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Examination of thermophysical characteristics of food products

Z. Burova[1], S. Ivanov[2], T. Roman[3], V. Vasiliv[1], M. Zheplinska[1], M. Mushtruk[1], I. Palamarchuk[1], V. Sarana[1], M. Gudzenko[1]

[1]National University of Life and Environmental Sciences of Ukraine
[2]Institute of Technical Thermophysics of the National Academy of Sciences of Ukraine
[3]National University of Food Technologies

Abstract. The development of food, biotechnological, and processing industries, the invention of new ingredients, optimisation and improvement of technological processes require reliable information about the main thermophysical characteristics of raw materials and materials of biological origin. This paper presents the results of the cooperation of specialists from leading universities and scientific institutions of Ukraine, embodied in the developed methods of analysing the parameters of thermodynamic and mass transfer processes and determining the thermophysical characteristics of the latest substances and products using modern metrologically certified devices and information-measurement systems. The main problem in analysing materials of biological origin is the inhomogeneity and heterogeneity of the structure of samples. It is demonstrated that it is advisable to determine the coefficient of effective thermal conductivity of bulk materials and cereals in a stationary thermal mode on a device for determining the thermophysical characteristics of materials and thermal effects, equipped with heat flow and temperature sensors, in which a symmetric scheme of the thermometric measurement method is implemented. The simultaneous use of four measuring cells allows for performing a synchronous comparative analysis of several samples, and the rotary-clamping mechanism helps to minimise contact resistances. The developed method of measuring the coefficient of effective thermal conductivity considers the features of bulk food products and substantially improves the accuracy of the examination by introducing a correction for the contact resistance of the wall layer. Long-term observations allow for analysing thermolabile materials, examining thermal effects in samples, and evaluating volumetric and integral heat generation. It is necessary to use the STA system to conduct calorimetric studies of a wide range of biological materials and substances with the necessary accuracy, which

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*Corresponding author

implements methods of step-by-step scanning and synchronous thermal analysis to determine the specific heat capacity, the heat of evaporation, and the ratio of free and bound moisture in non-homogenous materials. These characteristics are necessary parameters for analysing the kinetics and optimisation of heat and mass transfer processes, in particular, drying, in the calculation and design of technological equipment

Keywords: inhomogeneous materials, coefficient of effective thermal conductivity, heat dissipation, specific heat capacity, heat of evaporation, drying

Relevance

The main task of the food industry is to process agricultural products into high-quality food products. It should be conducted with the lowest financial and material costs, which is impossible without using the achievements of modern science. Science is the basis of modern technologies. Any technology is a set of processes by which raw materials are converted into the final product. Deep knowledge of the regularities of processes conducted during food production allows for intensifying processes, creating new types of apparatuses, and developing methods for optimal process control.

Most of the processes of food, biotechnological, and processing industries are thermal, the speed of which is described by the laws of heat transfer (heating, cooling, condensation), and mass transfer – diffusion, which are characterised by the transfer of one or more components of the initial substance from one phase to another (drying, sorption, rectification, etc.). Most often, these processes are interrelated and occur simultaneously. Many papers by Ukrainian and foreign researchers are devoted to the examination of the laws of heat and mass transfer.

But any such calculation is impossible without knowledge of the basic thermophysical characteristics of materials and substances, which include, in particular, the coefficients of heat and temperature conductivity, specific heat capacity, heat of evaporation, and their temperature dependences. Usually, such data is taken from the reference literature, and until recently, specialists in the food and processing industries used well-known reference books [1; 2]. Currently, modern editions have been published [3; 4] containing the main thermophysical characteristics of semi-finished products and products necessary for calculating processes and equipment for the food industry. In addition to tabular data, the thermophysical parameters of many products, especially bulk and non-homogeneous ones, are presented in the form of empirical dependencies. This allows for performing technological and engineering calculations with a certain accuracy, which is currently insufficient for research works.

The invention of new ingredients, the creation of food products based on them, and the development of technological processes for their manufacture require updating the existing base of thermophysical characteristics. This requires additional research on a modern instrument base. Imported instruments can meet all the requirements for accuracy and reproducibility of measurement results, but the main problem with their use is the need for periodic calibration to ensure proper metrological indicators.

The specialised scientific Institute of Technical Thermophysics (ITTP) of the National Academy of Sciences of Ukraine has accumulated more than half a century of experience in determining the main physical parameters of thermodynamic and mass transfer processes in various sectors of the national economy. The achievements of thermometry, electronics, and metrology of heat flow measurements are embodied in devices and systems for precision measurements of thermal conductivity and heat capacity of materials and substances, the study of energy effects in the physicochemical and biological processes of the food and processing industry.

Research Analysis

Difficulties in obtaining qualitative and adequate information about the thermophysical characteristics of substances of biological origin are usually associated with their inhomogeneity and heterogeneity of structure. For example, bulk food materials – crops and cereals as objects of research have specific physical characteristics: flowability, self-sorting, and duty cycle. Mechanisation and automation of grain processing processes in the flow [5], the use of pneumatic and vibrotransport, the introduction of new drying methods [6] require definitions of their heat, temperature, and thermal conductivity, heat capacity, ability to self-heat [7; 8].

Therewith, the thermodynamic parameters of air, which is an integral part of the grain mass and affects all the processes that occur with it, play a huge role. In particular, air gaps contribute to the transfer of heat by convection and the movement of moisture in the form of steam. Due to self-sorting, the porosity of the grain mass, that is, the presence of gaps between its solid particles filled with air, can be uneven. The porosity and bulk density of grain also depend on the shape, elasticity, size, and surface condition of solid components. These factors together lead to variability in the value of contact resistance between material particles and should be considered when developing a measurement methodology, because they can substantially distort the results of examination of thermophysical characteristics.

Calorimetric studies are used to calculate the thermodynamic characteristics of substances, chemical equilibria, establish a relationship between the thermodynamic characteristics of a substance and its properties and structure, and draw up thermal balances of technological processes in the food, biotechnological, and pharmaceutical industries [9]. Differential scanning calorimetry (DSC) is used to obtain reliable calorimetric information about the material during its linear or stepwise heating or cooling. DSC is also used to determine the melting point and assess the degree of purity of substances, investigate the kinetics of drying, lyophilisation, and crystallisation processes, investigate the stability and thermal decomposition of substances and determine their shelf life, determine the glass transition temperature of amorphous substances, etc. [10]. DSC in combination with thermogravimetric analysis (TGA) forms a method for synchronous thermal analysis of materials and substances (STA).

Now there is a wide range of foreign devices for synchronous thermal analysis, the principle of operation of which is based on the simultaneous determination of mass reduction and the amount of heat consumed by liquid evaporation. Their versatility and wide temperature range are their undoubted advantages. However, most of them are poorly adapted for analysing samples of plant origin, the liquid in which is a

mixture of water and numerous complex substances (saccharides, organic acids, plant pigments, colloidal solutions of pectins, essential butyric acids, aldehydes, alcohols, terpenes, etc.). Another negative factor is that the size of the crucibles of modern devices is calculated for a weight of the order of a milligram, which is very small and not informative for plants due to the size of their cells.

Analytical determination of the specific heat of evaporation of plant raw materials is also associated with substantial difficulties and is often almost impossible since it is necessary to calculate simultaneously the characteristics of a mixture of several liquids and insoluble substances [11]. This is especially important when calculating and optimising the parameters of the drying process of any raw material of plant origin, which is associated with the removal of moisture, free and bound [12]. The experimental method of synchronous thermal analysis is much more appropriate for this purpose.

The purpose of the study is the development of a methodology for measuring the coefficient of effective thermal conductivity of bulk food products, in particular, cereals and crops, and examination of the specific heat capacity and heat of moisture evaporation during the drying process of biological raw materials.

Materials and Methods for Analysing Thermal Conductivity

Various experimental methods for determining the thermophysical characteristics of bulk materials, including stationary and non-stationary heat flow, are known – probe and non-contact – optical [13; 14]. The presence of air between the particles of bulk materials allows for predicting that their thermal conductivity is commensurate with the thermal conductivity of heat-insulating materials, therefore, the method of analysing the coefficient of thermal conductivity regulated in ISO 8301-1991 can be applied to them [15].

The essence of the thermometric method regulated in ISO 8301 is to create a stationary heat flow through a flat sample directed perpendicular to its front (largest) surfaces. The coefficient of thermal conductivity is determined by the results of measurements of the thickness of the sample, the difference in the temperature values of its working surfaces and the surface density of the heat flow that passed through the sample, provided that it is unidirectional and uniform.

Studies are conducted in a stationary thermal mode on a device for determining the thermophysical characteristics of materials and thermal effects, developed at the ITTP of the National Academy of Sciences of Ukraine, which implements a symmetric scheme of the thermometric method [16]. The device, which is displayed in Figure 1, is an information-measurement system consisting of a functionally combined thermal unit 1, which is displayed in Figure 2, an electronic unit 2 with a built-in temperature control device for the reference junctions of thermocouples and a computer with specialised software 3.

Main technical characteristics of the device:

• range of measured heat flux density 5…500 W/m^2;

• limits of permissible relative error ±3%;

• operating temperature range minus 40°C…180°C;

• sample size:

– 1 sample 250×250×(10…120) mm;

– 4 samples Ø100×(10×50) mm.

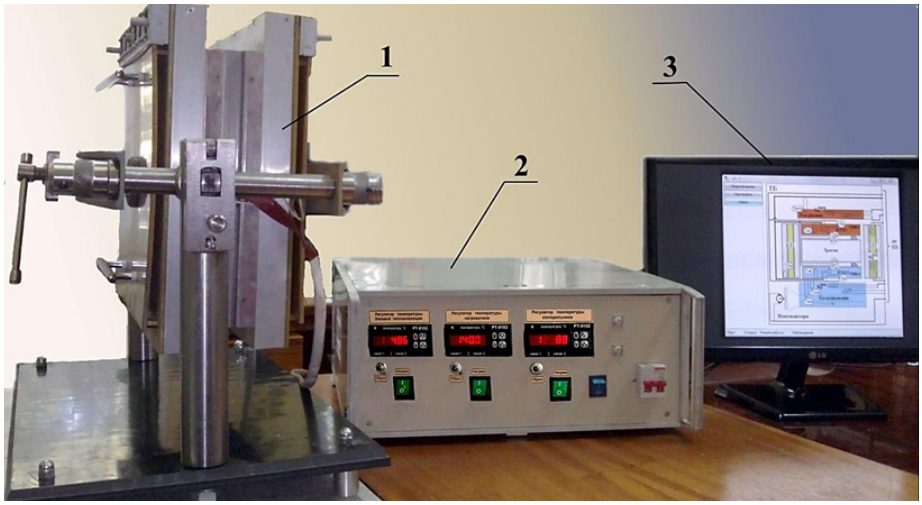

Figure 1. Appearance of the device (operating position):
1 – thermal unit, 2 – electronic unit, 3 – software

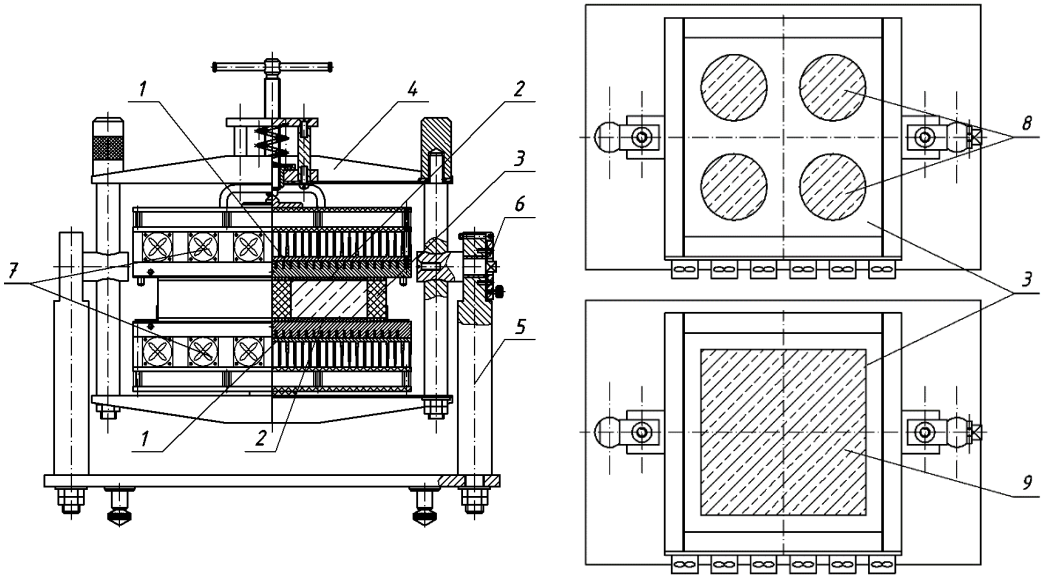

Figure 2. Scheme of the thermal unit of the device: 1 – temperature control units; 2 – heat-measuring units; 3 – thermal insulation inlay; 4 – rotary clamping device; 5 – guide posts; 6 – retainer; 7 – fan units; 8, 9 – measuring cells

A characteristic design feature of this device is the presence of a rotary mechanism, which allows setting the heat unit in the working position at an angle of 90°, as presented in Figure 1. This allows ensuring the necessary accuracy of measuring the heat flow and temperature of samples during the experiment. When assembled, four (8, Fig. 2) or one (9, Fig. 2) measuring cell, designed to accommodate samples of experimental material and provide the necessary thermal and temperature conditions. The use of four measuring cells allows for performing a synchronous comparative analysis of four samples at once.

The temperature control units 1 with the inlay 3 installed between them and the prototypes are placed in the rotary-clamping device 4, which is a frame structure on the guide posts 5 and is designed to fixate the samples and minimise the contact resistances between them and the heat-measuring units in the measuring cells. The force is set by means of a screw mechanism with a power spring. The structure is rotated by an angle of 90° and set to the working position (vertical, Fig. 1), securing with a retainer 6.

The software of the device is designed for long-term (from several hours to several days) indication and recording of the values of temperature and density of heat flow in the sample for further processing and analysis of thermal processes, calculation of thermal resistance and coefficient of effective thermal conductivity of samples of bulk materials.

Calculation formula for the coefficient of thermal conductivity λ, W/(m*K), has the form:

$$\lambda = h \cdot (\Delta T / \bar{q} - R_{\text{K}})^{-1}, \quad (1)$$

where: h – thickness of the prototype equal to the thickness of the thermal insulation inlay, m; $\Delta T = T_{\text{B}} - T_{\text{H}}$ – temperature difference T_B and T_H, respectively, the upper and lower working surfaces of the sample, K; $\bar{q} = 0{,}5 \cdot (q_{\text{B}} + q_{\text{H}})$ – mean value of the heat flux density, W/m^2, passing, respectively, through the upper q_B and the lower q_H working surfaces of the sample; R_K – correction for the total contact thermal resistance of the measuring cell, which is determined during calibration of the device, m*K/W.

The value of the coefficient of thermal conductivity of samples of the experimental material is determined as the mean value, considering the measurement error according to the formula:

$$\bar{\lambda}_T = \frac{1}{N} \sum_{i=1}^{N} \lambda_{T,i} + \delta\,, \quad (2)$$

where: $\bar{\lambda}_T$ – mean value of the coefficient of thermal conductivity for the temperature value T; $\lambda_{T,i}$ – value of the thermal conductivity coefficient i- th sample at temperature T; N – number of samples; δ –measurement error.

Research results of samples of grain mass in the range of average temperature values from 35 to 70°C are displayed in Fig. 3.

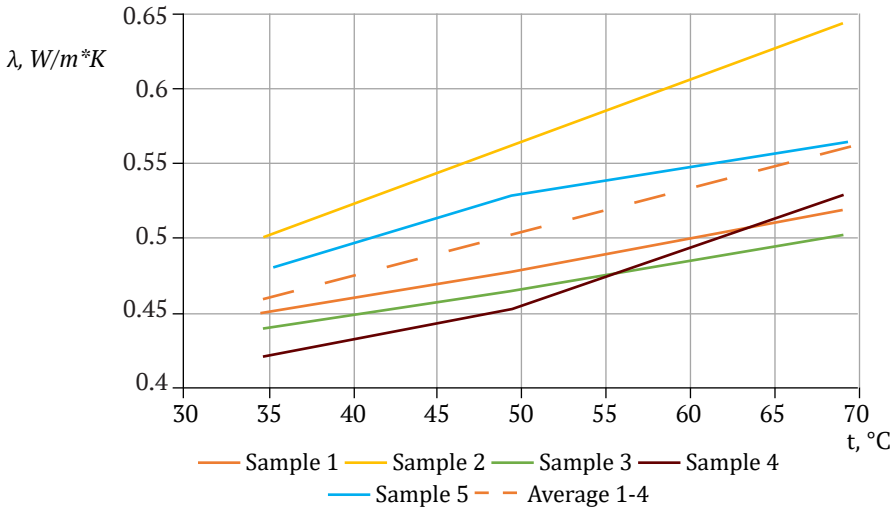

Figure 3. Results of the examination of the coefficient of effective thermal conductivity of grain mass

Samples 1 through 4 were examined simultaneously in cells Ø100 mm, and sample 5 was examined in a 250×250 mm frame. The bulk density of all samples was within ±3%. The average graph for the four samples correlates well with the results obtained for sample 5.

The device can also be used to study the thermal effects that accompany the examination of thermolabile materials, for example, in the presence of heat release in samples. Therewith, the information and measurement system records and processes signals from primary sensors throughout the entire process time, resulting in graphs of changes in heat fluxes on the sample surfaces, as presented in Figure 4.

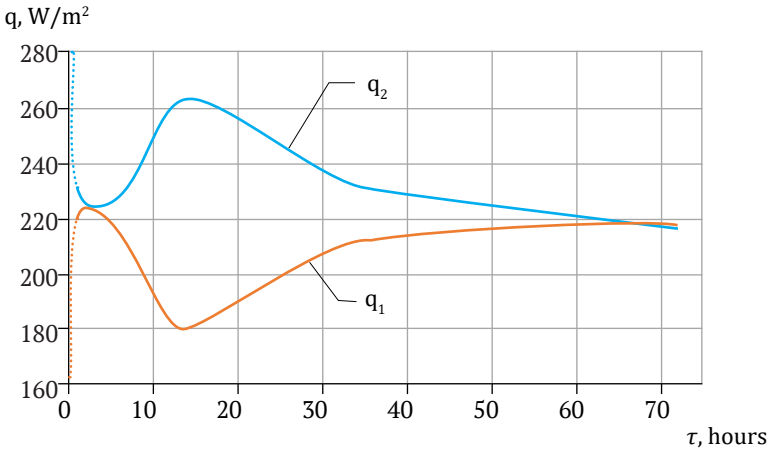

Figure 4. Graphs of changes in the surface density of heat flow on sample surfaces during heat release at a temperature of 20°C

The following formula is used to determine the volumetric heat release:

$$q_v = \frac{(q_2 - q_1)}{h} \quad (3)$$

Values of integral heat releases Q_τ, kJ/m^3, for the time τ, are obtained using the formula:

$$\boldsymbol{Q_\tau} = \int_{\tau_0}^{\tau} qv\, \boldsymbol{d\tau}, \quad (4)$$

where τ - current time value, h, τ_0 – value of the heat release start time, h.

The results of calculations of heat release of chicken droppings samples in four temperature conditions are presented in Figure 5.

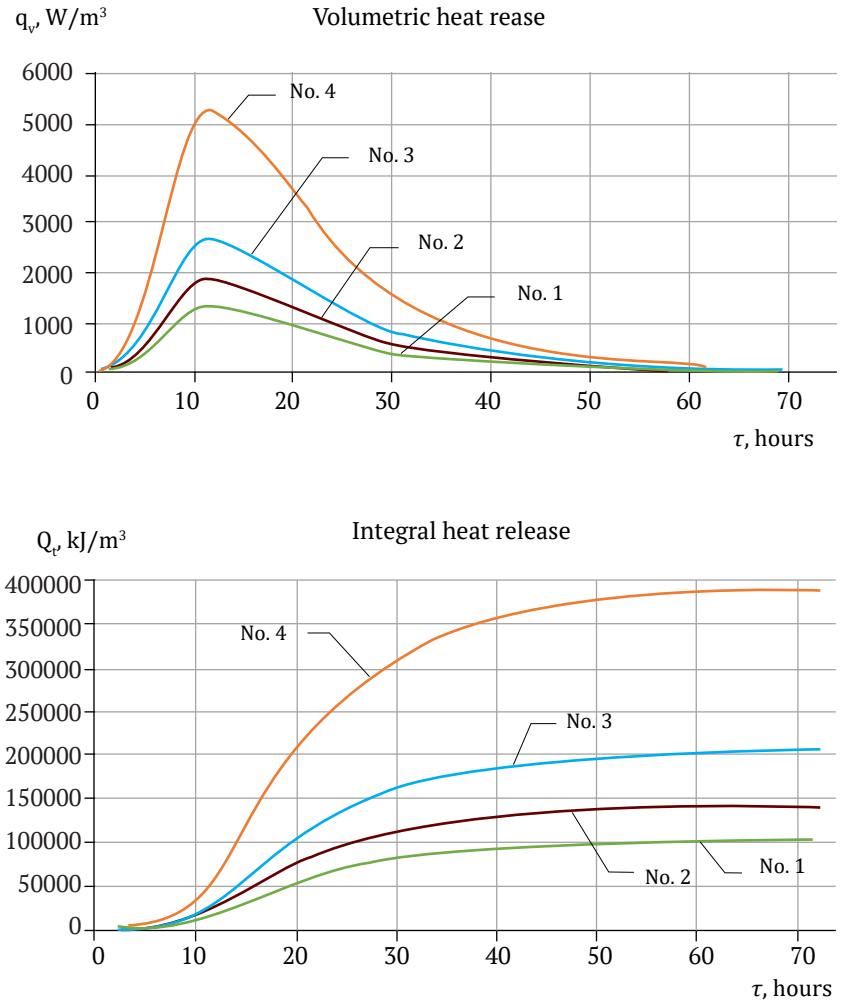

Figure 5. Volumetric and integral heat release of samples in temperature conditions: No. 1 – 20°C, No. 2 – 30°C, No. 3 – 40°C, No. 4 – 50°C

Therefore, the presence of a limited volume of cells allows for maintaining the same bulk density of the material in different experiments, and measurements simultaneously on

four samples give a substantial gain in time. Comparison of experimental data for different sample thicknesses allows compensating for the influence of the contact resistance of the wall layer on the result of measurements of the thermal conductivity of bulk grain material.

The method of conducting long-term studies enables the investigation of the thermal effects and changes in sample parameters during heat release in real time, which expands the functionality of the device.

Materials and methods for analysing the heat capacity and heat of evaporation

As mentioned above, it is advisable to use the synchronous thermal analysis (STA) method for analysing the processes of dewatering plant raw materials, which covers the following analysis methods:

- differential microcalorimetry – measurement of the expenditure of energy for a phase transition in the test sample,
- thermogravimetry – recording changes in sample mass loss over time.

The STA system developed by ITTP of NAS of Ukraine combines calorimetric and thermogravimetric analyses and allows determining with sufficient reliability the specific heat of evaporation during the drying of a thin layer of wet dispersed material and liquids in the chemical, microbiological, pharmaceutical, and food industries [17]. The appearance and block scheme are presented in Figure 6.

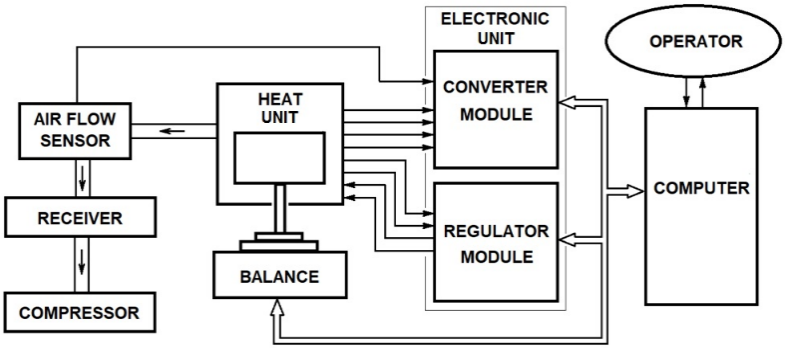

Figure 6. Appearance and block scheme of the STA system

The STA system is an information and measurement complex of a functionally combined thermal unit, analytical scales, compressor, electronic unit, and personal computer with the appropriate software. The main difference between this system and its well-known analogues is the ability to perform measurements under the optimal temperature regime, maintaining the surface temperature of the product approximately equal to the temperature of the dynamic medium. This is achieved due to the fact that the calorimeter platform has independent temperature control.

The object of research can be both pure liquids (water, alcohols, organic solvents) and various materials: food and vegetable products (grain, vegetables, fruits, etc.), pharmaceuticals, lacquers, paints, etc. for determining the evaporation of both free and material-bound liquids.

Main technical characteristics of the STA system:

- range of measured specific heat of evaporation from 500 to 2500 J/g;
- limits of the permissible relative error of measuring the specific heat of evaporation ±0.5%;
- temperature range from 18 to 105°C;
- limits of the permissible error of temperature measurement ±0.5 K;
- range of mass values of the sample of the test solid is from 1 to 5 grams.

In the thermal unit of the installation, the scheme of which is presented in Fig. 7, there is a working chamber with a replaceable calorimetric platform for analysing samples.

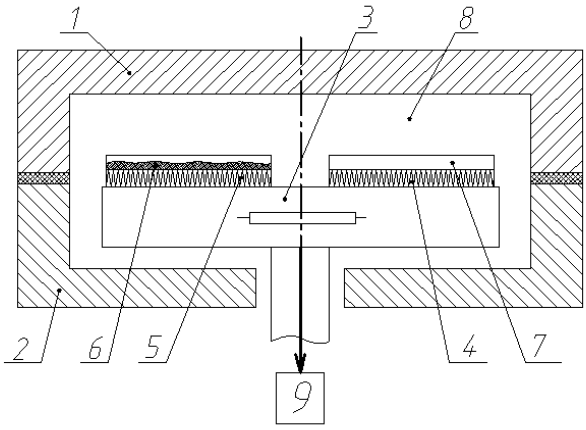

Figure 7. Schematic diagram of the working chamber of the heat unit : 1 – upper thermostatic unit; 2 – lower thermostatic Unit; 3 – calorimetric platform with the main electric heater; 4,5 – heat flow sensors; 6 – cell with a sample of the test substance; 7 – reference cell; 8 – working chamber; 9 – analytical scales

The working chamber is formed by two thermostatic units with built-in heaters, which allows for maintaining an isothermal mode in the working chamber during the experiment. The calorimetric platform is mounted on a coaxial rack, which is placed on analytical scales used to record the mass reduction of the wet sample during the drying process. Therewith, the platform is not mechanically connected to the static elements of the thermal unit, and electrical communication is conducted using a special collector consisting of loop-shaped radially arranged wires with a diameter of 0.03 mm. This design of the current collector minimises the impact of electrical wires on mass measurement.

Replaceable calorimetric platforms are represented by three versions of calorimetric cells (Fig. 8), which expands the range of types of materials suitable for the study, depending on their characteristics.

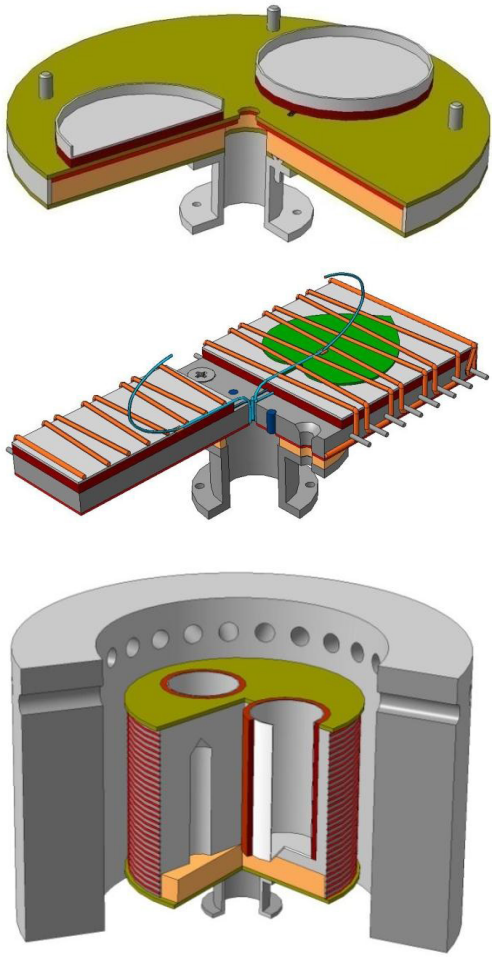

Figure 8. Variable calorimetric platforms with open cells, flat cells with sample fixation and high cylindrical cells

In each of the designs, the cells are made as similar as possible in both geometric and thermophysical parameters. Each cell is equipped with heat flow sensors (HFS). One cell is a working cell and is intended for placing the test sample in it. The second cell is a reference cell and remains empty during the experiment, or serves to place the comparison substance. The platform contains an electric heater and two platinum resistance thermometers, one of which registers the platform temperature, and the second is part of the platform temperature control system.

The open-cell calorimetric platform is equipped with two cup-shaped open cells with heat flow sensors under the bottom of each of them. Such a platform is designed to examine the heat of evaporation of solvents from solutions, pasty materials, liquid homogeneous samples, and the heat capacity of solid samples with a prepared surface that provides thermal contact with the flat bottom of the cell.

The platform with high cylindrical cells is designed for analysing samples with a dispersed structure and high thermal resistance between particles. A special feature of this platform is that the heat flow sensors of the cells are located on the perimeter along the cylindrical walls of the cell. This allows for obtaining correct information about the thermophysical and thermodynamic characteristics of inhomogeneous materials due to the almost complete coverage of the sample by the heat flow sensor. This platform is convenient for analysing the heat capacity of a wide range of materials, including wet samples of moderately large sizes.

Determining the specific heat of evaporation of liquids from some materials may be difficult due to changes in their geometric parameters during drying. Deformation during drying of samples such as leaves of medicinal plants, thin sections of parenchymal tissues of fruits, some organic thin-leaf materials, and sections of tissues of small thickness leads to a disruption of the thermal contact of the sample with the flat surface of the cell. This introduces an additional error or completely distorts the measurement information. For such studies, a platform with flat cells of rectangular shape with heat flow sensors under the bottom of each and a sample holder – a flexible tape of small diameter was developed.

The system implements the possibility of using two different research methods: the method of synchronous thermal analysis for analysing the heat of evaporation and the method of step-by-step scanning, regulated by ISO 11357-4:2014 [18], for analysing the heat capacity. The preparation of the sample for the study also differs depending on the structure and characteristics of the sample material, and the type of calorimetric platform chosen.

During the study of the specific heat capacity, the temperature range in which the measurement will be performed is divided into equal intervals (steps) of sufficient duration to establish an equilibrium state in the working chamber of the system and maintain it for at least 20 minutes. If the temperature of the heaters increases to the next interval, the heat flow sensors of the cells record the amount of heat that is spent on heating the working cell with the sample and the reference cell to the set temperature. The signals of all primary temperature and heat flow sensors are recorded by the information-measurement system, processed, and displayed on the computer monitor in the form of graphical dependencies (Fig. 9).

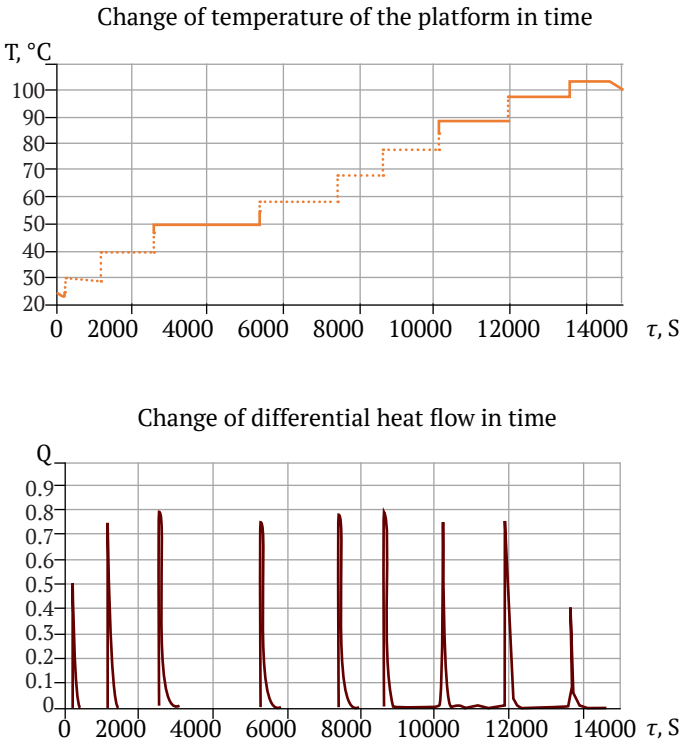

Figure 9. Graphs of step-by-step temperature changes and corresponding heat flow values over time

The value of the specific heat capacity for a single interval is calculated by the formula:

$$c = 1/m \cdot \left| \int_{\tau_1}^{\tau_2} \Delta Q(\tau) d\tau / \Delta T - C_K + \Delta C_{BAL} \right| \quad (5)$$

where: m – mass of the test sample; ΔQ – difference in heat fluxes recorded by the working cell and the reference cell for the time from τ_1 to τ_2 (interval duration); ΔT – difference in temperature values between intervals; ΔC_{BAL} – parameter that considers the difference of the thermophysical parameters of the working cell and the reference cell; the heat capacity of the container C_K is considered if the test sample is in the container and the reference cell is empty.

During the study of the specific heat of evaporation by synchronous thermal analysis, the dependence of the mass loss of the sample over time and the amount of heat that is spent on the evaporation of liquids from the sample in an isothermal medium for the corresponding period of time is recorded. The study continues until the evaporation of liquids from the sample stops, which is determined by the cessation of the decrease in mass readings and the stabilisation of the signal of the heat flow sensors of the cells.

Mean value of the specific heat of evaporation over the time interval from the initial moment τ_i until the final moment τ_j is calculated using the formula:

$$\bar{r}_{ij}(T,m,\tau) = \frac{\int_{\tau_i}^{\tau_j}[Q_1(T)-Q_2(T)+Q_{HT}(T)]d\tau}{m(\tau_i)-m(\tau_j)} \quad (6)$$

where: Q_1 – heat flow passing through the working cell; Q_2 – heat flow passing through the reference cell; Q_{HT} – uncontrolled heat exchange of the sample with the medium, which is not detected by heat flow sensors; $m(\tau_i)$ – $m(\tau_j)$ – loss of mass of the sample over time from the moment τ_i until the moment τ_j.

Study results

Researchers of ITTP of the National Academy of Sciences of Ukraine, the National University of Food Technologies, and the National University of Life and Environmental Sciences of Ukraine conducted a number of studies of some food products and plant raw materials intended for the production of biofuels using the STA system. The purpose of these studies was not only to determine the thermophysical parameters of the samples but also to establish temperature and time parameters and optimise the drying process.

Thus, based on thermophysical experiments, experimental-statistical models of the drying process of the stem and cap of a cultivated Champignon mushroom (Fig. 10) are created, the expediency is proved, and a technological scheme for separate drying of Champignon is developed [19; 20].

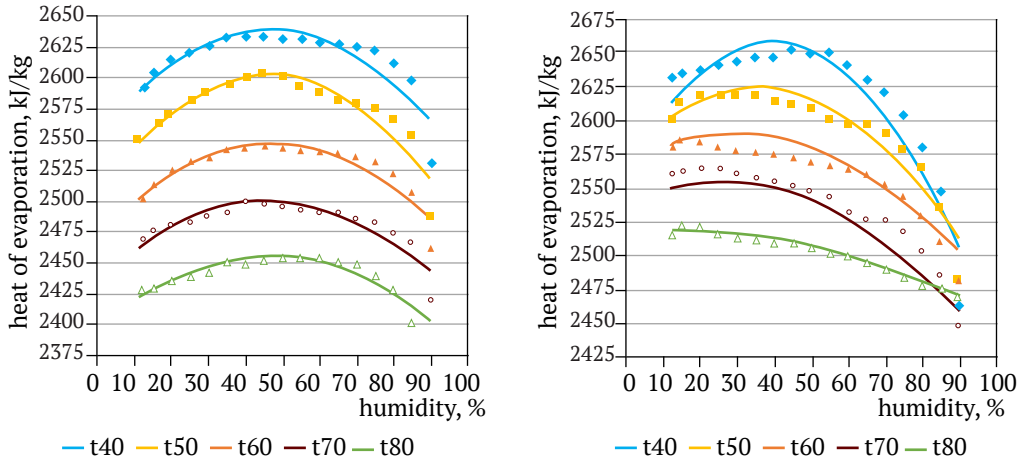

Figure 10. Dependences of changes in the heat of evaporation on humidity at different temperatures during the drying of the mushroom: a – stem, b – cap

The total increase in the specific heat of evaporation of moisture from native tissues of the cap at different temperatures compared to the table value for evaporation of pure water from the free surface is ~9%, and the nature of its dependence on humidity correlates with the dynamics of changes in the state of free and bound water in the case of dewatering of the fungus. A gradual increase in the total heat consumption for evaporation almost from the very beginning of the drying process of fungal tissues leads to a decrease in the proportion of free water and an increase in the proportion of bound moisture. In the further development of

this study, to solve the problem of determining the ratio of free and bound moisture in inhomogeneous materials, the concept of a cryocalorimeter for analysing the energy of the phase transition of moisture in a material is proposed [21].

Investigating the latest materials, for example, solutions for the manufacture of biodegradable polymer packaging and their dewatering parameters from 69-72% in the initial substance to 6% in the dried film/coating in production conditions is of interest [22].

Conclusions and Prospects

Food production technologies are constantly progressing, and the product range of processing enterprises in the industry is constantly increasing. Modern science offers a wide range of studies of the parameters of thermodynamic and mass transfer processes and the determination of the thermophysical characteristics of the latest substances and products. Positive is the fact that Ukraine has its own material and technical base of metrologically certified devices and systems for measuring temperature and heat flow, thermal resistance, coefficients of thermal conductivity, and heat capacity of various materials and substances.

The developed method of measuring the coefficient of effective thermal conductivity considers the specific features of studies of bulk food products and enables the introduction of a correction for the contact resistance of the wall layer of bulk materials, which substantially increases the accuracy of analysing their thermal conductivity. The possibility of long-term observations allows for analysing thermal effects in samples and calculating volumetric and integral heat dissipation.

The STA system provides the ability to determine the specific heat capacity by step-by-step scanning and the heat of evaporation by synchronous thermal analysis during the study of a wide range of substances and products of biological origin.

Studies of the thermophysical characteristics of non-homogenous materials and substances will allow for optimising production processes and further developing technologies in the food, biotechnological, and processing industries.

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Дослідження теплофізичних характеристик харчових продуктів

З. А. Бурова1, С. О. Іванов[2], Т. О. Роман[3], В. П. Василів[1], М. М. Жеплінська[1], М. М. Муштрук[1], І. П. Паламарчук[1], В. В. Сарана[1], М. М. Гудзенко[1]

[1]Національний університет біоресурсів і природокористування України
[2]Інститут технічної теплофізики НАН України
[3]Національний університет харчових технологій

Анотація. Здорове харчування є одним з найважливіших елементів збереження здоров'я та зміцнення імунітету нації, неодмінною умовою досягнення активного довголіття нинішніх та майбутніх поколінь. Винайдення нових інгредієнтів та створення харчових продуктів на їхній основі, розробка нових та вдосконалених наявних технологій потребує достовірної інформації про основні теплофізичні характеристики сировини та матеріалів біологічного походження для розрахунку й оптимізації тепло масообмінних процесів переробки і виробництва. Сучасна наука пропонує широке коло досліджень параметрів термодинамічних та масообмінних процесів, визначень теплофізичних характеристик новітніх речовин та продуктів із застосуванням метрологічно атестованих приладів та інформаційно-вимірювальних систем. Основною проблемою під час дослідження матеріалів біологічного походження є їхня негомогенність та неоднорідність структури зразків. Визначення коефіцієнта ефективної теплопровідності сипких матеріалів та круп доцільно проводити в стаціонарному тепловому режимі на приладі для визначення теплофізичних характеристик матеріалів і теплових ефектів, у якому реалізована симетрична схема теплометричного методу вимірювань із застосуванням сенсорів теплового потокутатемператури. Використання чотирьох вимірювальних комірок дає можливість проводити синхронний порівняльний аналіз декількох зразків, а поворотно-притискний механізм сприяє мінімізації контактних опорів. Розроблена методика вимірювань коефіцієнта ефективної теплопровідності враховує особливості сипких харчових продуктів та значно підвищує точність дослідження їхньої теплопровідності через введення поправки на контактний опір

пристінного шару. Можливість проведення довготривалих спостережень дає можливість досліджувати термолабільні матеріали, аналізувати теплові ефекти в зразках, оцінювати об'ємнета інтегральнетепловиділення. Калориметричні дослідження широкої гами біологічних матеріалів та речовин із достатньою точністю можна проводити на системі STA, у якій реалізовано методи покрокового сканування та синхронного теплового аналізу для визначення питомої теплоємності та теплоти випаровування, дослідження співвідношення вільної та зв'язаної вологи в негомогенних матеріалах. Ці характеристики є невід'ємними параметрами під час дослідження кінетики тепломасообмінних процесів, зокрема сушіння, для розрахунку і проєктування технологічного обладнання. Дослідження теплофізичних характеристик негомогенних матеріалів та речовин дадуть змогу оптимізувати виробничі процеси та надалі розвивати технології харчової, біотехнологічноїта переробної галузі

Ключові слова: неоднорідні матеріали, коефіцієнт ефективної теплопровідності, тепловиділення, питома теплоємність, теплота випаровування, сушіння