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Rationalisation of commercial and technological features of biscuit semi-finished products during baking

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Abstract. Each type of flour-based confectionery requires specific thermophysical conditions to be achieved within the selected oven. Sponge cake semi-finished products have unique baking characteristics that must be taken into account when designing and adjusting baking equipment. This study aimed to examine heat flux densities across the surfaces and layers of sponge cake

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products using technical instrumentation, and to provide recommendations for industrial thermal regimes. Temperature measurements were carried out using thermocouples and compact, low-inertia heat flux sensors. Baking was performed in a laboratory oven using traditional metal moulds, as well as with anti-adhesive paper inserts placed inside the same moulds. The inserts were prepared by priming paper or cardboard with a 10% polyvinyl alcohol solution, followed by coating with a water-based emulsion of silicone fluid mixed with polyvinyl alcohol and a small amount of curing catalyst. The experiments were conducted at temperatures ranging from 140 to 200°C. The paper presented data on the baking kinetics of the upper layer of sponge semi-finished products, both in metal moulds and with paper inserts under optimal heating conditions. Two series of tests were carried out using a laboratory oven with combined convective and radiant heat input. The optimal baking regime was determined to be 170-180°C with equal heat supply from the top and bottom. The results confirmed the effectiveness of anti-adhesive paper inserts, which reduce the thickness of the bottom crust, minimise product breakage, and improve sanitary conditions during production and distribution. The study identified optimal baking regimes for sponge semi-finished products in industrial bakery ovens, based on technological, quality, and economic considerations. The practical value of this work lies in the applicability of its findings at baking and confectionery enterprises seeking to optimise the baking modes of biscuit semi-finished products and to improve the quality and efficiency of production

Keywords: kinetics of baking; thermometry; heat metering; thermal and physical characteristics; thermal resistance

Introduction

The production of semi-finished biscuit products is one of the most widespread segments of the flour confectionery industry, one that combines high demands for quality consistency, process energy efficiency, and the competitiveness of finished products. Modern market conditions necessitate the rationalisation of the commodity and technological properties of biscuits at the baking stage, since this process determines the formation of structure, volume, colour, crust texture, and crumb, whilst also affecting the keeping quality and consumer characteristics of the product. Inconsistency in thermal regimes or the design parameters of moulds leads to increased energy consumption, uneven baking, deformation, and product losses. In this regard, improving approaches to controlling heat and mass transfer processes during the baking of semi-finished biscuit products constitutes an urgent scientific and practical task.

In recent years, considerable research attention has been directed towards modelling thermal processes during baking. S. Simpson (2023) found that the distribution of heat flux between the upper and lower zones of the oven significantly affects the rate of crust formation and the final moisture content of the crumb, and that optimising the ratio of convective to radiant heating allows the duration of the process to be reduced without adversely affecting textural indicators. Studies by P. Jayapragasam *et al*. (2021) showed that controlling heat flux density makes it possible to minimise temperature gradients within the volume of the biscuit mass and to produce a more uniform porous structure. The influence of recipe factors on the formation of technological properties during baking was examined by B. Inanlar & F. Altay (2024), who demonstrated that altering the ratio of egg foam to flour significantly modifies the rheological characteristics of the dough and determines the behaviour of gas bubble expansion during the initial period of heat treatment. D. Nekesa *et al*. (2024) found that the use of alternative protein ingredients modifies the mechanism of protein coagulation and requires adjustment of the temperature regime in order to preserve product volume.

A separate area of research concerns the energy efficiency of the baking process. S. Chakraborty & K. Dash (2023) concluded that adaptive temperature control during the baking cycle can reduce energy consumption by up to 12% by limiting overheating in the final phase. Similar results were obtained by A. Görgülü (2025), who demonstrated that the use of heat flux sensors in laboratory and industrial ovens contributes to more accurate determination of the end point of baking and a reduction in excess energy consumption. Research aimed at improving contact surfaces and mould materials is also noteworthy. W. Yang *et al*. (2025) demonstrated that the use of non-stick coatings based on silicone emulsions reduces the intensity of heat transfer through the base of the mould, which in turn affects the thickness of the bottom crust and reduces the risk of scorching. P. Zarzycki *et al*. (2024) showed that the use of paper liners with polymer treatment provides more uniform heating of the side layers and facilitates product removal without mechanical damage.

The structural formation of biscuits during baking was studied by H. Dizlek & A. Altan (2021), who established that the rate of dehydration of the surface layers correlates with the formation of an elastic crust and determines the subsequent redistribution of moisture within the product. N. Mattioli *et al*. (2025), by contrast, emphasised that excessive heat flux intensity at the initial stage leads to premature fixation of the structure and a reduction in specific volume, which adversely affects the commercial properties of the product. The analysis of the foregoing studies indicates significant progress in understanding the mechanisms of heat and mass transfer during the baking of biscuit semi-finished products, as well as growing interest in energy- and material-saving technologies. Nevertheless, most research focuses either on recipe aspects or on individual parameters of the thermal regime, without a comprehensive assessment of their combined impact on the commodity and technological characteristics of the product. The question of coordinating heat supply modes, the design features of moulds, and quality indicators from the standpoint of rationalising the production process remains insufficiently studied.

The purpose of the study was to substantiate and experimentally verify approaches to the rationalisation of the commodity and technological properties of biscuit semi-finished products during baking, based on the optimisation of thermal regimes and conditions of product formation.

Materials and Methods

The research was conducted in 2023 in an educational and scientific laboratory and under the experimental and industrial conditions of a small-scale enterprise. This approach made it possible to combine the controllability of a laboratory experiment with verification of the results obtained in a production environment. The research programme was designed according to a factorial scheme with variation of the heating medium temperature and heat supply conditions. The experimental design was a full factorial with two main factors – temperature and the presence or absence of an anti-adhesive insert – with fixed recipe parameters. Each experiment was carried out in at least three replications. The control conditions were defined as baking in traditional metal moulds without paper inserts at 170°C with uniform heat supply from above and below. Comparison with the control allowed the impact of design and regime changes on commodity and technological indicators to be assessed.

Baking regimes covered a temperature range of 140-200°C in increments of 10°C.

The duration of the process ranged from 18 to 30 min depending on the temperature and mass of the workpiece. The laboratory oven provided combined convective-radiant heat supply with the ability to adjust the ratio of heat fluxes from above and below. Relative humidity in the working chamber was maintained at 20-35%; in some experiments, the effect of short-term humidification at the initial stage of baking was additionally assessed. Air velocity in the working space was 0.5-1.2 m/s and was monitored by an anemometer. Biscuit semi-finished products were prepared according to a standardised recipe with a fixed ratio of the main ingredients. After mixing and aeration, the dough was divided into samples weighing 210 ± 1 g and placed in metal moulds of identical diameter. Some of the moulds were fitted with anti-adhesive paper inserts with a polymer coating. The geometric parameters of the workpieces (diameter and layer height) were measured prior to baking in order to correctly determine the characteristic dimension for thermophysical calculations.

Temperature at different points of the workpiece and the heating medium was recorded using chromel-alumel type K thermocouples connected to a multi-channel data logger. Heat flux density was measured using low-inertia heat flux sensors with dimensions of 10×10×1.2 mm. Prior to each experimental series, the thermocouples were calibrated in a water bath and a dry-block calibrator over the range of 20-200°C. The maximum absolute error of temperature measurement did not exceed ±0.5°C, and that of heat flux density ±5%. Calibration was rechecked after every 30 baking cycles. Heat fluxes were measured from the top, bottom, and through the side surface of the mould, and temperature profiles along the height of the workpiece were recorded at 5 mm intervals. Mass loss was determined by weighing on an electronic balance with an accuracy of ±0.01 g before and after baking and cooling. To assess the efficiency of the thermal process, specific heat consumption per unit mass of product and the time required to reach the protein coagulation temperature in the central zone were additionally calculated.

The quality of the finished products was assessed using standardised methods. The mass fraction of moisture was determined by drying to constant mass in accordance with current regulatory requirements for flour confectionery products. Specific volume was determined by the rapeseed displacement method. Crust thickness was measured with a calliper at four equidistant points. Textural profile was analysed using a texture analyser by the double-compression method, with determination of elasticity, cohesiveness, and crumb hardness. Ease of removal was assessed as the percentage of products showing no mechanical damage.

Statistical processing of the results was performed using an applied statistics software package. Mean values, standard deviations, and confidence intervals were calculated. The influence of factors was assessed by analysis of variance (ANOVA) at a significance level of $p \leqslant 0.05$. Correlation analysis was used to establish relationships between thermal process parameters and quality indicators. Errors were expressed as the standard error of the mean based on three or more replications. The combination of a controlled factorial design, metrologically verified measuring instruments, and statistically sound data processing ensured the reliability of the results obtained and the feasibility of their practical application in the rationalisation of baking modes for biscuit semi-finished products.

Results and Discussion

The need to bake biscuit semi-finished products in industrial ovens in the most rational manner – with respect to both energy and material resources and to the organoleptic and commercial characteristics of the product – necessitated preliminary laboratory investigation. The article by A. Dorohovich *et al*. (2012) represents an attempt to link thermal, physicochemical, structural, and mechanical processes during the baking of flour confectionery products, and presents experimental data on baking kinetics and volume increase of cakes and biscuits in traditional metal moulds. Certain data on the thermal conductivity of flour confectionery products are also provided, though the conditions and methods under which these values were obtained are not specified.

S. Dudko *et al*. (2017) calculated the Biot number for baking "massive" or "thin" bodies as $Bi = \alpha l/\lambda$, where α, W/(m$^2 \cdot$K) is the heat transfer coefficient at the surface of the flour confectionery product; l, m – the characteristic dimension of the product; λ, W/(m·K) – its thermal conductivity. The authors derived the values of α, l and λ from verified experimental data on the baking of flour confectionery products under laboratory and industrial conditions. Biscuit semi-finished products are appropriately classified as "massive" bodies. In the articles by S. Bagliuk *et al*. (2015) and A. Bolger *et al*. (2021), the quality of semi-finished biscuits made according to different recipes is characterised by the Biot (Bi) and Grashof (Gr) similarity numbers. However, the heat transfer coefficient α required for the calculation of Bi cannot be determined directly from the experimental setup described, since in this context α represents the total heat transfer coefficient (comprising convective, radiant, and mass transfer components, the last of which may take a negative value). The thermal conductivity of the dough cannot be derived from $q = -\lambda\ gradT$ either, since the heat flux density q, W/m^2 was not measured. The Grashof similarity number Gr is conventionally a hydrodynamic parameter and, in this context, relates to the leavening force acting on the dough.

Baking was carried out both in traditional metal tins and with inserts made of anti-adhesive paper, or in anti-adhesive cardboard cases. To impart anti-adhesive properties, paper or cardboard was primed with a 10% polyvinyl alcohol solution and then coated with an aqueous emulsion of organosilicon liquid mixed with polyvinyl alcohol solution and a small amount of curing catalyst. No adverse chemical interactions between these materials and the dough or finished biscuit were observed during baking or storage. The dough of confectionery workpieces has a low viscosity (0.4-0.7 Ns/m^2), which causes heat flux sensors placed on its surface to sink into the mass. A small piece of gauze placed on the surface of the product proved sufficient to carry the sensor upward along with the rising dough during baking. Other sensors were embedded entirely within the dough and fixed at the centre of the bottom and side surfaces of the tin.

As noted by A. Farisieiev *et al*. (2023) and S. Soleimanifard *et al*. (2024), for baking flour confectionery products in commercial catering settings, only steam convection ovens offer practical prospects among non-traditional baking equipment, whilst microwave ovens are appropriate for domestic use. The search for a rational baking mode for biscuit semi-finished products was conducted in a laboratory electric oven fitted with top and bottom heating elements; the influence of baking chamber temperatures in the range of 140-200°C was investigated. The temperature was either maintained constant or varied according to a prescribed pattern. The proportions of thermal energy supplied to the workpiece from above and below were also varied. Comparable findings regarding thermal conditions for baking semi-finished biscuit products at chamber temperatures of 160-200°C were reported by A. Cappelli *et al*. (2021) and I. Davidson (2024).

The heat balance was calculated by three independent methods in the experiments: from the equation of heat consumption for heating and physicochemical and phase transformations; from the sum of local heat fluxes multiplied by the area of the corresponding surfaces; and from the analysis of the temperature fields of the workpiece during baking. In all experiments, agreement between the three methods was satisfactory. The heat consumption estimated from heat flux sensor signals was generally slightly higher, which is attributable to the sensors being positioned at the centre of each surface, where energy flux density is greatest. Since the discrepancy between heat balance estimates did not exceed 11%, no additional experiments were conducted in this series. On the basis of these studies, the following rational baking mode for biscuit semi-finished products is proposed: a constant baking chamber temperature of 170-180°C with equal intensity of heat supply from above and below.

In a number of experiments, heat flux sensors were positioned at different depths within the workpiece, also using gauze supports. Study of the kinetics of heat distribution through the layers of the workpiece revealed a wave-like pattern in each layer. This is explained by the fact that, in addition to heat transfer by conduction, various phase and physicochemical transformations occur simultaneously – evaporation, crystallisation, caramelisation, and others. As noted by O. Kepko *et al*. (2018), in certain cases the phase shift between the heat flux and temperature signals from a pair of sensors positioned on opposite sides of a layer allows the sensor pair to be treated as a flow calorimeter with directed energy transit or accumulation. This makes it possible to simultaneously characterise the technological and thermophysical properties of the material – as was demonstrated for cream in V. Fedorov *et al*. (2014) – directly during technological processing.

Figure 1 presents the results of one such experiment. The signal from heat flux sensor 1, positioned at the centre of the upper surface of the workpiece, first rises sharply and then gradually decreases as the temperature difference between the heating medium and the biscuit surface diminishes. The signal from sensor 2, located 5 mm below sensor 1 with a layer of dough between them, rises considerably more slowly (as part of the energy is consumed in heating this layer), and at the 7th minute equals the signal at the inlet of the layer; this equality persists until the 11th minute. In accordance with the theory of complex thermophysical characterisation, a transient cycle with temperature perturbation (highlighted area) is followed by a quasi-stationary process. This is confirmed by the temperature readings on the upper (3) and lower (4) surfaces of the dough layer. From these data, the effective volumetric heat capacity can be calculated: at a mean temperature of $t = 39$°C, it was $c = 1.2$ MJ/(m$^3 \cdot$K). The effective thermal conductivity during the quasi-stationary process ranged from 0.19 to 0.21 W/(m · K), averaging $\lambda = 0.2$ W/(m · K). These results are in good agreement with the thermophysical characteristics of biscuit dough of the same recipe reported by A. Dorohovich *et al*. (2012) and V. Fedorov *et al*. (2014).

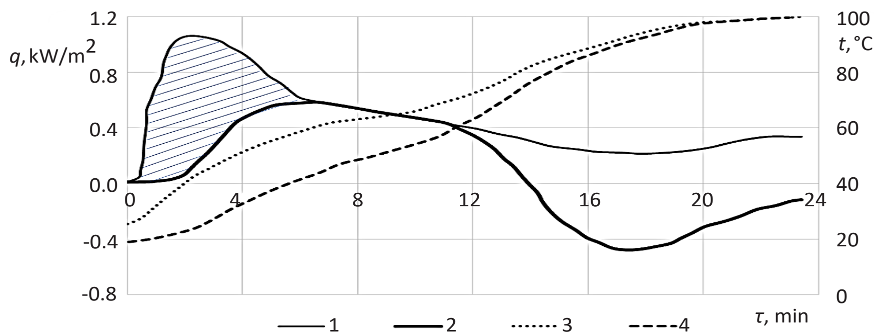

Figure 1. Kinetics of baking the upper layer of biscuit semi-finished product
Note: 1, 3 – heat flux density and temperature on the upper surface; 2, 4 – the same at the depth of 5 mm
Source: created by the authors

The kinetics of heat flux density 2 through the lower surface of the upper dough layer revealed an anomaly: during crust formation, the heat fluxes decrease sharply, and from the 14th minute onwards become negative. This indicates that heat is being conducted into the layer beneath the upper crust not from above, but from below. Consequently, the layer immediately beneath the upper crust is the last to be baked. It may therefore be appropriate to include an assessment of this zone in the technological criteria for product readiness and marketable quality. These experiments enabled a comparative study of baking biscuit semi-finished products in plain metal tins (the traditional method) and in identical tins fitted with anti-adhesive paper inserts. The use of such inserts reduces the rate of product breakage during demoulding and improves sanitary conditions. Furthermore, the inserts reduce the thickness of the bottom crust by lowering the intensity of heat flux at the base of the product.

The heating medium temperature was maintained at 165-175°C. Dough weighing 210 g was poured into tins to a height of 30 mm. Heat flux sensors with thermocouples were placed at the centre of the upper, lower, and one of the lateral surfaces of the dough. A comparison of the kinetics of heat fluxes and temperatures shows that, whilst the magnitude and variation of heat fluxes at the upper (curve 1) and lateral (curve 2) surfaces remained unchanged with the use of inserts, heat fluxes from below decreased and the thickness of the bottom crust was reduced, particularly during the first half of the process (Figs. 2, 3).

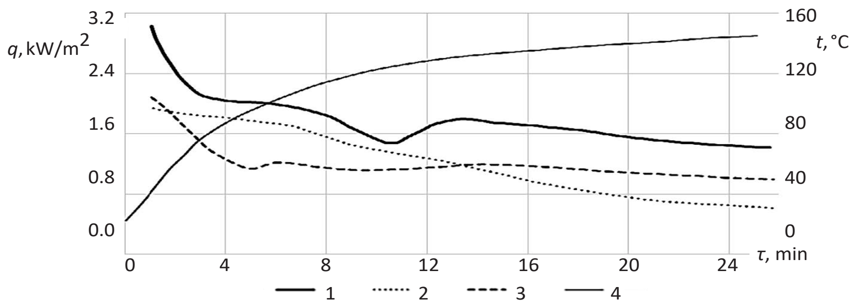

Figure 2. Kinetics of baking biscuit semi-finished products in metal tins under optimal heating medium temperature conditions

Note: 1, 2, 3 – heat flux density at the upper, lower, and lateral surfaces of the product; 4 – mean surface temperature of the product

Source: created by the authors

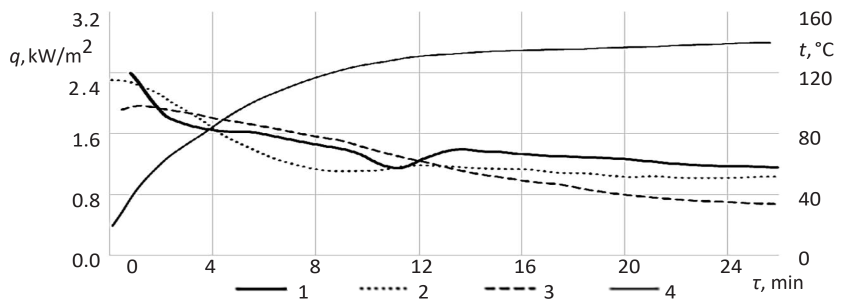

Figure 3. Kinetics of baking products with paper inserts

Note: 1, 2, 3 – heat flux density at the upper, lower, and lateral surfaces of the product; 4 – mean surface temperature of the product

Source: created by the authors

In both experimental series, the reduction in heat flux from below was moderate, which may be attributed to the increased thermal resistance of the product resulting from vapour generation. Once the product temperature reached 80°C, protein denaturation and starch gelatinisation began to occur intensively, causing a renewed rise in heat fluxes (curve 1). The cost of producing inserts for metal tins or cardboard cases is more than offset by savings in fat used for greasing tins and by reduced labour input; consequently, the retail price of the biscuits is not adversely affected.

Conclusions

Based on comprehensive laboratory studies employing thermocouples and low-inertia heat flux sensors, a rational baking regime for biscuit semi-finished products in industrial ovens was substantiated through integrated analysis of local heat fluxes, temperature fields, and heat balances. The discrepancy between heat balances calculated by three independent methods did not exceed 11%, confirming the reliability of the experimental data. During the quasi-stationary stage, the effective thermal conductivity of the biscuit dough averaged 0.20 W/(m·K), whilst the effective volumetric heat capacity at 39°C reached approximately 1.2 MJ/(m^3·K), consistent with reference thermophysical values and thereby validating the applied methodology. A wave-like pattern of heat propagation through the product layers was experimentally confirmed, arising from phase and physicochemical transformations including evaporation, protein denaturation, and starch gelatinisation. An anomaly in heat transfer beneath the upper crust was identified: from the 14th minute of baking onwards, the heat flux density through the lower boundary of the upper layer became negative, indicating that heat was supplied predominantly from below. This finding substantiates the need to assess product readiness specifically in the layer beneath the upper crust, as it constitutes the most thermally inert zone.

The optimal baking mode was found to be a constant chamber temperature of 170-180°C with equal heat input from the top and bottom. Under conditions of 165-175°C, a dough mass of 210 g, and a fill height of 30 mm, the use of non-stick paper or cardboard liners reduced the heat flux from below during the first half of baking, decreasing the thickness of the bottom crust and minimising mechanical damage during demoulding. Heat transfer through the upper and lateral surfaces remained unchanged, confirming the selective thermal effect of the liners. Their production costs are offset by reduced fat consumption and labour savings. The results are directly applicable to industrial oven design, energy optimisation, and quality stabilisation. Further research should focus on the scaling of baking regimes, the influence of recipe variations, and the development of real-time thermometric control systems.

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Conflict of Interest

None.

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Раціоналізація товарних і технологічних властивостей бісквітних напівфабрикатів під час випікання

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Анотація. Кожен вид борошняних кондитерських виробів потребує визначення власних теплофізичних характеристик, дотримання яких має бути забезпечене в обраній печі. Випікання бісквітних напівфабрикатів має особливості, які необхідно враховувати при проєктуванні та налагоджуванні обладнання. Метою досліджень було вивчення за допомогою технічних засобів густини теплових потоків крізь поверхні та по шарах бісквітних напівфабрикатів, а також формулювання рекомендацій щодо теплового режиму для промислових умов. Для вимірювання температури використовували термопари та малогабаритні малоінерційні вимірювачі густини теплового потоку. Випікання бісквітних напівфабрикатів проводили у лабораторній печі в традиційних металевих формах, а також у формах із використанням вкладишів з антиадгезійного паперу. Для надання антиадгезійних властивостей папір або картон ґрунтували розчином полівінілового спирту 10 %, після чого покривали водною емульсією кремнійорганічної рідини у суміші з розчином полівінілового спирту та невеликою кількістю каталізатора затвердіння. Дослідження проводили в інтервалі температур 140-200°C. У статті наведено результати вивчення кінетики випікання верхнього прошарку бісквіта, процесу в металевих формах за раціональної температури гріючого середовища та кінетики випікання виробів із паперовими вкладишами. За допомогою лабораторної печі з підведенням конвективної та променистої теплоти встановлено раціональний режим: температура гріючого середовища 170-180°C, інтенсивність підведення енергії зверху та знизу – однакова.

Доведено доцільність випікання виробів у вкладишах з антиадгезійного паперу, що дозволяє зменшити товщину нижньої скоринки, знизити ломкість продукту та покращити санітарні умови виготовлення й реалізації. На основі результатів визначено раціональні за технологічними, товарними та економічними ознаками режими випікання бісквітних напівфабрикатів у промислових печах. Практична цінність роботи полягає у можливості застосування її результатів на підприємствах для оптимізації процесів випікання та підвищення якості й економічності виробництва

Ключові слова: кінетика випікання; термометрія; теплометрія; теплофізичні характеристики; термічний опір