Received:23.05.2025 | Accepted: 26.05.2025
Technical Sciences
doi: 10.31210/spi2025.28.02.44
UDC 62-5:004.896:57.08
ORIGINAL ARTICLE
Scientific Progress & Innovations 28 (2) 2025
https://journals.pdaa.edu.ua/visnyk

Justification of the methodology of technical measurements with elements of mechatronics in biological processes

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Citation: Padalka, V., Gorbenko, O., & Chumak, M. (2025). Justification of the methodology of technical measurements with elements of mechatronics in biological processes. *Scientific Progress & Innovations*, 28 (2), 277–282. doi: 10.31210/spi2025.28.02.44

Article info

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Researchers are faced with the challenge of selecting, among existing control and measuring devices, such modern measurement tools that meet the requirements of accuracy, data flow rate, and the ability to record information on data carriers for subsequent processing. This work presents a generalization and a new solution to the scientific problem, which consisted in the development and substantiation of a methodology for measuring technological parameters in scientific research of biological material processing using control and measuring devices built on mechatronic principles. The applicability of the proposed methodology was investigated through research into technological parameters (specifically, temperature in dough layers) during the preparation of bakery products. Technical recommendations were developed for the design of a reading-recording module and the potential for its use in studies of mass production technologies. An analysis of known temperature measuring instruments was conducted, and it was determined that strain gauge sensors are the most suitable for the conditions of our research. A five-channel reading and recording module was used in the experiment. Known bread baking technologies were analyzed, and measurement conditions and the required discreteness were substantiated. The temperature range during the process was between 30–160°C, with an adequate measurement discreteness of 1 second. An experimental research plan was developed, including procedures for measurements and ensuring their accuracy. Laboratory equipment was fabricated to determine temperature parameters in the bread baking process. Baking is accompanied by pulsed action of the heater, maintaining the bowl temperature within 35–150°C throughout kneading and baking. At the start of baking, the temperature at each measurement point changes according to specific patterns. In the 1 cm layer of dough, the temperature reaches 100±5°C and does not rise further, which is due to the formation of a crust with lower moisture content compared to the crumb. In deeper layers beyond 1 cm, the temperature stabilizes around 105±5°C and remains constant during the entire process. These values are conditioned by the specific thermodynamic behavior of the vapor-liquid phase of water present in the dough.

Keywords: measurement, temperature, energy, mechatronics, scientific research, experimental methodology, bread baking.

Обґрунтування методики технічних вимірювань з елементами мехатроніки в біологічних процесах

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Дослідження технологічних процесів, які пов'язані з біологічними матеріалами, швидкоплинні та аналіз енергетичних та температурних показників їх протікання потребують високої дискретності вимірювань в широких діапазонах. Перед науковцями виникає науково-дослідницька проблема: серед існуючих контрольно-вимірювальних приладів вибрати такі сучасні засоби вимірювання, що мають задовольняти за точністю, потоковістю інформації та можливості її запису на носії інформації з подальшою обробкою. У роботі наведене узагальнення і нове вирішення наукового завдання, що полягало у розробці та обґрунтуванні методики вимірювань технологічних параметрів у наукових дослідженнях переробки матеріалів біологічного походження з застосуванням контрольно-вимірювальних приладів побудованих за принципами мехатроніки. Дослідження пристосованості запропонованої методики проводилося на прикладі наукових досліджень технологічних показників (температури в прошарках тіста) технологій приготування хлібобулочних виробів, розроблені технічні рекомендації до конструкції зчитуючо-записуючого модуля та можливості його застосування в дослідженнях технологій масового виробництва. Проведено аналіз відомих засобів вимірювання температури та встановлено, що найбільш придатним для умов нашого дослідження є тензо-вимірювальні датчики. В експерименті застосовано п'яти канальний зчитуючо-записуючий модуль. Проаналізовані відомі технології випікання хліба та встановлені умови вимірювань показників та обґрунтована дискретність їх проведення. Температурний діапазон знаходиться в межах 30–160°С та достатня дискретність вимірювань 1 с. Розроблено план експериментальних досліджень, виконання вимірів та точність їх проведення. Виготовлено лабораторне устаткування для визначення температурних показників в технології випікання хліба. Процес випікання супроводжується імпульсної дією нагрівача, який підтримує температуру чаші в діапазоні 35–150°С на протязі всього часу замісу та випікання. На початку процесу випікання, температура у кожній позиції змінюється за особливими закономірностями. У прошарку 1 см хлібної маси температура досягає 100±5°С, та більше не підіймається, що обумовлено утворенням хлібної коринки зі зменшеною вологістю порівняно з м'якушем. В інших прошарках на глибину більше 1 см температура тримається на рівні 105±5°С і не змінюється на протязі всього процесу. Ці показники обумовлені особливістю термодинамічних процесів паро-рідинної фази води, що знаходиться в тісті.

Ключові слова: вимірювання, температура, енергія, мехатроніка, наукові дослідження, методика експериментів, випікання хліба.

Бібліографічний опис для цитування: *Падалка В. В., Горбенко О. В., Чумак М. В.* Обґрунтування методики технічних вимірювань з елементами мехатроніки в біологічних процесах. *Scientific Progress & Innovations*. 2025. № 28 (2). С. 277–282.

Introduction

A key factor in the development of modern science and technology is thorough and high-quality scientific research. The accuracy and quality of measurements of technological parameters in various processes directly depend on the correct choice of conditions and instruments used for these measurements. Existing control and measuring instruments do not always meet modern requirements for accuracy and data resolution [1–3]. There are certain challenges related to the accumulation and storage of data on modern media, followed by its processing using mathematical statistics software [4–6].

The study of technological processes involving biological materials, which are often rapid in nature, and the analysis of their energy and temperature parameters require high-resolution measurements across wide ranges [7, 8]. Researchers face a scientific challenge: among the available control and measuring devices, it is necessary to select modern measurement tools that meet the criteria for accuracy, data throughput, and the ability to record information for subsequent processing. The relevance of selecting appropriate measurement tools and methods is a pressing scientific issue.

Thermocouples or resistance temperature detectors (RTDs) are most commonly used for this purpose, typically requiring direct contact with the measurement object (solid surface or liquid). Despite partial overlap in their operating temperature ranges, each of these sensors offers unique advantages for specific applications [9].

When selecting a suitable temperature sensor, key parameters to consider include the measurable temperature range, required accuracy, response time, signal stability, scale linearity, and sensitivity. RTDs are the optimal choice when high sensitivity and flexible applicability are prioritized. It should be noted that RTDs are generally more expensive than thermocouples. Therefore, a well-founded choice of a temperature sensor for a specific application requires an understanding of the fundamental operating principles of each type.

There are four main types of temperature measuring instruments, each based on a distinct physical principle:

1. Mechanical (liquid-in-glass, bimetallic, bulb and capillary, pressure-based);
2. Thermoelectric (thermocouples);
3. Thermoresistive (RTDs and thermistors);
4. Radiation-based (infrared and optical pyrometers).

The operation of mechanical thermometers is based on converting temperature-induced changes into mechanical motion. This usually occurs due to the property of most materials to expand when heated. The construction of such thermometers may involve liquids, solids, or gases as temperature-sensitive substances [10].

A thermoelectric thermometer (thermocouple) is a temperature sensor consisting of two dissimilar metals joined at one end. This junction generates a small electrical voltage (measured in millivolts) that depends on the temperature. The junction of the two metals is called the hot junction and is connected to extension wires. A thermocouple can be formed by any combination of two different metals. When two dissimilar metals are joined, a small voltage known as the thermoelectric electromotive force arises at the junction. This phenomenon is known as the Peltier effect [11].

Changes in temperature at the junction lead to proportional changes in this voltage, which can be detected by the input circuit of an electronic controller. The output signal of a thermocouple is a voltage whose magnitude depends on the temperature difference between the hot junction and the free ends of the conductors. This phenomenon is referred to as the Thomson effect [12].

A combination of both effects is used for temperature measurement [13]. By maintaining one junction at a known stable temperature (cold junction) and measuring the voltage, the temperature at the hot junction can be determined. The generated voltage is directly proportional to the temperature difference between the hot and cold junctions.

Thermoresistive temperature measurement devices operate based on the dependence of a material's electrical resistance on temperature. By measuring the change in resistance, the corresponding temperature change can be determined. There are two main types of such devices: resistance temperature detectors (RTDs) and thermistors.

An RTD consists of a thin metal wire wound into a coil or a metal film formed on a substrate (similar to a strain gauge). Platinum is most commonly used in RTD construction.

RTDs function on the principle that the electrical resistance of a metal changes in a predictable, nearly linear and stable manner with temperature. These sensors have a positive temperature coefficient, meaning their resistance increases as temperature rises. The resistance of the sensing element at a given base temperature is directly proportional to its length and inversely proportional to its cross-sectional area.

To measure temperature with an RTD, an electrical circuit is typically used to detect the change in the sensor's resistance. Based on this change, the temperature variation is calculated. As the temperature rises, RTD resistance increases, much like a strain gauge's resistance increases with strain.

It is well known that there are two main types of radiation-based temperature measuring devices: infrared pyrometers and optical pyrometers.

Infrared temperature sensors, also known as pyrometers or non-contact thermometers, are used to measure an object's temperature remotely. This differentiates them from most other temperature sensors that require physical contact. Non-contact measurement is particularly useful when direct contact is impractical or impossible, such as in hard-to-reach areas or with objects at very high temperatures that could damage contact sensors [14, 15].

Infrared sensors operate on the principle that all bodies emit energy proportional to their temperature. As the object's temperature increases, so does the intensity of the emitted radiation. Infrared thermometers determine temperature by measuring the intensity of this emitted radiation.

In many fields – from industry to science and everyday life – the accuracy of temperature determination is of utmost importance. The reliability of measurement results depends on several key factors.

Firstly, the level of accuracy varies with the type of sensor used. For example, thermocouples may have errors of several degrees, while high-precision RTDs can achieve accuracy to tenths or even hundredths of a degree. Thermistors are highly accurate but only within a limited temperature range. Radiation pyrometers are more prone to error, especially if the emissivity of the object's surface is not properly accounted for.

The quality of the reading device that processes the sensor signal and displays the temperature value is also crucial. Higher precision instruments result in lower intrinsic errors.

Calibration plays a key role in ensuring accuracy, a regular procedure in which sensor and instrument readings are compared against reference values at known temperatures, with appropriate adjustments made.

Environmental conditions such as ambient temperature, humidity, electromagnetic interference, and airflow can also affect measurement accuracy.

Furthermore, proper sensor installation, ensuring effective thermal contact with the measurement object, is essential for accurate results. Improper installation can cause significant deviations.

The conditions and methodology of energy parameter measurement will be illustrated using the example of bread baking technology. Baking is the final and critical stage in bread and bakery production. During this process, the product attains its final volume and shape, the crust and crumb form, the surface browns, and characteristic flavor and aroma develop.

In bread making, most preliminary processes aim to create optimal thermal and biological conditions for dough development. The final product results from the complex interaction of thermal, physical, biological, and chemical processes occurring in the dough during baking. Physical processes, in particular, drive dough expansion at the initial heating stage, while the subsequent slowing of this expansion is associated with rising internal temperatures of the product [16, 17].

A decisive factor determining the quality of finished bread is the heating process, namely, baking. The theory of the processes occurring in the dough piece during baking has been thoroughly described in numerous studies [18–20].

One of the indicators of bread doneness is the achievement of uniform internal temperature within the crumb. However, due to the specific physical properties of dough and uneven moisture evaporation, the baking process occurs unevenly. Often, in an attempt to accelerate baking, producers increase the oven temperature, which may lead to the outer part of the product burning while the inside remains underbaked. Additionally, temperature regimes vary across different zones of the oven.

In the baking chamber, heat is transferred primarily through radiation from heated surfaces, with only a small portion delivered via air convection [21]. Under these conditions, the dough heats unevenly: the outer layers warm first, followed by gradual heat penetration toward the center. This leads to instability in the product's structural formation [22].

Considering the rheological properties of bread dough during shaping and baking, there is scientific interest in exploring the patterns of heat transfer at key cross-sectional points of the product as it transforms from dough to bread. The subject of this scientific and technical investigation is the study of heat transfer processes along defined planes from the crust toward the center of the bread during baking. This research can be carried out by discrete temperature data logging, accounting for the geometric dimensions of the baking form.

Existing studies on the bread baking process indicate that the temperature range across all stages spans 25–200°C, with humidity reaching 100 %. The total duration of the entire process can be up to 4 hours, with the direct baking time lasting up to 1 hour.

The aim of the study

The aim of this study is to develop a methodology for the technical measurement of technological parameters (using energy indicators as an example) in scientific research focused on the processing of biologically derived materials, employing control and measuring instruments based on mechatronic principles.

To achieve this objective, the following tasks must be accomplished:

1. Examine and identify the measurement limits and conditions for energy parameters, using the common example of bread baking technology;
2. Develop measuring instruments capable of long-term data logging onto storage media, with the possibility of subsequent statistical analysis;
3. Design and conduct experiments to investigate the energy characteristics of bread baking according to a known technology.

Materials and methods

The scientific objective is to analyze temperature variations within the bread baking zone – specifically, within a 1 cm surface dough layer, at a depth of 5 cm, and at the center of the product. To eliminate the influence of variability and specific characteristics of the baking process on the measurement results, a standardized baking method was employed. This method used fixed quantities of recipe components and a consistent thermal treatment program typical of domestic bread-making appliances from well-known brands (equipment from LG was used in the experiments). This approach ensures that experimental conditions do not affect the outcome.

The experimental setup includes a commercially available LG domestic bread maker (***Fig. 1***) and a custom-designed read/write module capable of recording temperature data to a storage medium with a sampling interval of 1 second.

The temperature data acquisition and recording module is shown in ***Fig. 2***.

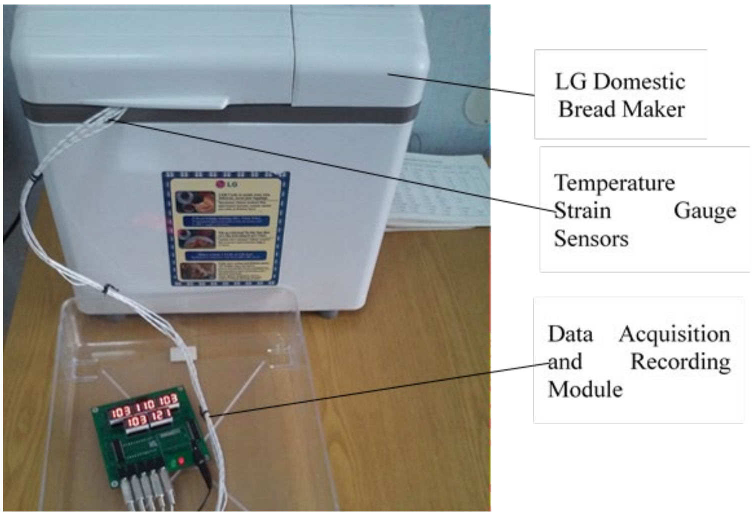

Fig. 1. Experimental Setup for Justifying the Methodology of Temperature Measurement in Bread Baking Technology

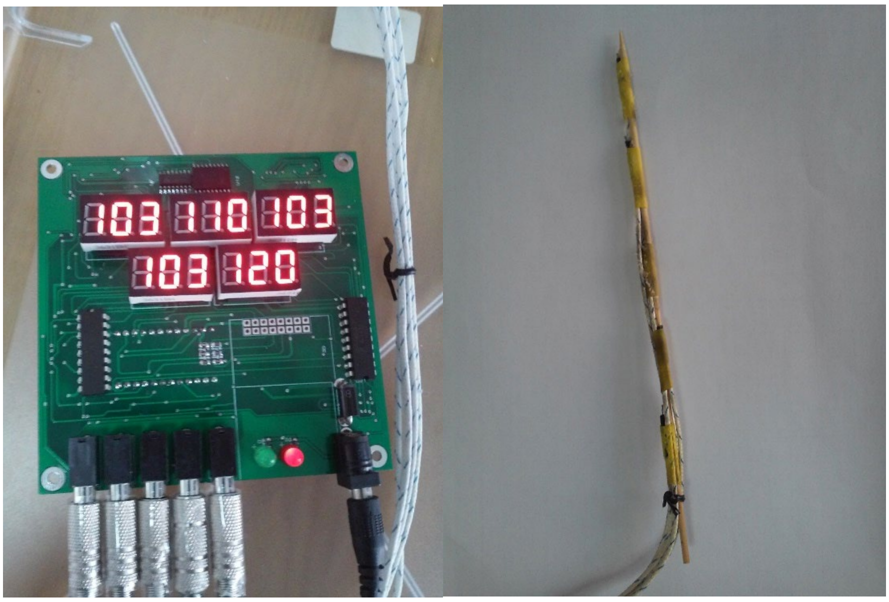

Fig. 2. The temperature data acquisition and recording module (a), incorporates a temperature strain gauge sensor (b).

According to the established recipe, the ingredients are placed into the baking chamber and the automatic baking program is initiated. During the initial stages of bread preparation (mixing and dough rising), temperature measurement is not feasible due to the mechanical mixing process.

At the final stage of dough proofing, temperature strain gauge sensors are inserted into the dough. Their placement within the product's plane is maintained using a wooden stand. The sensors are connected to the corresponding ports of the data acquisition and recording module. The module is then powered on, and the temperature recording to a digital storage device is initiated.

Measurements are taken every 1 second across five channels. Approximate readings can be visually monitored on the corresponding displays during the experiment. Data recording continues until the bread baking process is complete, as indicated by the bread maker’s control system. At that point, data recording is stopped.

The collected data is transferred to a personal computer via the storage medium in the form of a text file.

Results and discussion

Based on the described methodology, a series of experiments was conducted. Temperature values recorded at the specified sampling rate were transferred to spreadsheet software, where statistical analysis of the data was performed (***Table 1***).

The proposed methodology for studying temperature indicators in bread baking technology allows for real-time data acquisition at specific locations within selected bread layers.

The constructed temperature distribution chart demonstrated that dough rising is maintained at a temperature of 35 ± 5°C across all dough layers. This is achieved due to the thermal capacity of the baking chamber and the periodic activation of the heating element in the shaping zone (***Fig. 3***).

Table 1
Fragment of experimental data on temperature (°C) indicators of the technological process

Number experiment	position 1	position 2	position 3	position 4	position 5
1	34	32	32	31	31
2	34	33	34	34	36
141	58	38	52	94	141
137	59	39	56	95	137
141	61	39	59	97	141
148	64	40	63	101	148
150	64	42	66	104	150
148	69	44	69	105	148
141	71	48	73	105	141
141	75	51	76	104	141

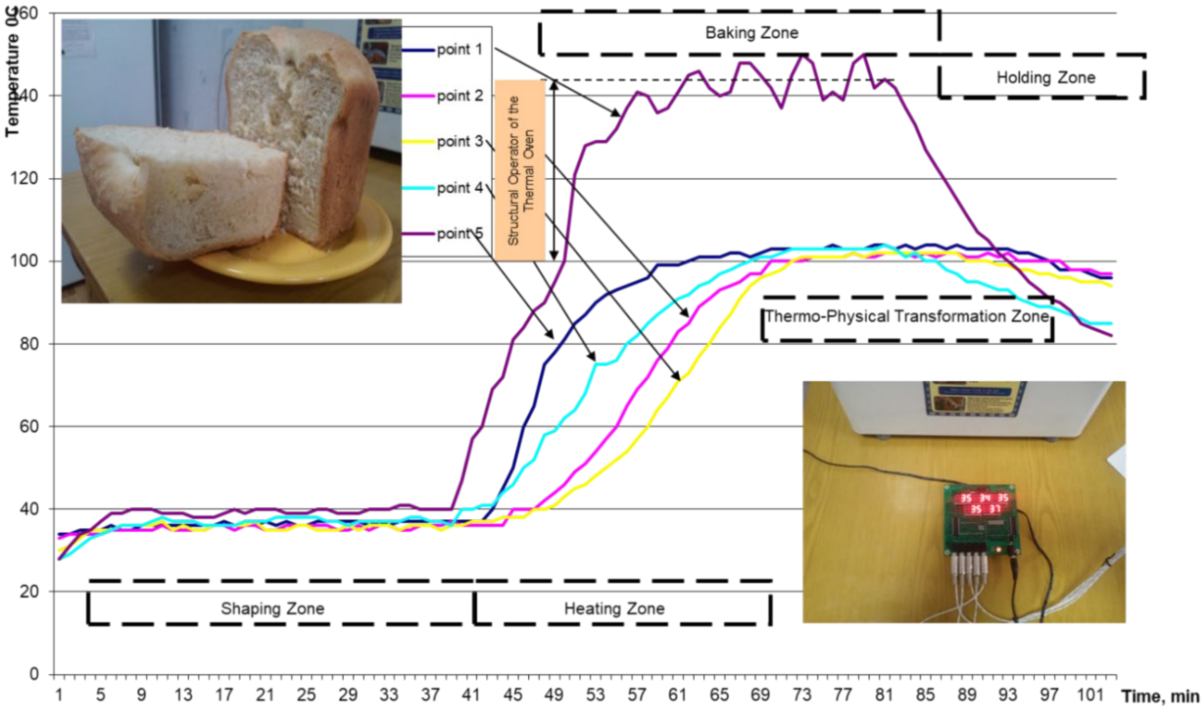

Fig. 3. Temperature Profile Diagram of Dough Material During Baking

The baking process is accompanied by pulsed activation of the heater, which maintains the temperature of the baking chamber within the range of 35–150°C throughout the entire mixing and baking cycle.

At the beginning of the baking stage, the temperature at each measurement point changes according to specific patterns, determined by the heating rate of the dough mass (heating zone, ***Fig. 3***).

In the 1 cm surface layer of the bread, the temperature reaches 100 ± 5°C and does not rise further. This is due to the formation of the bread crust, which has a lower moisture content compared to the crumb (thermo-physical transformation zone, ***Fig. 3***).

In deeper layers beyond 1 cm, the temperature stabilizes at approximately 105 ± 5°C and remains constant throughout the entire process. These values are attributed to the thermodynamic characteristics of the vapor-liquid phase of water present in the dough.

The baking zone and the holding (curing) zone are also characteristic components of the bread baking technological process.

The temperature data obtained using this methodology are of both scientific interest and practical value. They can be used to adjust and optimize the baking process of bread and bakery products at commercial baking facilities.

Conclusions

This study presents a novel solution to the scientific challenge of developing and substantiating a methodology for measuring technological parameters of biologically derived materials using control and measurement instruments based on mechatronic principles.

It was established that, under the research conditions, strain-gauge temperature sensors are the most technically suitable for temperature measurement. A five-channel readout and recording module was employed in the experiment. The temperature range of the studied objects was between 30°C and 160°C, with a measurement interval of 1 second, which ensures sufficient accuracy and reliability of the data obtained. Laboratory equipment was developed to determine temperature parameters in the bread-baking process.

It was found that the baking process involves the pulsed action of a heater that maintains the bowl temperature within the range of 35°C to 150°C throughout the kneading and baking phases. At the beginning of the baking process, the temperature at each measurement point changes according to specific patterns. In the 1 cm layer of bread dough, the temperature reaches 100±5°C and does not increase further, due to the formation of a crust with lower moisture content compared to the crumb. In deeper layers (beyond 1 cm), the temperature remains stable at 105±5°C throughout the entire process. These values are determined by the unique thermodynamic behavior of the vapor-liquid phase of water present in the dough and require further scientific investigation.

Conflict of interest

The authors state that there is no conflict of interest.

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