheese bulk, and on the cheese surface. The amount of heat supplied by the IR heaters is also recorded. The temperature and pressure, and weight sensors are connected with the PC through the interface block. The signals received from the temperature and pressure sensors and load cell (strain gage), which are proportional to the change in the corresponding process parameters, are digitized by the analog-to-digital converter 12 and are input into the PC to be stored and processed.

## RESULTS AND DISCUSSION

Moisture is among the most important components of cheese. The moisture content of cheese has an effect on the ripening process, cheese structure, and the thermophysical properties of cheese. We quantified different forms of moisture and their bonding energies in some cheeses (Tables 1, 2).

**Table 1.** Amounts of different forms of moisture in cheeses, %

| Cheese brand | Physicochemical binding | | | Physicomechanical binding |
|---|---|---|---|---|
| | adsorbed moisture | | osmotically bound moisture and microcapillary moisture | wetting moisture and macrocapillary moisture |
| | monomolecular adsorption | polymolecular adsorption | | |
| Sovetskii | 7.0 | 11.0 | 12.0 | 10.0 |
| Gollandskii | 5.0 | 8.0 | 19.0 | 12.0 |
| Ozernyi | 4.0 | 6.0 | 21.0 | 17.0 |

**Table 2.** Moisture binding energies in cheeses $10^{-5}$, J/kg

| Moisture–material binding form | Cheese brand | | |
|---|---|---|---|
| | Sovetskii | Gollandskii | Ozernyi |
| Physicochemical binding | | | |
| 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 moisture | 0.45–0.12 | 0.65–0.10 | 0.60–0.10 |
| Physicomechanical binding | | | |
| Microcapillaries | 0.45–0.12 | 0.65–0.10 | 0.60–0.10 |
| Wetting and macrocapillary moisture | <0.10 | <0.10 | <0.10 |

The total weight fraction of moisture is 40% in Sovetskii cheese, 44% in Gollandskii, and 48% in Ozernyi. Sovetskii cheese has the largest proportion of bound moisture, specifically 18.0%; the bound water content of Gollandskii is 13.0%, and that of Ozernyi is 10.0%. Sovetskii cheese, which contains the smallest total amount of moisture among the three cheeses considered, contains the largest proportion of bound moisture. The proportion of high-energy bonds in cheeses depends on the production technology and on the ripening time. P.F. Krasheninin and V.P Tabachnikov established that cheeses gain water-holding capacity as they ripen. That is, in the first approximation, the ripening time can be viewed as a factor in the amount of bound water in cheese: the longer the ripening process, the higher the bound water content of the cheese. This correlation is in full agreement with our data.

Our studies demonstrated that the forms of bound moisture differ in their energetic characteristics and, on passing from free moisture (wetting and macrocapillary moisture) to bound moisture (mono- and polymolecular adsorption), the moisture–dry cheese matter binding energy increases markedly. The binding energy ($\times 10^{-5}$, J/kg) is <0.10 for wetting and macrocapillary moisture, 0.45–0.12 for osmotically bound and microcapillary moisture, 2.30–0.50 for polymolecularly adsorbed moisture, and 4.20–2.50 for monomolecularly adsorbed moisture. Therefore, monomolecularly and polymolecularly adsorbed moisture is most strongly bound owing to its highest binding energy. In view of this, monomolecularly adsorbed moisture is the main index of the hydration of cheese components and is essential for dried foods to be reconstitutable.

Dry foods are known to absorb water from ambient air during storage until they come to the equilibrium state. The equilibrium moisture content of dairy products has been investigated by R.I. Ramanauskas.

We studied the hygroscopic properties of a number of cheeses (Table 3).

**Table 3.** Hygroscopic properties of cheeses

| Relative air humidity, % | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|
| Sovetskii cheese | | | | | | | | | |
| Equilibrium moisture content, % | 7.0 | 10.0 | 11.5 | 13.5 | 15.5 | 17.5 | 19.5 | 22.0 | 26.5 |
| Gollandskii cheese | | | | | | | | | |
| Equilibrium moisture content, % | 5.0 | 6.5 | 8.0 | 9.5 | 11.0 | 13.0 | 17.0 | 25.0 | 33.0 |
| Ozernyi cheese | | | | | | | | | |
| Equilibrium moisture content, % | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 10.0 | 15.0 | 22.0 | 31.0 |

The equilibrium moisture content of cheese decreases with a decreasing relative humidity of ambient air. As the equilibrium air humidity decreases, the energy of binding between moisture and the dry matter of the product increases.

Table 4 lists thermophysical characteristics of cheeses. In order to find appropriate drying conditions for any product, including cheese, it is necessary to know not only its physicochemical properties, but also its thermophysical characteristics. Knowledge of thermophysical characteristics is essential for finding both processing conditions and technological parameters. When choosing processing conditions (temperature, heat flux density, and residual pressure), it is necessary to know the heat capacity and thermal diffusivity of the product for gaining insight into the temperature profile across the bed and into the temperature variation rate. In the determination of technological parameters (thickness of the bed to be dried and degree of comminution), it is necessary to know the heat conductivity of the product, because the optimum thickness of the bed being dried depends on this property.

**Table 4.** Thermophysical properties of cheeses

| Cheese | Thermophysical property | | | |
|---|---|---|---|---|
| | density, kg/m$^3$ | heat conductivity, W/(m K) | eat capacity, J/(kg K) | thermal diffusivity, $10^{-6}$ m$^2$/s |
| Sovetskii | 1070 | 0.34 | 2570 | 0.135 |
| Gollandskii | 1060 | 0.35 | 2530 | 0.133 |
| Ozernyi | 1040 | 0.35 | 2540 | 0.132 |

Drying kinetics is commonly understood as the variation of the volume-average moisture content of the material being dried (φ) and its temperature (*t*) with time τ. The drying process is most precisely described by drying curves in the time–moisture content coordinates, by drying rate curves in the moisture content–drying rate coordinates, and by temperature curves in the moisture content–material temperature coordinates. The performances of driers differing in output capacity cannot be compared in terms of material weight variation during drying. This is done by plotting the moisture content of the material versus time (φ versus τ curves).

Data required for constructing these curves are usually obtained in the laboratory by recording the weight and temperature of the material during its drying. Here, drying is commonly carried out using hot air under fixed conditions. For vacuum drying, fixed conditions mean a constant material temperature and residual pressure. Naturally, the laboratory measurements need to be corrected prior to be carried over to the industrial process, in which drying is typically conducted under variable conditions. The time variation of the volume-average moisture content of the material, $\varphi = f(\tau)$, is graphically represented as the so-called drying curve. In the general case, the drying curve consists of several segments corresponding to different drying stages. Fi-gure 5 shows vacuum drying curves (heat load versus time, temperature versus time, and moisture weight fraction versus time) for Shveitsarskii cheese.

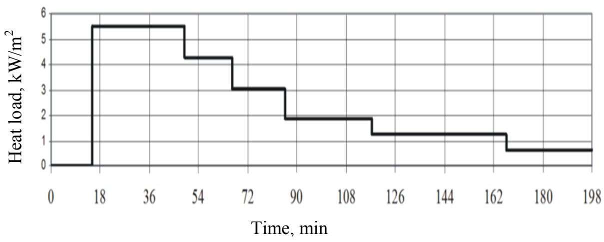
For 9–15 min, until the preset residual pressure (2–3 kPa) is reached, no heat is supplied from the heaters (Fig. 5a) and the cheese temperature decreases from 17–15 to 12–10°C.

This decrease in temperature is due to the intensive evaporation of moisture from the cheese surface. The decrease in the moisture weight fraction during the period of time required to bring the drier to the preset operating conditions is 2–3%. The segment A–B indicates the time required to reach the preset residual pressure (2–3 kPa). This period is followed by the first drying period, specifically, the constant-rate drying period, represented by the segment B–$K_1$ of the moisture weight fraction curve. In the first period, the moisture weight fraction decreases at a practically constant rate; that is, equal amounts of moisture are removed in equal periods of time.

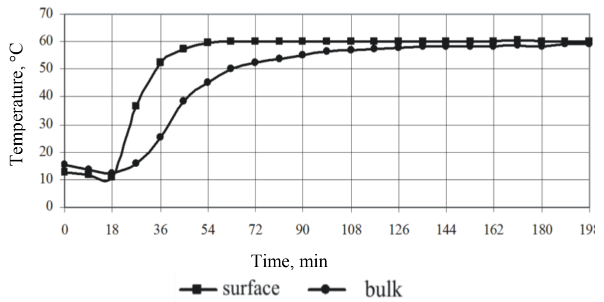
The cheese temperature increases owing to the heat supplied from the heaters. The cheese temperature in the first period reaches the preset value and is maintained at this level (Fig. 5b). By the end of the first period, the temperature distribution in the bulk of the cheese being dried becomes uniform. The heat load at the beginning of the first period has the maximum allowable value. Once the cheese has reached the preset temperature, the heat load is reduced. This decrease in heat load is necessary to prevent the cheese drying temperature from exceeding the preset value.

In the first drying period, the amount of moisture removed from the cheese is the largest. In this period, the moisture weight fraction decreases by 24% in Shveitsarskii cheese, by 23% in Gollandskii cheese, and by 34% in Poshekhonskii cheese. The duration of the first drying period is 74 min for Shveitsarskii cheese, 83 min for Gollanskii cheese, 92 min for Kostromskoi cheese, and 80 min for Poshekhonskii cheese. The constant drying rate period lasts until the first critical moisture content point. The point $K_1$ in the moisture weight fraction versus time curve indicates the instant the straight line $BK_1$ turns into the $K_1C$ curve. The critical moisture content point is the boundary between the constant drying (first) period and the decreasing drying rate (second) period.

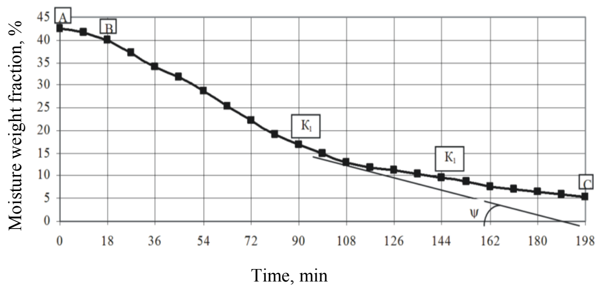
In the constant drying rate period, the intensity of the process is determined only by the parameters of the drying agent and is independent of the moisture content (moisture weight fraction) and physicochemical properties of the material. At a certain value of the moisture weight fraction, the moisture removal rate starts decreasing and the second, decreasing drying rate period begins. The onset of the second period corresponds to the critical moisture content of the material. In the second period, the moisture that is most strongly bound to the product is removed. Here, the evaporation rate decreases, the drying process slows down, and the temperature equalizes throughout the cheese bulk.




(a)




(b)




(c)

**Fig. 5.** Drying curves for Shveitsarskii cheese: (a) heat load, (b) surface and bulk temperatures, and (c) moisture weight fraction. Drying conditions: $t = 60°C$, $q = 5.52\ kW/m^2$, $P = 2–3$ kPa, and $h = 10$ mm.

In the decreasing drying rate period, the drying rate falls as the moisture content of the material decreases. In this period, bound moisture is removed and the gradual decrease in the drying rate is due to the increasing moisture–material binding energy.

In the decreasing drying rate period (segment $K_1C$), the moisture weight fraction of Shveitsarskii cheese decreases by 12%; that of Gollandskii cheese, by 15%; that of Kostromskoi cheese, by 24%; that of Poshekhonskii cheese, by 12%. The duration of this period is 108 min for Shveitsarskii cheese, 100 min for Gollandskii cheese, 17 min for Kostromskoi cheese, and 100 min for Poshekhonskii cheese.

The curve segment representing the decreasing drying rate period ($K_1C$) can be divided into segments corresponding to the first and second phases of this period ($K_1K_2$ and $K_2C$). The junction point $K_2$ for the two phases of the decreasing drying rate period indicates the second critical moisture content. By the second critical point, the evaporation zone reaches deep layers of the product. At this point, moisture is transferred only as vapor and adsorbed moisture is mainly evaporated.

At the end of drying, the moisture weight fraction versus time curve asymptotically approaches the equilibrium moisture content for the given drying conditions. Once the equilibrium moisture content is attained, drying stops; that is, the drying rate becomes zero.

By taking the first derivative of the $\varphi = f(\tau)$ function, we obtain the drying rate understood as a change in the moisture content of the material per unit time ($d\varphi / d\tau$, %/min). The drying rate curves were constructed by graphical differentiation of drying (moisture weight fraction) curves: the drying rate at a given point in time is defined as the slope of the tangent to the drying curve at the corresponding moisture content point (Fig. 5c):

$$\tan\psi = \frac{d\varphi}{d\tau}. \quad (1)$$

The maximum drying rate $N$ in the constant drying rate period is

$$\tan\psi = \left(\frac{d\varphi}{d\tau}\right)_{max} = N,\ \%/\text{h or } \%/\text{min} \cdot \quad (2)$$

At the end of the process, when the equilibrium moisture content is reached, the drying rate is

$$\frac{d\varphi}{d\tau} = 0\ \cdot$$

Figure 6 plots the drying rate curves for the cheeses examined. At the beginning of the drying process, as the residual pressure decreases to the preset value, the drying rate increases from zero to its maximum value. The maximum drying rate is 0.62 %/min for Shveitsarskii cheese, 0.71 %/min for Gollandskii cheese, 0.88 %/min for Kostromskoi cheese, 0.78 %/min for Poshekhonskii cheese, 0,92 %/min for Rizhskii cheese, and 0.75 %/min for Rossiiskii cheese.

In the constant drying rate period, the drying rate takes its maximum value. In this period, the moisture content of Shveitsarskii cheese decreases by 18%; that of « Gollandskii cheese, by 17%; that of Kostromskoi cheese, by 22%; that of Poshekhonskii cheese, by 28%; that of Rizhskii cheese, by 48%; that of Rossiiskii cheese, by 32%.

The drying rate begins to decrease at the first critical point. The run of the curves in the decreasing drying rate period is typical of colloidal, capillary porous gels.

The second critical point $K_2$ indicates the second critical value of moisture content. It corresponds to the moisture content limit at which the mechanism of moisture transfer in the material changes. This point indicates the onset of the removal of polymolecularly adsorbed moisture.

The second critical point occurs at the following moisture weight fractions in the cheeses: Shveitsarskii, 10%; Gollandskii, 10%; Kostromskoi, 13%; Poshekhonskii, 8%; Rizhskii, 10%; Rossiiskii, 9%. The moisture weight fraction in the dry cheeses is 4–5%. The difference between the moisture weight fraction at the second critical point and the moisture weight fraction in the dry cheeses is the amount of polymolecularly adsorbed moisture; therefore, the weight fraction of polymolecularly adsorbed moisture in the cheeses is 4–9 %.

The temperature curves, $t = f(\varphi)$, are very informative. These curves, introduced by A.V. Lykov, are of high significance for drying analysis. Figure 7 presents the temperature curves for the vacuum drying of the cheeses.

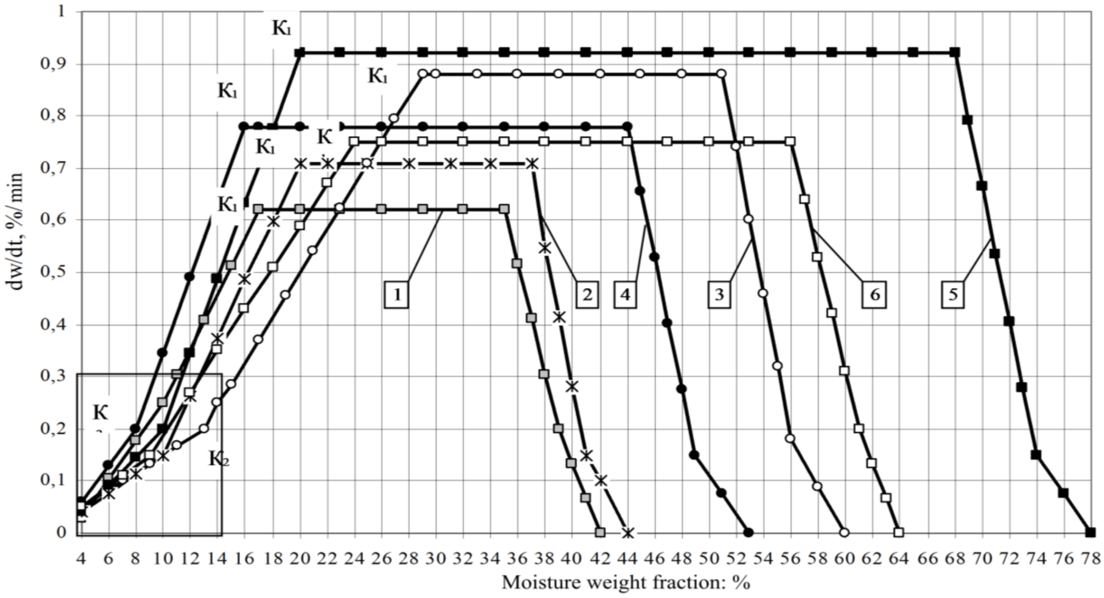



**Fig. 6.** Cheese drying rate curves: (*1*) Shveitsarskii, (*2*) Gollandskii, (*3*) Kostromskoi, (*4*) Poshekhonskii, (*5*) Rizhskii, and (*6*) Rossiiskii.

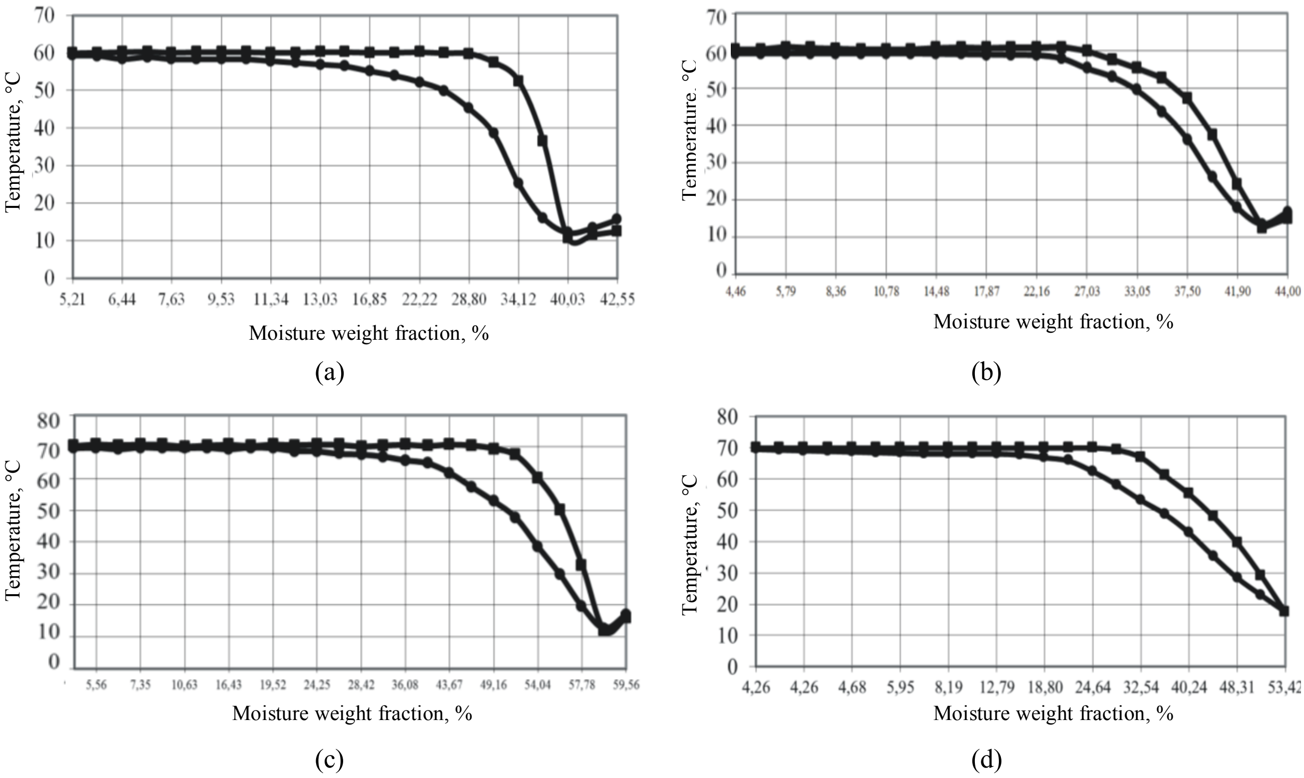



**Fig. 7.** Temperature curves for the vacuum drying of cheeses: (a) Shveitsarskii, (b) Gollandskii, (c) Kostromskoi, and (d) Poshekhonskii.

At the early stages of drying, the cheese temperature decreases, because no heat is supplied from the heaters. At the beginning of the first period of drying, once the heaters are switched on, the surface temperature of the material begins to rise to reach the wet bulb temperature. In this period, heat removal is most intensive and almost all of the heat supplied to the material is spent on moisture evaporation. By the end of this period, the temperature equalizes throughout the bulk of the cheese bed.

Starting at the first critical point, the moisture removal rate decreases. Once the moisture content of the cheese has reached its equilibrium value, the drying process is complete. The equilibrium moisture content of Shveitsarskii cheese is 5.21%; that of Gollandskii cheese if 4.46%; that of Kostromskoi cheese is 5.46%; and that of Poshekhonskii cheese is 4.26%.

Most materials (peat, grain, leather, dough, bread, etc.) shrink throughout the drying process. However, some materials (clay, ceramic masses, and some others) shrink during the constant drying rate period and their shrinkage ceases near the critical moisture content if the moisture content gradient in the material bulk is not large. Other materials (wood, coal) shrink only in the decreasing drying rate period, starting at approximately critical moisture content.

The lowest shrinkage is observed for cheese processed at a residual pressure of 2–3 kPa. It was established that the shrinkage ratio of Gollandskii, Kostromskoi, and Poshekhonskii cheeses increases with an increasing size of cheese pieces and with an increasing thickness of the cheese bed being dried. As the bed thickness is increased from 10 to 30 mm, the shrinkage ratio changes from 3 to 14%. At a bed thickness of 40 mm, the shrinkage ratio is 15–24%. Cheese drying at appropriate regime and technological parameters minimizes moisture weight fraction drops and the shrinkage ratio and leaves the shape of cheese pieces unchanged.

Figure 8 plots the shrinkage ratio of cheese as a function of the initial moisture weight fraction.

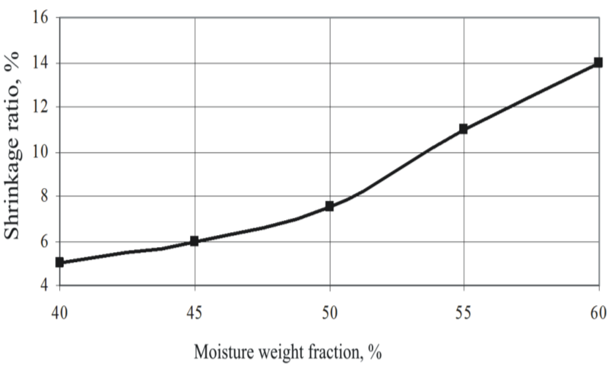



**Fig. 8.** Shrinkage ratio of cheeses as a function of moisture weight fraction.

The shrinkage ratio increases with an increasing moisture weight fraction in cheese. The largest increase in the shrinkage ratio is observed at moisture weight fractions over 50%. As the moisture weight fraction in cheese changes from 40 to 50%, the shrinkage ratio increases by 2.5%; and, as the moisture weight fraction increases from 50 to 60%, the shrinkage ratio increases by 6.5%.

The surface layers, which have an effect on the particle size of the material being dried, tend to shrink in proportion to the moisture content of the surface rather than the average moisture content. This is the reason why almost no shrinkage is observed starting at some moisture content (moisture weight fraction), as is shown in Fig. 9.

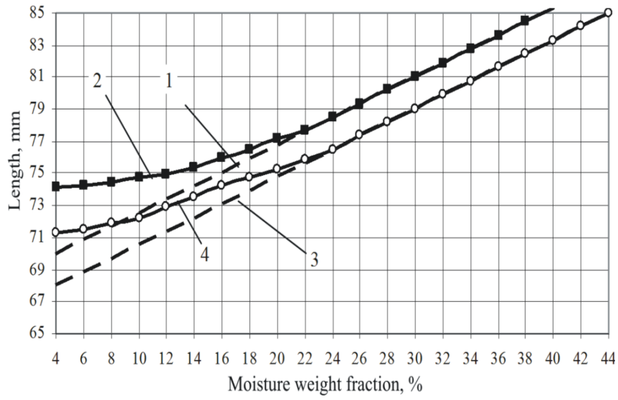



**Fig. 9.** Shrinkage curves for (*1*, *2*) Sovetskii and (*3*, *4*) Gollandskii chesees:
(*1*) $t = 60°C$, $q = 5.52$ kW/m$^2$, $P = 2–3$ kPa;
(*2*) $t = 80°C$, $q = 5.52$ kW/m$^2$, $P = 2–3$ kPa;
(*3*) $t = 60°C$, $q = 7.36$ kW/m$^2$, $P = 2–3$ kPa;
(*4*) $t = 80°C$, $q = 7.36$ kW/m$^2$, $P = 2–3$ kPa.

The shrinkage curves for Sovetskii cheese (curve *1*) and Gollandskii cheese (curve *3*) were recorded at the prescribed drying temperature, 60°C. Shrinkage curves *2* and *4* were obtained at 80°C, above the prescribed temperature. At this elevated temperature, surface layers dry up rapidly. Inner layers have a rather large moisture weight fraction. The shrinkage ratio at the increased temperature is smaller, but the dry cheese has a large moisture weight fraction.

As the drying temperature is raised, the shrinkage ratio decreases because of the increasing moisture weight fraction gradient inside the material. When there is a moisture weight fraction gradient, the surface layers tend to shrink to a larger extent than the inner layers. However, the shrinkage of the surface layers is impeded by the inner layers, which are richer in moisture than the former. As a consequence, the actual shrinkage of the surface layers is smaller than the shrinkage that is equivalent to the amount of moisture removed from them. Therefore, an increase in the moisture weight fraction drop between the inner and surface layers leads to an increase in the difference between the actual shrinkage and the theoretical shrinkage corresponding to the amount of liquid removed.

Thus, the shrinkage ratios of cheeses were correlated with the thickness of the bed being dried and with the shape and size of cheese pieces. At a bed thickness of 10 to 30 mm, the shrinkage ratio of the cheeses is 3 to 14%, depending on the shape and size of cheese pieces. The shrinkage ratio increases with an increasing moisture weight fraction in cheese. Shrinkage was observed to proceed uniformly in both periods of vacuum drying. As the drying temperature is raised over the prescribed value, the shrinkage ratio decreases because of the increasing moisture weight fraction gradient in the bulk of the material.

The shrinkage of a wet material at a uniform moisture content and temperature distribution is a physical property of the material, its response to loss of liquid, and does not induce any detrimental stresses. However, the shrinkage of a material at a nonuniform moisture content distribution does bring the material into a stressed state that can lead to cracking of the body and to breaking of its structure. Therefore, the main obstacle to the rapid drying of many materials is their cracking. This cracking (local disruption) and complete breakup (structure disintegration) are caused by the development of bulk stresses in the material being dried that exceed the stress limit set by the strength of the material.

This stressed state of the material results from a nonuniform moisture content and temperature distribution in the material bulk [15–18].

The existing method of investigating shrinkage stresses does not exclude use of a phenomenological approach in the study of the shrinkage of moist bodies. Note that the capillary and disjoining pressures of a liquid phase in a solid are functions of moisture content. Accordingly, the field of capillary contractions under isothermal conditions will be similar to the moisture content field. Therefore, a nonuniform moisture content distribution (nonuniform moisture content field) is the most significant characteristic of the bulk-stressed state of a moist body being dried.

A similar situation is observed for thermal stresses. In the phenomenological approach, the bulk-stressed state of a body being heated is considered to be unambiguously determined by the nonuniform temperature distribution, or by the temperature field. The main cause of drying-induced cracking is the existence of high-gradient moisture content and temperature fields.

Figure 10 shows moisture content profiles along the thickness of cracky and noncracky cheese beds.

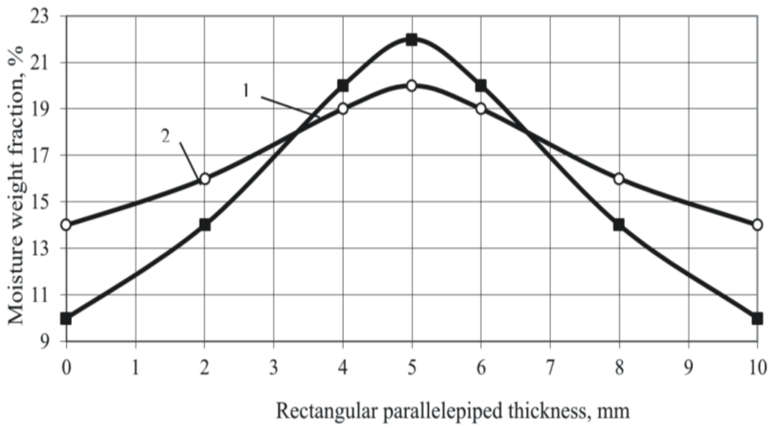



**Fig. 10.** Moisture content profiles along the thickness of (1) cracky and (2) noncracky cheese beds.

The drying of cheese as 10-mm-thick rectangular parallelepipeds at a moisture weight fraction drop of 12% causes cracking, but there are no cracks at a moisture weight fraction drop of 6%.

## CONCLUSIONS

Cheese was investigated as an object of drying. The physicochemical composition of a number of cheeses was studied, binding forms and binding energies of moisture in the cheeses were considered, the hygroscopic properties of the cheeses were investigated, and the thermophysical characteristics of the cheese were analyzed.

The kinetics of the vacuum drying of the cheese was investigated. It was found that the vacuum drying of the cheeses includes two periods, namely, constant and decreasing drying rate periods. Drying curves (heat load versus time, temperature versus time, moisture weight fraction versus time) for various cheeses were recorded and examined. Drying rate curves for the cheeses were constructed by graphical differentiation of drying curves. The maximum drying rates were determined for some cheeses: Shveitsarskii, 0.62 %/min; Gollandskii, 0.71 %/min; Kostromskoi, 0.88 %/min; Poshekhonskii, 0.78 %/min. Using the same method, the amount of polymolecularly adsorbed moisture in the cheeses was determined to be 4–9%. Cheese temperature curves (temperature versus moisture weight fraction) were investigated. Equilibrium values of moisture content were determined for vacuum-dried cheeses.

The shrinkage ratios of cheeses were correlated with the thickness of the bed being dried and with the shape and size of cheese pieces. At a bed thickness of 10 to 30 mm, the cheese shrinkage ratio is 3 to 14%, depending on the shape and size of cheese pieces. The shrinkage ratio increases with an increasing moisture weight fraction in the cheese. Cheese shrinkage in both vacuum drying periods takes place uniformly. Raising the temperature over the prescribed value diminishes the shrinkage ratio owing to the increase in the moisture weight fraction gradient in the bulk of the material.

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