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Application of infrared vision system for potato thermal control

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Application of infrared vision system for potato thermal control

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Abstract. The article proposes a solution to the problem of determining the values of potato tubers tissue thermophysical characteristics. The solution of this problem makes it possible to calculate the optimal regime parameters of potato quality active thermal control, which can be used for automatic sorting. In order to solve this problem, we propose a non-contact non-destructive control method based on a pulsed laser heating of a potato tuber flat surface area and subsequent use of time integral characteristics of temperature and heat flow, as well as a measuring device developed on the basis of physical and mathematical models of the method. The method was used by the authors to determine the thermal conductivity, heat capacity and coefficient of thermal diffusivity of different quality potato tissues: both healthy and affected by phyto-diseases. The studies have shown that the thermal conductivity of plant tissues depends on the presence of structural disturbances in them as a result of phyto-diseases. This fact confirms the possibility of using thermal non-destructive control of potatoes tissues provided the correct choice of power and the duration of the thermal effect on the object of control.

1. Introduction

Thermophysical characteristics (TPCs) of potato tissue are responsible for calculating the regime parameters of the potato storage and heat treatment [1]. Meanwhile, potato TPCs are significantly influenced by the physicomechanical, physicochemical and chemical characteristics of potato tissue [2]. Moreover, there is a great difference between heat capacity of healthy plant and heat capacity of defective tissue cause by phyto-diseases or external mechanical effects as been previously revealed in [3]. Thus, thermal control methods can be successfully applied to sort out agricultural products during storage and shipping to the consumer.

Modern methods of plant non-destructive testing are mainly based on the vision systems in the visible spectral range [4] as well as in the near infrared radiation range [5]. Meanwhile, the technical vision systems in the middle range of infrared radiation with the use of thermal imaging cameras have the advantage of image analysis simplification [6]. However, the effectiveness of such control largely depends on the conditions and regime control parameters.

In the process of thermal control, it is important to maintain parameters as the power and duration of thermal stimulation, which must be determined by mathematical modeling methods at TPC values measured during thermophysical experiment. In this connection, the problem of developing a method for non-destructive testing of potato TPCs arises. Meanwhile, plant TPCs measurement is largely influenced by specific tissue structure of most vegetables and fruits. Typically, plant tissue is a heterogeneous medium consisting of water, solids and gas (air) pores. Therefore, during the measurement, the following conditions must be fulfilled.

The aim of the paper was to develop a method for non-destructive testing of potato TPCs.

2. Theoretical basis and experimental part

Differently sized and shaped piece of fruits and vegetables were objects of our research. Therefore, it was advisable to take a semi-bounded body as a physical model of the investigated sample. The thermal effect on the surface area of this body could cause a multidimensional thermal process in it. It was possible to restore values of the sample's thermal conductivity and thermal diffusivity by registering the parameters of this process.

2.1. Development of method for non-destructive testing of potato TPCs

The organization of a semi-bounded body heating was carried out through a section of the simplest geometric form. Based on the possibility of practical implementation and a simple mathematical description of the thermal process in a solid, we selected the circle as a sample under study surface section. The heat flux entered through this surface section.

To solve multidimensional heat conduction problems, we used the apparatus of temperature and heat flow integral characteristics. The mathematical models of the relative and absolute methods of non-destructive TPCs testing (thermal conductivity and thermal diffusivity), developed earlier and described in [7-9], assumed 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 reached a stationary value. In these methods, the main experimental parameter was 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 $S(t)$ was measured mean-integral temperature of the heated circle, and p was Laplace transform parameter.

We assumed that in the experiment the investigated body was semi-bounded $0 \le z < \infty$, $0 \le r < \infty$ (Figure 1) and had a constant initial temperature (0 degrees Celsius. We also proposed that the heat flux was time-limited:

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

Thus, in the developed method and apparatus we supposed that the thermal effect was generated by time-limited heat flux.

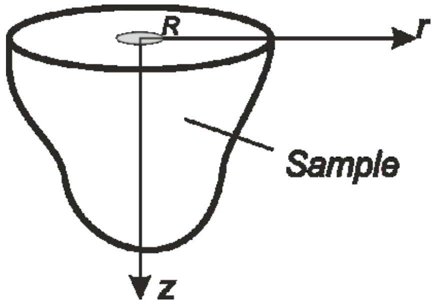

Figure 1. Physical model of the thermal process in the heated body: R – radius of the heated surface area, r - horizontal axis, z - vertical axis.

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

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

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

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

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

In equation (5) ε is a coefficient of surface radiation emissivity of the body under investigation.

We apply to the problem (2) - (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, $0\le r<\infty$, $0\le z<\infty$. We obtain an equation:

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

with boundary conditions

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

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

where

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

We apply the integral Hankel transform with respect to the coordinate r to (6) - (8) and, using properties of the integral Hankel transform [8], 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

$$\tilde{U}^*(p,\xi,z)=0$$

for $z\to\infty$ and

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

where $\widetilde{U}^*(p,\xi,z) = \int\limits_0^\infty r \cdot U^*(p,r,z) \cdot J_0(\xi \cdot r) dr$, $\widetilde{q}^*(p,\xi) = \int\limits_0^\infty r \cdot q^*(p,r) \cdot J_0(\xi \cdot r) dr$, $\xi \geq 0$ is Hankel integration parameter, J_0 is Bessel function of the first kind of zero order.

Solving equation (9) with conditions (10), and also, taking into account that 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 $\widetilde{U}^*(p,\xi,0)$ with the surface-time integral characteristic of the heat flux $\widetilde{q}^*(p,\xi)$ can be found.

Solving equation (9) with boundary conditions (10), and applying method discussed in [9] an equation for calculating thermal diffusivity coefficient *a*, thermal conductivity λ and volumetric heat capacity cρ can be obtained:

$$a = \frac{p \cdot R^2}{g(p)} \tag{11}$$

$$\lambda = \frac{2\varepsilon \cdot R \cdot q^*(p)(1-e^{-t_2 \cdot p})}{S^*(p)} V(g(p)) \tag{12}$$

$$c\rho = \frac{\lambda}{a} \tag{13}$$

where $g(p)$ and $V(g(p))$ are functions computed according to the method described in [9].

2.2. Development of automated control system

To implement the described method, we developed automated control system consisted of the functional blocks presented on the Figure 2. The laser had a maximum output power of 0.5 W and a wavelength of 405 nm. Focusing of the laser made it possible to obtain a light spot with a diameter of several tenths of a millimetre to 10 mm at a distance of 10 mm to 200 mm to the object surface. The laser power control unit allowed the output power controlled by pulse width modulation.

To obtain the primary thermal information from the body surface, a thermal imager manufactured by FLIR Model A35 was used. Then we designed thermal imager which generated 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, received the image from the thermal imager, time-by-frame processes it using the NI Vision technology, and determined the integral temperature $S^*(p)$ on the circular object surface with radius *R*. The TPCs measured with the presented system were used in the automated device 8 (Figure 2) of an active potato quality control to determine the heat treatment regimes in automatic sorting complexes.

An algorithm of the experimental data processing is shown on the block diagram (Figure 3) and is described below.

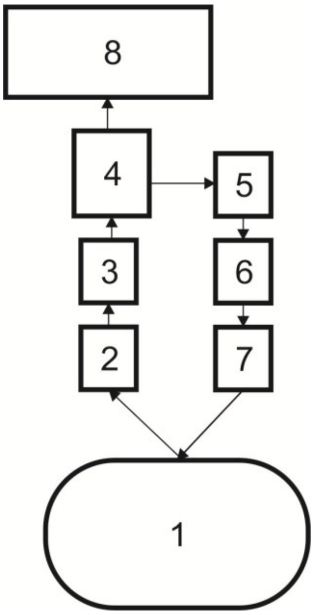

Figure 2. Measuring unit: 1 – object of control, 2 – thermal imager, 3 – adapter, 4 – personal computer, 5 – control unit, 6 – power supply, 7 – laser, 8 – automated device.

At first the image grabbing parameters must be set. These parameters include the camera model, resolution, temperature sensitivity, shooting speed. Then the correct port of the input-output board must be set in order to control the laser heating device. When the parameters are set a test sample should be heated by laser radiation. Region of interest (ROI) should be set by moving the cursor. Then from this ROI and the image a mask is created in order to take into account only temperature points in ROI. From this mask an array of temperature points is obtained. Then an integral surface characteristics in the ROI can be calculated for each period of time. These points are displayed at the thermogram graph. Image from the camera also is displayed. A test sample is heated until the temperature has reached the target value. Then the laser is switched off. After that the calculation step begins. A user should set the Laplace transform parameter p and the coefficient k. All the parameters and TPC are calculated. At the last step the calculated TPC are displayed.

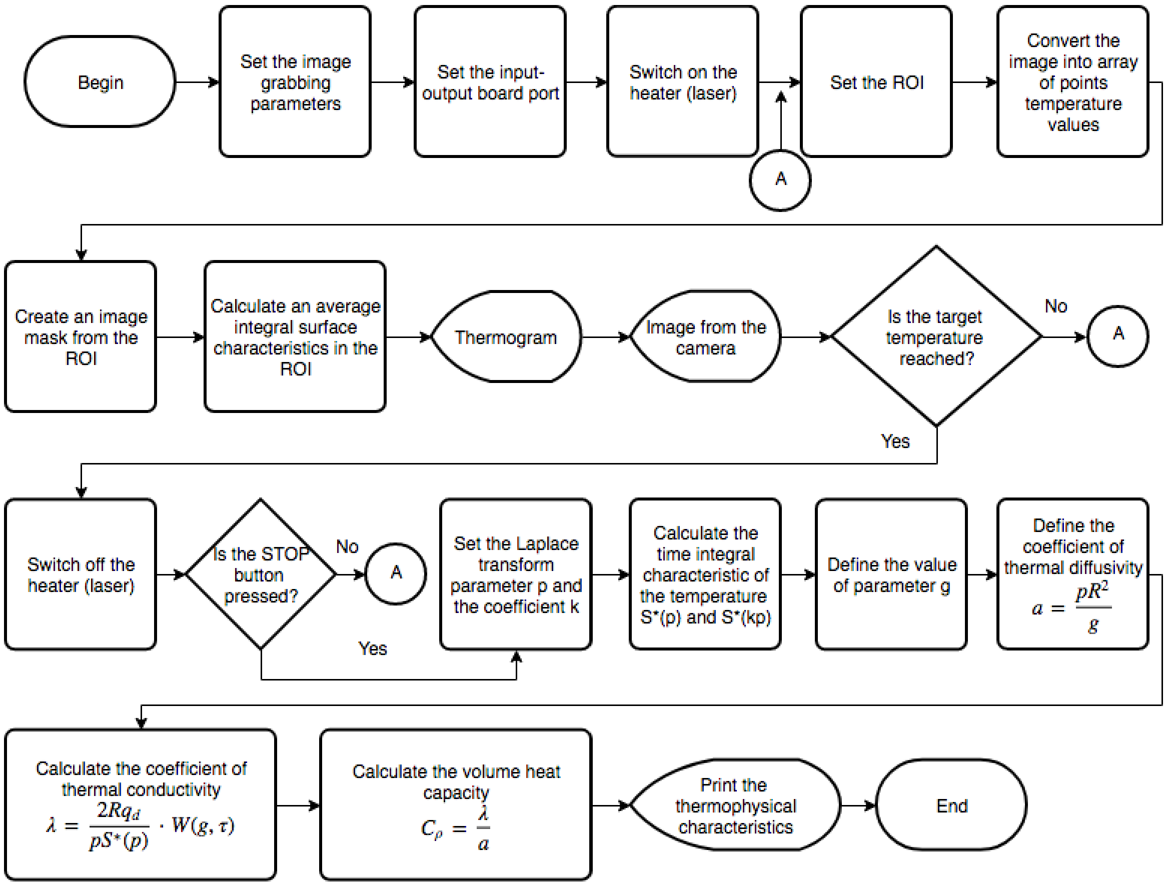

Figure 3. Block diagram of the experimental data processing.

2.3. Experimental approval of the developed approach
Using the presented measuring device, we carried out experiments on the tissue of an early-adapted sort of potato “Udacha” selected from the Tambov region, Russian Federation in 2017 year immediately after harvest. Both samples had known TPCs. 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. We analyzed two samples of potatoes – healthy potato and rotten plant – potato after 10-days rot under the influence of high temperature and high humidity.

The thermal conductivity measurement error using the pilot plant was determined by comparison with the results of the measurements obtained with the certified ITP-MG4-100 instrument ("SKB Stroypribor" LLC, Russian Federation). The experimental samples consisted of four parallelepipeds cut from the potato tubers with a size of 50x50x15 mm. Four samples were combined into one with a size of 100x100x15 mm. Taking into account the basic relative error of 5% of the ITP-MG4-100 instrument, the limit of the thermal conductivity measurement error using the pilot plant was no more than 12%. The error source appears to be the part of the radiation reflection from the object surface. The influence of the radiation reflection can be reduced by refining the coefficient k in the formula (5).

Experiments with potato tissue have shown 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).

Table 1. Thermal conductivity of healthy and rotten potato tissues.

The test sample	λ, $W \cdot m^{-1} \cdot K^{-1}$
Healthy potato tissue	0.50 ± 0.06
Rotten potato tissue	0.40 ± 0.06

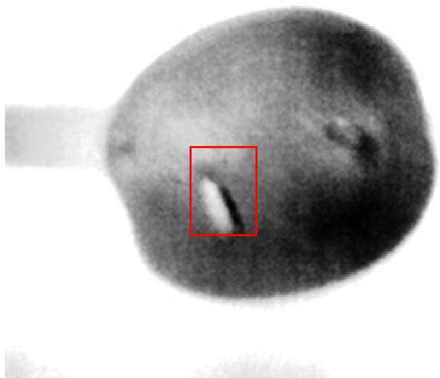

Figure 4. Potato with defect (the defective zone is highlighted with red rectangle).

The results of thermal conductivity measurement are indirectly confirmed by thermal imaging of potato tubers, which tissue has a dry rot type defect. The images clearly show the defective zones in the form of pixels sets with a different brightness (Figure 4). This fact allows using of NI Vision library standard tools for image processing and defect search.

Conclusion
The fact that plant thermal conductivity strongly depends on structural disturbances confirms the possibility of using thermal non-destructive control of plant tissues by selecting power and the duration of thermal exposure. In order to obtain a confidently detectable temperature contrast between the defective and defect-free zones of monitored samples, it is necessary to organize a thermal action of a certain power and duration as shown in the paper. At the same time, in the process of non-

stationary heat exchange, a temperature difference arises on the surface of an object with defects, caused by the heterogeneity of its structure, and as a result, by unequal TPC. This temperature difference is the most informative parameter, according to which the presence of not only surface but also subsurface defects is judged. In order to determine thermal conditions, it is necessary to simulate non-stationary process of heat transfer, in a mode when thermal radiation with known characteristics acts on the monitoring object. The developed method for non-destructive testing of potato TPCs allows the use of thermal control to detect rotten tubers.

For a reliable detection of a rotten potato, it is necessary to obtain an image of its entire surface, which can be achieved by the use of multiple cameras, rotation of a sample at equal rotation speed and shooting frequency. In addition, the presence of thermal interference from the contact of the monitored object with the conveyor belt or rollers that rotate the object should be taken into account. The use of thermal control in conjunction with technical vision makes it possible to detect not only surface, but also sub-surface defects that cannot be detected visually.

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