The procedure for defining the temperature conditions for food dehydration

V M Arapov, D A Kazartsev, A B Emel'yanov, G N Egorova, M V Babaeva and S V Zhukovskaya

1 K.G. Razumovsky Moscow State University of technologies and management (The First Cossack University), Zemlyanoy val str., 73, Moscow, 109004, Russian Federation
2 Voronezh State University of Engineering Technologies, 19, Revolutsii Ave., Voronezh, 394036, Russian Federation

E-mail: kda_79@mail.ru

Abstract. At present, there are no reliable criteria for acceptable drying temperatures; so, a new approach is proposed to determine the range of acceptable drying conditions based on a joint solution of the equations that determine the drying kinetics and the kinetics of changes in the process characteristics of the product. For a given product quality, the logarithm of the maximum allowable drying time linearly depends on the reciprocal of the absolute temperature of the drying agent. The method for calculating the drying time is simplified based on a new product characteristic - equivalent moisture content. The criterion of acceptable conditions, which is the maximum temperature of the drying agent, is a function of the magnitude of the thermal effect, the parameters of the drying kinetics, and the kinetics of the process properties of the product.

1. Introduction
For the production of many food products, drying is one of the energy-intensive technological processes, significantly affecting both the economic and quality indicators of the final product.

As a result of drying, the food product must acquire, in accordance with the standard, the following qualitative characteristics: physicochemical, organoleptic, structural-mechanical, and others. Therefore, drying must be considered simultaneously from two points of view: as a heat and mass transfer process, accompanied by the removal of moisture from the product, and as a technological process in which it is necessary to form product’s qualitative characteristics. From the standpoint of heat and mass transfer, increasing the temperature of the drying agent is one of the effective methods of intensification of drying. On the other hand, increasing the temperature of the drying agent can lead to unacceptable physicochemical and other changes in the product.

In this connection, when developing innovative technologies and drying techniques or optimizing existing manufacturing processes, the problem arises of determining the entire range of acceptable temperature conditions for drying for a particular food product in an apparatus of a certain design. This study is undertaken for solving this problem, the purpose of which is to develop a procedure for determining the acceptable temperature conditions of food drying.
2. The state of the issue and research objective setting

2.1. Heat influence on the product during the drying process

Analysis of the scientific and technical literature on the problem under study shows that there is no consensus among scientists on the choice of parameters for the drying process or product, which should be taken as a criterion for the acceptable temperature regime of drying [1…9]. From the standpoint of considering the physical and chemical phenomena observed during drying, it is necessary to determine the changes in the technological properties of the product — structural, mechanical, biological, physical, chemical, thermos-physical, optical, and others, that occur in the product under the influence of heat. However, only certain properties set by the standard determine the quality of a dry product. Therefore, it is necessary that these properties be preserved or even improved, if possible, while others will inevitably change. For example, when drying food-grade wheat according to [2, 5], it is necessary to preserve the quantity and quality of gluten in grain, while when drying seed wheat, seed germination capacity shall be preserved. However, other properties of grain (heat capacity, mechanical strength, density) do not fundamentally affect the quality of the dried grain. The quality of dry baker's yeast is determined by its dough-raising power. Therefore, when drying the yeast one seeks to preserve its biological properties [5]. In this regard, according to the authors, the concept of a heat-sensitive product feature should be introduced: a heat-sensitive indicator of a product, by which it is proposed to interpret as the most thermo-labile indicator, undergoes the greater change in its quality, for the product from the numerical indicators provided by the relevant standard. Consequently, germination capacity is a heat-sensitive indicator for seed grains, and dough-raising power is the one for yeast.

From the standpoint of thermodynamics, drying should be described by the magnitude of the thermal effect on the dry components of the product. In association with the problem under consideration, a quantitative assessment of the thermal effect should be assessed not by the amount of heat absorbed by the product, but by the change in the value of the heat-sensitive indicator of the product, which occurs under the influence of heat. Moreover, according to the authors, the value of the thermal effect should be understood as the relative (in percentage) expression of the change in the heat-sensitive indicator of the product.

2.2. Criteria of the acceptable temperature conditions

Thus, an acceptable temperature regime should be understood as such where the change in the temperature-sensitive indicator of the product is kept within the standard value. However, it is necessary to ascertain which of the parameters of the drying regime should be taken as a criterion for the permissible thermal regime.

Analysis of the scientific and technical literature over the past several decades [1…10] shows that the magnitude of the thermal effect on the product is a function, first of all, of the temperature and the duration of the thermal effect. In this regard, many scientists [2, 5, 8] take the maximum allowable temperature of the drying agent at the inlet to the apparatus or the maximum allowable temperature for heating the product during drying as the criterion of the acceptable temperature conditions of drying. In [10], the authors propose to set the acceptable temperature for heating the product based on the definition of special features of the product, such as heat resistance, thermal integrity, and thermal stability. However, numerous recommendations in the academic literature on determining the acceptable temperature of a drying agent or the heating temperature of a product are not clear and very contradictory even for the same product. For instance, the maximum temperature of wheat grain heating when preparing it for baker’s flour production is 48…50 °C according to [2], while according to [5] it is 50…55 °C, and S.S. Pabis believes that when drying, the grain the temperature of the fluidized bed can be 70 °C. According to Maltry, \( t_{\text{max}} \) for corn seed drying is 44 °C, while according to Aror it is 60 °C [9]. If we consider cord seed germination capacity reduction by 10% acceptable, and the drying duration does not exceed 60 minutes, then, according to [8], \( t_{\text{max}} \) may be up to 130 °C.
Probably, in this connection, in practice, the temperature of the drying agent \( T_c \) at the inlet of the apparatus is used as a criterion for the acceptable temperature regime. However, the limits of the acceptable values of \( T_c \) are even more uncertain and must take into account a large number of process factors. Convincing evidence of the insolvency of the use of \( T_c \) as a criterion for the acceptable temperature regime of drying is given in [4], which shows that with the development of technology and procedures for drying casein over 60 years, the maximum value of \( T_c \) changed from 40 ... 50 °C to 400 °C.

The most rigorous scientific justification for choosing the criterion of acceptable temperature conditions is contained in works where the value of the maximum temperature of the product is related to the duration of the process [5, 7]. Thus, S.D. Ptitsyn [5] proposed to determine \( t_{\text{max}} \) for seed grain by the empirical equation:

\[
t_{\text{max}} = \frac{2350}{0.37(100-W_i)+W_i} + 20 - l\tau
\]

where \( W_i \) – initial moisture content of the grain, %; 
\( \tau \) – drying duration, min.

2.3. Research objective setting

However, to date, no relationship has been determined between temperature, the duration of the process, and the magnitude of the thermal effect on the product during its drying. In this connection, to achieve this goal it is necessary to solve the following problems.

1. To develop a mathematical model of the relationship between the temperature of the drying agent and the duration of drying of the product while maintaining the required quality.
2. To develop a procedure of drying duration determination.
3. To develop a mathematical model of the criterion for acceptable temperature conditions for food drying.

3. Research results

3.1. Formulation of the basic scientific hypothesis

Analysis of the above research results on this problem made it possible to formulate the following scientific hypothesis. The theoretical basis for determining the range of acceptable temperature conditions should be a joint consideration of the kinetics of drying the product with the kinetics of a complex of various transformations that determine the quality of the product and accompany the drying process. Based on this, it is possible to develop a procedure for determining the drying time, the value of which should, on the one hand, ensure the receipt of a product of a given final humidity, and on the other hand, keep the value of the temperature-sensitive indicator within the limits set by the standard. Therefore, the criterion of the acceptable temperature regime of drying can be the maximum allowable temperature of the drying agent, at which the drying time does not exceed the maximum allowable time for heat treatment of the product by this agent, while the value of the heat-sensitive indicator is within the specified limits.

3.2. The mathematical model of the relationship between the temperature of the drying agent and the duration of drying of the product while maintaining the required quality

Let us consider a food product containing several thermo-labile components. We select the thermo-labile component, which undergoes the greatest change under the influence of heat, as the heat-sensitive indicator of the product. Its relative change is denoted by:

\[
\alpha = \frac{M(\tau)}{M_i},
\]

where \( M_i, M(\tau) \) – correspondingly, initial and current amount of the thermo-labile component.
The rate of change of the heat-sensitive indicator is determined based on the laws of chemical kinetics according to the Arrhenius equation [11]:

\[
\frac{da}{d\tau} = f(\alpha) \cdot A \cdot \exp\left(-\frac{E}{RT(\tau)}\right),
\]

where \(\alpha\) – relative change of the heat-sensitive indicator;
\(\tau\) – process duration, sec;
\(A\) – pre-exponential factor, sec\(^{-1}\);
\(E\) – activation energy for the heat-sensitive indicator, J/mole;
\(T(\tau)\) – absolute temperature of the heat-sensitive indicator, K;
\(R\) – molar gas constant, J/(mole\cdot K);
\(f(\alpha)\) – transformation function of heat-sensitive indicator.

The most universal expression of the transformation function suitable for describing many physicochemical transformations is a power law model of the form:

\[
f(\alpha) = (1 - \alpha)^n,
\]

where \(n\) – coefficient called reaction order.

Let the drying mode be characterized by the absolute temperature at the inlet of the apparatus \(T_c\). Drying in this mode can be carried out until the value \(\alpha\) reaches the maximum allowable standard value \(\alpha_{\text{max}}\). The maximum allowable drying time in this mode is determined from the condition:

\[
\int_0^{\alpha_{\text{max}}} \frac{da}{(1-\alpha)^n} = \int_0^{T_{\text{max}}} A \cdot \exp\left(-\frac{E}{RT(\tau)}\right) d\tau.
\]

As the temperature of the material \(T(\tau)\) during drying is functionally dependent on the temperature of the drying agent \(T_c\), then for the integral of the right-hand side of the equation we hypothetically assume (with subsequent verification) the possible equality:

\[
\int_0^{T_{\text{max}}} A \cdot \exp\left(-\frac{E}{RT(\tau)}\right) d\tau = A' \cdot \exp\left(-\frac{E}{RT_c}\right) \cdot \tau_{\text{max}},
\]

where \(A'\) – empirical coefficient, sec\(^{-1}\).

Then, taking into account the mathematical expressions (6), (7) and (8), the mathematical model of the relationship between \(T_c\) and the duration of the product drying while maintaining its quality indicators is:

\[
\ln \tau_{\text{max}} = a + b \frac{1}{T_c},
\]

where \(a, b\) – empirical coefficients for the given material.

For experimental verification of the mathematical model (7), we used the results of a study of drying corn grain [8, 9] and carotene losses from the heating temperature in carrot roots [1].

As can be seen from the above graphical dependencies, they are in good agreement with the mathematical model (10).
3.3. The procedure of drying duration determination

In the general case the duration of drying is determined as follows:

\[ \tau_c = \int_{U_f}^{U_i} \frac{dU}{N(U)}. \]  \hspace{1cm} (8)

where \( N(U) \) – drying rate, sec\(^{-1}\);

\( U_i, U_f \) – initial and final moisture content in the product, kg/m\(^2\) dry matter.

In the theory of drying, a period of constant and decreasing drying rate is identified. The period of constant rate, ending when the product reaches critical moisture content, does not depend on moisture content, and is a function of temperature and other parameters of a particular drying method. In the educational and scientific literature numerous analytical and experimental methods for determining the constant drying rate for food can be found [6, 12]. The drying time of this (first) period \( \tau_1 \) is calculated from the expression:

\[ \tau_1 = \frac{U_i - U_{cr}}{N_1}. \]  \hspace{1cm} (9)

where \( U_i, U_{cr} \) – initial and critical moisture content in the product, kg/m\(^2\) dry matter;

\( N_1 \) – constant drying rate, sec\(^{-1}\).

Obtaining analytical dependences on the temperature of the drying agent and other process parameters for a period of decreasing rate, as is known from [6, 12], is significantly difficult. Therefore, an empirical approach based on probability theories, mathematical statistics, similarity, and
modeling [12] is often used for these purposes. Moreover, for specific drying methods one tends to use simpler mathematical expressions. In this regard, in engineering practice, a method of modeling the drying rate based on the approximation and generalization of kinetic curves in the form of the relationship \( N_2(U) = N_1 \cdot f(U) \) is widely applied. For instance, the model proposed by G. K. Filonenko [12] for the second period gives satisfactory results for engineering practice:

\[
N_2(U) = N_1 \frac{(U-U_p)^m}{(A+B(U-U_p))^m},
\]

(10)

where \( N_2(U) \) – reducing drying rate, sec\(^{-1}\);

\( A, B, m \) – constants, defined by trial;

\( m \) – describes the form of connection of moisture and the product and does not depend on other factors.

Based on (10) we calculate the duration of second period of drying:

\[
\tau_2 = \frac{1}{N_1} \int_{U_i}^{U_f} \frac{dU [A+B(U-U_p)]^m}{(U-U_p)^m} = \frac{W_2}{N_1},
\]

(11)

where \( W_2 \) – the result of calculating the define integral, kg\(_{w,kr}\)/kg\(_{dry\,matter}\).

If \( A, B, m \) do not depend on process parameters, then value \( W_2 = const \).

From the expressions (9) and (10) we get:

\[
\tau_1 \cdot N_1 + \tau_2 \cdot N_1 = \tau_c \cdot N_1 = W_1 + W_2 = W_{rev} = const,
\]

(12)

where \( W_1 = U_i - U_p \).

In establishing the physical meaning of the values \( W_1, W_2, \) and \( W_{rev}, \) we proceed from the following reasoning. The dimension of these values coincides with the dimension of the moisture content of the product. Therefore, \( \tau_1 \cdot N_1 \) corresponds certain estimated amount of moisture content, which could be removed from the product at a constant rate during the time equal to the drying time of the product in an industrial apparatus. We suggest naming value \( W_{rev}, \) and the total equivalent moisture content, while \( W_1 \) and \( W_2 \) are, correspondingly, equivalent moisture contents of the first and second drying periods. Knowing \( W_{rev} \) and \( N_1, \) we easily calculate \( \tau_c. \)

Since \( W_{rev} \) is a constant value for a specific product in a particular design of a drying unit, it can be comparatively easy determined experimentally from the drying curve (the dependence of the moisture content \( U \) on the drying time \( \tau \)).

3.4. Experimental definition of the total equivalent moisture content

The experimental procedure for determining the total equivalent moisture content and verification (12) are shown on the experimental drying curves of various products borrowed from literature [ ]. To determine \( W_{rev} \) on the graph of the drying curve, it is necessary to construct a grid of equivalent moisture content, with the scale equal to the scale of the grid of moisture content of the product. The point \( U_i \) corresponds to zero on the grid \( W, \) the axis of which is directed opposite to the axis \( U. \) The drying time \( \tau_c \) is determined from the value of \( U_c. \) We draw a tangent to the graph \( U = f(\tau) \) from the point \( U_0 \) on the drying curve, which describes the process of removing the equivalent moisture content with a constant rate \( N_1. \) According to a previously determined drying time, \( W_{rev} \) is calculated.

The experimental data presented in Figures 4 and 5 are widely known to the scientific community, their reliability is not in doubt, which proves the validity of our reasoning.
3.5. The mathematical model of the criterion for acceptable temperature conditions for food drying

The provision for the acceptable temperature conditions is defined from the expression:

\[ \tau_c \leq \tau_{\text{max}}. \]  

(13)

Based on that and taking into account (12) and (13) we can record:

\[ \tau_c = \frac{W_{\text{rev}}}{N_1} \leq \tau_{\text{max}} = \exp\left(\alpha + b \frac{1}{\tau_c}\right). \]

(14)

From which it follows:

\[ T_{\text{c}}^{\text{max}} \leq \frac{b}{\ln \frac{W_{\text{rev}}}{N_1} - a}. \]

(15)

Inequality (15) in general terms represents a mathematical model of acceptable temperature conditions for drying a specific product, which relates the temperature regime \( T_{\text{c}} \) to the magnitude of the thermal effect (coefficients \( a \) and \( b \) are determined at \( \alpha_{\text{max}} \)) and to structural and other drying parameters, the influence of which on the process is reflected at the maximum drying rate \( N_1 \).

4. Conclusion

From the above, we can draw the following conclusions.

The fixed values of the maximum allowable heating temperature of the product or the maximum allowable temperature of the drying agent, currently accepted as criteria for permissible temperature regimes for drying food products, do not provide a reliable correlation between the magnitude of the thermal effect on the product and the value of these criteria.

To obtain an objective assessment of the relation between the magnitude of the thermal effect on the product and the temperature regime of drying, it is necessary to jointly consider the kinetics of drying the product with the kinetics of changes in the technological characteristics of the product occurring under the influence of heat. This approach to the considered problem is fundamentally different from the previous ones, in which attempts were made to link the final result of thermal exposure to the product with one of the parameters of the drying regime, such as the temperature of...
the drying agent or the heating temperature of the product, without taking into account the kinetic laws of the occurring phenomena. For a given value of the thermal effect on the product, the logarithm of the maximum allowable drying time is a linear function of the reciprocal of the absolute temperature of the drying agent.

The condition for the acceptable temperature conditions is the excess of the duration of the product heat treatment by a drying agent with a given temperature that is acceptable from the condition of preserving the quality of the product over the required duration of drying to the final moisture content.

The proposed procedure for determining the drying time, based on the experimentally determined value of the total equivalent moisture content, greatly simplifies this calculation in comparison with existing methods. The value of the total equivalent moisture content characterizes the product as an object of drying, is easily determined by the experimental drying curves, and is a constant value for a particular product when it is dried in a specific apparatus.

It was understood that the maximum allowable temperature of the drying agent, as a criterion of acceptable temperature conditions, is not a constant value, as many scientists believed. It is a function of the magnitude of the thermal effect, the kinetics of the change in the technological properties of the product, and the parameters that determine the maximum drying rate of the product at a given temperature in a particular dryer. In this case, the parameters of the temperature regime should be determined on the Kelvin scale, and not on the Celsius scale, as was done previously.

References
[1] Altuhov I V 2015 Energy-saving technology of impact infrared drying of root crops Doctoral dissertation for the degree of Doctor of Technical sciences Irkutsk.
[2] Kurdyumov V I, Pavlushin A A, Karpenko G V and Sutyagin S A 2013 Heat treatment of grain in contact-type apparatus (Ulyanovsk: USAA named after P.A. Stolypin)
[3] Semenos G V, Krasnova I S and Petkov I I 2017 Choice of regime parameters for vacuum sublimation dehydration of dry thermos-labile materials with the set quality level Bulletin of the International academy of cold 1 18–24
[4] Arapov V M and Polyanskiy K K 1996 Analysis of development of the technology and technique of casein drying Dairy industry 4 14–16
[5] Ginzburg A S 1976 Technology of food drying (Moscow: Food industry)
[6] Sazhin B S and Sazhin V B 1997 The scientific bases of drying technique (Moscow: Science)
[7] Tutova E G and Kuts P S 1987 Drying of microbiological manufacture products (Moscow: Agropromizdat)
[8] Urazov M Ju 1998 Increase in the efficiency of convective drying of corn grain in dense layer Author’s abstract of Candidate dissertation for the degree of Candidate of Technical sciences, Moscow
[9] Myul’bauer V 1980 Study of the process of corn grain drying in the dryer with co-current flow (Moscow: VTsPNTLD)
[10] Mushtaev V I, Ul’yanov V M and Timonin A S 1984 Drying in pneumatic conveying (Moscow: Chemistry)
[11] D’yachenko A N and Shagalov V V 2014 Chemical kinetics of heterogeneous processes (Tomsk: Tomsk technical university)
[12] Lykov A V 1968 Theory of drying (Moscow: Energy)