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Non-Destructive Thermal Control of Vegetables and Fruits Using a Machine Vision System

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The article presents the description of a non-contact non-destructive method and a measuring device to control thermophysical properties of Vegetables and Fruits tissues. The proposed method was used to determine the thermal conductivity, heat capacity and coefficient of thermal diffusivity of potato tissues of various quality - both healthy and affected by various phyto-diseases. The results of the measurements were used to determine the process parameters of thermal control for automated sorting of potatoes using a machine vision system in the infrared region of the spectrum. The proposed method for determining thermophysical characteristics is based on the use of pulsed laser action on a flat surface area of a potato tuber, contact-free recording of the time variation of the temperature field of the tuber surface including the heat-affected zone, processing of the experimental data using the LabVIEW 2016 programming environment.

1. Introduction

The thermophysical characteristics (TPC) of potato plant tissue must be known for calculating the regime parameters of the storage and heat treatment processes (Divin, 2017). Potato's TPCs are significantly influenced by the physico-mechanical, physicochemical and chemical characteristics of its plant tissues.

During the authors' studies with using contact methods (Divin, 2017), a difference in the TPC of healthy plant tissues and damaged by to phyto-diseases or external mechanical effects was revealed. This made it possible to apply thermal methods of control using vision systems in the infrared spectrum region when sorting out agricultural products for storage, or shipment to the consumer (Ginesu, 2004).

Modern methods of nondestructive testing of objects of plant origin are mainly focused on the use of vision systems in the visible spectral range (Du, 2004), as well as in the near infrared radiation range (Kim, 2008). Meanwhile, the machine vision systems in the middle range of infrared radiation together with thermal imaging cameras can greatly simplify the image analysis (Vadivambal, 2011). However, the effectiveness of such control largely depends on the conditions and control parameters.

In the process of thermal control, it is important to maintain the power and duration of thermal stimulation. These parameters are to be determined by mathematical modeling methods at TPC values measured during a thermophysical experiment.

In this connection, the task of developing a method for nondestructive testing of TPCs of potato plant tissues arises. The method for performing measurements of thermal properties of plant tissues depends on the structure of vegetables and fruits. Typically, plant tissue is a heterogeneous medium consisting of water, solids and gas (air) pores. During the measurement, the following conditions has to be fulfilled:

- Firstly, it is necessary to ensure rapid measurements without disrupting the integrity and basic characteristics of the samples;
- Secondly, it is necessary to ensure the required accuracy;
- Thirdly, experimental studies should be carried out on samples of various shapes and small sizes; therefore, it is important to develop small-sized measuring devices.

During control of these materials, when they are a wet fine-dispersed medium, reduction in the time of the experiment and the duration of heating allows preserving their original properties.

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2. Theoretical basis of the method

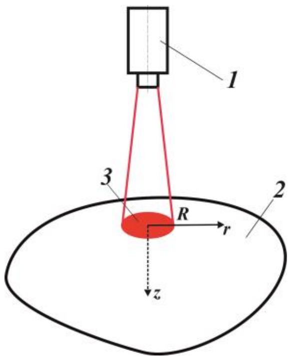
Samples of various shapes and relatively small sizes are subject to thermophysical control; therefore, it is advisable to take a semi-bounded body of the sample under study as a physical model. The thermal effect on the surface area of this body will cause a multidimensional thermal process in it. Once its parameters are registered, it will be possible to restore values of thermal conductivity and thermal diffusivity.
Heating of a semi-bounded body can be done through a section of a geometric form. Proceeding from the possibility of practical implementation and a simple mathematical description of the thermal process in a solid, we selected the circle as a section of the surface of the sample under study through which the heat flux entered. To solve multidimensional heat conduction problems, we used the integral characteristics of temperature and heat flow.
The mathematical models of relative and absolute methods of non-destructive testing of thermophysical properties (thermal conductivity and thermal diffusivity), developed earlier and cited in (Gromov, 2016) assume thermal action by a constant density of heat flux over time $q(t) \equiv q = const$, due to which the temperature in the sample under study reaches a stationary value.
In these methods, the main experimental parameter is the time integral characteristic of the surface temperature of a heated sample:

$$S^{*}(p) = \int_{0}^{\infty} e^{-p \cdot t} \cdot S(t) dt, \quad p > 0, \tag{1}$$

where $S(t)$ is measured mean-integral temperature of the heated circle, p is Laplace transform parameter.
We assume that in the experiment the following conditions are satisfied:
- the body under investigation relative to the thermal influence is semi-bounded $0 \le z < \infty$, $0 \le r < \infty$ (Figure 1);
- the heat flux that is constant along the density coordinate $q(t,r) \equiv q(t)$ is fed to the body through a circular $0 \le r < R$ surface area $z = 0$ (Figure 2);
- the heat flux is limited in time;

$$q(t) = \begin{cases} q(t), \; t \le t_2, \\ 0, \; t > t_2; \end{cases}$$

- the body has a constant initial temperature (we assume it to be zero).
In the developed method and apparatus, we assume that the thermal effect is generated by a limited in time heat flux.



1.The radiation source; 2. The object of control; 3. The heated section

Figure 1. The physical model of the thermal process in the heated body

Under these assumptions, the temperature field in the semi-bounded body is described by solving the following axially symmetric boundary value problem:

$$\frac{1}{a} \cdot \frac{\partial U(t,r,z)}{\partial t} = \frac{\partial^2 U(t,r,z)}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial U(t,r,z)}{\partial r} + \frac{\partial^2 U(t,r,z)}{\partial z^2}, \quad t > 0, \; 0 \le r < \infty, \; 0 \le z < \infty); \tag{2}$$

$$U(0,r,z)=0 \tag{3}$$

$$U(t,r,z)=0 \text{ for } r,z\to\infty\,;\ \left.\frac{\partial U(t,r,z)}{\partial r}\right|_{r=0}=0\,; \tag{4}$$

$$\lambda\left.\frac{\partial U(t,r,z)}{\partial z}\right|_{z=0}=\begin{cases}-q_1(t,r) \text{ for } 0\le r\le R,\\ 0 \text{ for } r>R;\end{cases}\quad q_1(t,r)=\begin{cases}K_i\cdot q(t) \text{ for } t\le t_2,\\ 0 \text{ for } t>t_2.\end{cases} \tag{5}$$

Authors applied to the problem Eq(2) to Eq(5) the integral Laplace transform with respect to the time coordinate t, assuming that, when heated, the function $U(t,r,z)$ is continuous and has continuous derivatives with respect to coordinates r and z in the region, $0\le r<\infty$, $0\le z<\infty$. An equation Eq(6) was applied:

$$\frac{p}{a}\cdot U^*(p,r,z)=\frac{\partial^2 U^*(p,r,z)}{\partial r^2}+\frac{1}{r}\cdot\frac{\partial U^*(p,r,z)}{\partial r}+\frac{\partial^2 U^*(p,r,z)}{\partial z^2}\,, \tag{6}$$

with boundary conditions

$$U^*(p,r,z)=0 \text{ for } r,z\to\infty\,;$$

$$\left.\frac{\partial U^*(p,r,z)}{\partial r}\right|_{r=0}=0\,; \tag{7}$$

$$\lambda\left.\frac{\partial U^*(p,r,z)}{\partial z}\right|_{z=0}==\begin{cases}-K_i(1-e^{-t_2\cdot p})\cdot q^*(p,r) \text{ for } 0\le r\le R,\\ 0 \text{ for } r>R;\end{cases} \tag{8}$$

where

$$U^*(p,r,z)=\int_0^\infty e^{-p\cdot t}\cdot U(t,r,z)dt,\quad q^*(p,r)=\int_0^\infty e^{-p\cdot t}\cdot q(t,r)dt,\ p>0\,.$$

The authors applied the integral Hankel transform with respect to the coordinate r to Eq(6) to Eq(8) and, using its properties (Vadivambal, 2011), we obtain a second-order differential equation in complete derivatives:

$$\frac{d^2\tilde{U}^*(p,\xi,z)}{dz^2}-\xi^2\cdot\tilde{U}^*(p,\xi,z)-\frac{p}{a}\cdot\tilde{U}^*(p,\xi,z)=0 \tag{9}$$

with boundary conditions

$$\tilde{U}^*(p,\xi,z)=0 \text{ for } z\to\infty \text{ and}$$

$$\lambda\left.\frac{d\tilde{U}^*(p,\xi,z)}{dz}\right|_{z=0}=-K_i(1-e^{-t_2\cdot p})\cdot\tilde{q}^*(p,\xi) \tag{10}$$

where

$$\tilde{U}^*(p,\xi,z)=\int_0^\infty r\cdot U^*(p,r,z)\cdot J_0(\xi\cdot r)dr\,,\ \tilde{q}^*(p,\xi)=\int_0^\infty r\cdot q^*(p,r)\cdot J_0(\xi\cdot r)dr,$$

$\xi\ge 0$ is Hankel integration parameter, J_0 is Bessel function of the first kind of zero order.

Solving Eq(9) with conditions Eq(10), and given the information is taken only from the surface of the body under investigation, for $z=0$, the dependence of the surface-time integral characteristic of the sample temperature $\tilde{U}^*(p,\xi,0)$ with the surface-time integral characteristic of the heat flux $\tilde{q}^*(p,\xi)$ can be found:

$$\tilde{U}^*(p,\xi,0)=\frac{\tilde{q}^*(p,\xi)\cdot K_i(1-e^{-t_2\cdot p})}{\lambda\cdot b}\,,\ b=\sqrt{\xi^2+\frac{p}{a}} \tag{11}$$

It is assumed that in the experiment the heat flux supplied to the surface circle $z = 0$ has a constant density along the coordinate *r*. Given the properties of the Bessel function under the Hankel transform for a constant value, the following expression for the surface-time integral characteristic of the heat flux can be obtained:

$$\tilde{q}^*(p,\xi) = \frac{q^*(p) \cdot R}{\xi} J_1(R \cdot \xi) \tag{12}$$

where J_1 is the Bessel function of the first kind of the first order.

Substituting Eq(12) into Eq(11) and applying the inverse Hankel transform (Vadivambal, 2011) to the obtained dependence, the relationship of the time integral characteristic of the surface temperature $z = 0$ with the time integral characteristic of the heat flux is found:

$$U^*(p,r,0) = \frac{q^*(p)\, K_i\, (1-e^{-t_2 \cdot p})\, R}{\lambda} \times \int_0^\infty \frac{1}{b} J_1(R \cdot \xi) \cdot J_0(r \cdot \xi)\, d\xi \,.$$

In the developed methods and devices for non-destructive testing of thermophysical properties, the basic information on the surface temperature takes the form:

$$S(t) = \frac{2}{R^2} \int_0^R U(t,r,0) \cdot r\, dr. \tag{13}$$

Taking into account Eq(13), the time integral characteristic of the temperature of the circle with the surface radius R of the investigated body will have the form:

$$S^*(p) = \frac{2K_i \cdot q^*(p)(1-e^{-t_2 \cdot p})}{\lambda} \int_0^\infty \frac{1}{b \cdot \xi} J_1^2(R \cdot \xi) d\xi \tag{14}$$

In order to find the calculated dependences, a dimensionless variable

$$g(p) = \frac{p \cdot R^2}{a} \tag{15}$$

is introduced into Eq(14) and integral is denoted

$$\int_0^\infty \frac{J_1^2(\mu) d\mu}{\sqrt{\mu^2 + g(p) \cdot \mu}} = V(g(p)) \tag{16}$$

where $\mu = R \cdot \xi$. Then expression (14) is transformed into the following:

$$S^*(p) = \frac{2K_i \cdot R \cdot q^*(p)\,(1-e^{-t_2 \cdot p})}{\lambda} V(g(p)) \tag{17}$$

According to the technique used in (Guiping, 2015), for two values of the integration parameter p and $(k \cdot p)$, ($k > 1$), the equation of non-destructive testing of the parameter $g(p)$ is obtained:

$$\frac{S^*(p) \cdot q^*(k \cdot p)(1-e^{-t_2 \cdot k \cdot p})}{S^*(k \cdot p) \cdot q^*(p)(1-e^{-t_2 \cdot p})} = \frac{V(g)}{V(k \cdot g)} \equiv \Phi(g,k). \tag{18}$$

The left-hand side of equation (16) is determined by calculation based on the results of the experiment. The right-hand side of this equation does not depend on the experimental data. The function $\Phi(g,k)$ is predefined for a certain one k . From dependence

$$\Phi(g,k) = \frac{V(k \cdot g)}{V(g)}$$

for a given fixed k g is determined from the numerical value of which the thermal diffusivity is found

$$a = \frac{p \cdot R^2}{g} . \tag{19}$$

The value of the thermal conductivity of the material is found from Eq(15) by the formula:

$$\lambda = \frac{2K_i \cdot R \cdot q^*(p)(1 - e^{-t_2 \cdot p})}{S^*(p)} V(g(p)) . \tag{20}$$

In order to calculate the values of thermal conductivity and thermal diffusivity, Eq(18), Eq(19) and Eq(20) require knowledge of the flow directed to the body under investigation. The value of the flux can be estimated by knowing the power of the energy source, the area of impact and the degree of blackness, in the case of using radiant energy.
The value of the specific volumetric heat was found by the formula:

$$c\rho = \lambda / a . \tag{21}$$

3. Measuring unit

To implement the described method, the automated control system of TPCs has been developed, which consists of the following main functional blocks: object of control 1, thermal imager 2, adapter 3, personal computer 4, control unit 5, power supply 6, laser 7, (Figure 2). The laser has a maximum output power of 0.5 W and a wavelength of 405 nm. Focusing of the laser makes it possible to obtain a light spot with a diameter of several tenths of a mm to 10 mm at a distance of 10 mm to 200 mm to the object surface. The laser power control unit allows the output power to be controlled by pulse width modulation.
To obtain the primary thermal information from the body surface, a thermal imager manufactured by FLIR Model A35 is used. The thermal imager is designed for vision systems and can generate a video stream at a rate of up to 60 frames per second. The software, which was developed in the LabVIEW 2016 graphical programming environment, receives the image from the thermal imager, time-by-frame processes it is using the NI Vision technology, and determines the integral temperature $S^*(p)$ on the circular surface of the object that has the radius R, and, from Eq(19) to Eq(21), determines the desired TPCs of the object of control.

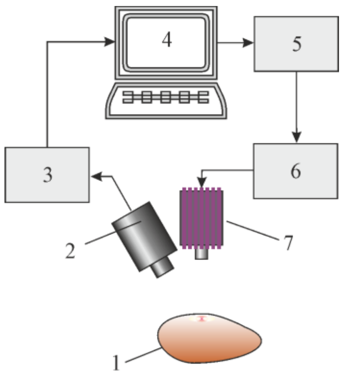


Figure 2. Measuring unit

4. Research results

Using the presented measuring device, experiments were carried out on poly(methyl methacrylate) (organic glass), which has known thermophysical characteristics, as well as on the potato “Gala” plant tissue. The heat was produced by a laser beam at a maximum power of 0.5 W at a distance of 15 cm, focused on the surface area of the object with a radius of R = 4 mm.
Experiments with poly(methyl methacrylate) showed that the thermal conductivity measuring error does not exceed 12 %, and the thermal diffusivity coefficient measuring error is under 15 %. The source of the error appears to be the part of the radiation reflection from the object surface. The influence of this source can be reduced by refining the coefficient k in Eq(5).
Experiments with potato plant tissue showed that the effective thermal conductivity of a healthy tissue differs significantly from a defective one, in particular from a tissue affected by dry rot.

Table 1: Thermal conductivity and of healthy and defective potato plant tissues

The test sample	λ, W/(m·K)	c, J/(kg· K)
Healthy potato plant tissue	0.48	3,600
Potato plant tissue affected by dry rot	0.40	3,450
Potato with a defect of phytophthora	0.55	3,800

Table 1 shows the arithmetic mean values of thermal conductivity and heat capacity from five measurement results. The limits of the confidence interval, taking into account the Student's ratio, are differ from the mean by the value ±0.03 W/(m·K) и $\pm 3 \cdot 10^2$ J/(kg·K), for the thermal conductivity and heat capacity of plant tissue. The measured values in the sample were obtained for the same potato tuber.

5. Conclusions

The advantage of the proposed method is the ability to determine the effective thermophysical characteristics of a local surface area of a control object containing various defects. The method can be applied not only for potato tubers inspection, but also for other plant origin objects: apples, pears, peaches, carrots, radishes and others, which can have mechanical damages or phyto-diseases symptoms.

Analysis of the obtained experimental data allows to conclude that the thermophysical characteristics of potato plant tissues depend on their structure and type of defects (damage or disease), which, in our opinion, is explained by the change the water amount in potato tissues. The tissues thermal conductivity changing by more than 20 % leads to nonuniform temperature field on the surface of the potato tuber under contactless heat effect. This allows the use of the thermal control method to detect defects. Knowing the thermophysical properties of potatoes healthy tissues and tissues which have defects allows us to determine the regime parameters of heat effect (power and time) by using mathematical modeling methods. Wherein, the necessary temperature difference between the defect and a healthy tissue is reliably recorded by modern thermal imaging technology. For example, the thermal imagers by FLIR Company have a resolution from 0.05 K, and the speed of the video stream to 60 frames per second and allow using them in the vision systems of sorting complexes.

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