Research of temperature zones during primary processing of silkworm cocoons using a modern thermal imaging camera

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Abstract. The article presents the results of studies conducted at the Tashkent State Technical University (based on the research project № F-A-2018-029) to determine the temperature zones in the vibrating infrared dryer using thermal imaging during the primary processing of silkworm cocoons. To ensure a uniform temperature and maintain the quality of the final product, one of the important tasks is to determine the temperature zones at different points of the device and eliminate heat loss in it. On the basis of the obtained results of the study with the help of a thermal imaging device, the drawbacks of the infrared vibrating drying unit associated with the emitters and the flow of heat flow in the primary processing of cocoons were eliminated, and the optimum temperatures were determined and uniform processing of mulberry silkworm cocoons was ensured.

1. Introduction
Thermal imaging camera is a device designed to detect thermal radiation on the studied surface. The research method is non-contact, provides smooth operation when studying moving objects. The device for controlling the temperature distribution of the surface under study. Principle of operation of thermal imager is based on conversion of infrared energy into electric signal which is amplified and reproduced on the screen of indicator. The temperature distribution is shown on the Imager display as a colored field, where a certain temperature corresponds to a certain color.

Today, thermal imaging cameras are the optimal tool for non-destructive thermal inspections in a wide variety of industries. The main areas of application of thermal imaging cameras are the food industry (in the process of drying agricultural products), diagnostics of electrical networks, control of production processes and other cases where the technical condition of the controlled objects can be judged by the non-uniformity of the thermal field. The use of thermal imaging cameras makes it possible to determine the points of heat loss during operation.

The paper by A.A.Gowena presents an overview of the theory, equipment and processing of thermal images. Recent advances and potential applications of thermal imaging for food safety and quality assessment, such as temperature checks, bruise and foreign body detection, and grain quality assessment are reviewed [1].

N.A.Nanj Gowda and N.A.Alagusundaram consider the importance of thermal imaging in grain storage. Grain spoilage occurs due to inadequate storage conditions, which leads to improper interaction of abiotic (temperature, humidity, gas composition) and biotic (the grain itself, insects, fungi, mold, mites) factors [2].
2. Materials and methods

In production processes, there are often the tasks of determining the temperature of the processed or heated objects. Optimizing these processes requires temperature data. The most convenient non-contact methods for determining the temperature, based on the registration of thermal radiation emitted by the surface of the heated object. In this case, thermal imagers are usually used. To correctly determine the surface temperature of the objects being processed, it is necessary to understand well the process of forming temperature readings in thermal imagers and be sure to take into account the thermal radiation coefficient $\varepsilon$ in [3].

2.1. Physical foundations of non-contact temperature measurement

Under conditions of thermodynamic equilibrium, bodies exchange equilibrium thermal radiation, the intensity and spectrum of which depend only on temperature. In this case, the energy given off by the body due to thermal radiation is equal to the energy received by the body when absorbing radiation emanating from other bodies. The spectral dependence of the intensity of this equilibrium electromagnetic radiation on the wavelength $\lambda$ is described by the Planck formula for the volumetric energy density of equilibrium radiation [4].

$$W(\lambda, T) = \frac{8\pi h c}{\lambda^5} \left( e^{\frac{hc}{kT}} - 1 \right)^{-1}$$  \hspace{1cm} (1)

where $h$ is Planck's constant, $c$ is the speed of light, $k$ is Boltzmann's constant, $T$ is the temperature determined by the laws of thermodynamics and which is measured by contact sensors.

The methods of non-contact temperature measurement (thermal imager) are based on recording the thermal radiation of the body emitted by the surface. When describing it, we use the surface radiation power density of equilibrium radiation or spectral luminosity

$$M(\lambda, T) = \frac{1}{4} W(\lambda, T) = \frac{8\pi h c}{\lambda^5} \left( e^{\frac{hc}{kT}} - 1 \right)^{-1} = \frac{c_1}{\lambda} \left[ e^{\frac{c_2}{\lambda T}} - 1 \right]^{-1}$$  \hspace{1cm} (2)

where $c_1=2\pi hc^2$ and $c_2=hc/k$ – the first and second radiation constants. As it can be seen from Figure 1, the spectral luminosity increases rapidly with increasing temperature, and the maximum of $M(\lambda)$ shifts towards shorter wavelengths.

It is clear that thermodynamic equilibrium is absent when measuring the temperature of heated bodies without contact. Thermal radiation of condensed media is formed by quantum mechanical phenomena during electronic transitions, vibrational and rotational movements of atoms or molecules. For a number of physical reasons, the spectral luminosity of the surface of real bodies turns out to be less than that calculated by expression (2). Therefore, to standardize measurements, it is necessary to use standard emitters (models of absolutely black bodies), the radiation of which is described by expression (2), and to introduce the concept of the spectral coefficient of thermal radiation $\varepsilon(\lambda, T)$ surface, i.e. attitude

$$\varepsilon(\lambda, T) = \frac{M(\lambda, T)}{M(\lambda, T)}$$  \hspace{1cm} (3)

where $M(\lambda, T)$ – spectral luminosity of a body. The value of $\varepsilon(\lambda, T)$ depends on the physical properties of the body material, configuration and state of its surface. Based on definition (3), the emissivity of an absolutely black body is equal to one, and $\varepsilon(\lambda, T)$ of real bodies is always less than one.

![Figure 1](image-url) 

**Figure 1.** Dependences of the spectral surface luminosity of an absolutely black body on the wavelength at different temperatures.
As it can be seen from the schemes for the formation of the fields of view of thermal imagers (Fig. 2), thermal radiation from the body is collected by their lenses on the photosensitive area of the photodetectors at a certain solid angle \( \varphi \). Moreover, the normal to the surface of the controlled body can form an angle \( \alpha \) with the direction to the center of the lens. Experimental measurements have shown that there is a dependence of \( \varepsilon(\lambda, T) \) on the angle \( \alpha \), i.e. many surfaces are not Lambert emitters, for which the brightness does not depend on the viewing angle [5]. This leads to a wide variety of dependences \( \varepsilon(\lambda, T, \alpha) \) when measuring temperature in real production conditions, which complicates the use of reference data obtained at \( \alpha=0 \).

In addition to the influence of the dependence \( \varepsilon(\lambda, T, \alpha) \) on the recorded values of the intensity of thermal radiation, in some cases an additive appears, caused by radiation from the external environment, which is reflected from the surface of the controlled body. The hemispherical reflection coefficient of radiation \( \rho \) for opaque bodies can be found from the ratio that follows from the law of conservation of energy (the incident flux is equal to the sum of the absorbed and reflected) and the equivalence (established by Kirchhoff) of the thermal radiation coefficient to the absorption coefficient.

\[
\varepsilon + \rho = 1
\]  

Under industrial conditions, this ratio is very difficult to use, since heat fluxes are collected by lenses in rather narrow solid angles at different values of \( \varepsilon \). In addition, the material, size and configuration of the food to be heated vary. Thus, to improve reliability, non-contact methods for measuring temperature should be invariant or resistant to changes in \( \varepsilon(\lambda, T, \alpha) \) and the influence of radiation from the external environment.

**Figure 2.** Simplified schemes for the formation of fields of view in thermal imagers: 1 – IR tubes; 2 – field of view; 3 – lens of a thermal imager with an entrance pupil diameter; 4 – plane of image formation; 5 – body image.

The transmission of the medium \( \tau(\lambda) \), through which the thermal radiation passes (Fig. 2), can also reduce the recorded heat fluxes. To exclude the influence of absorption of radiation by air, the registration of thermal radiation is carried out in the transparency windows of the atmosphere (Fig. 1). In the presence of dust and water vapor, some of the body’s heat radiation will be dissipated. The transmission of the medium must be taken into account by introducing the coefficient \( \tau(\lambda) \), which is less than one. Then the spectral flux of thermal radiation incident on the lens is proportional to the expression

\[
\Phi_{ob}(\lambda, T) \sim \tau(\lambda) [\varepsilon(\lambda, T, \alpha)M(\lambda, T) + \rho(\lambda, \alpha, \beta)E_{in}(\lambda)]
\]  

where \( \beta \) is the angle between the direction to the illumination source and the normal to the body surface, \( E_{in}(\lambda) \) is the spectral illumination of the body surface by an external source.

In thermal imagers, the energy of thermal radiation is converted into electrical signals that are proportional to the input flux \( \Phi_{ob}(\lambda, T) \) incident on the lens, the transmission of the objective \( \tau_{obj} \), the area of the entrance pupil of the objective and also depend on the spectral sensitivity of the
photodetector, transmission of the used optical filters, etc. The temperature is determined by comparing the magnitude of the recorded signal with the calibration dependence of the thermal imager, obtained using a reference emitter - a black body model.

For the convenience of visual perception, the field of view of thermal imagers is formed quite wide and the focusing is used, which is necessary to obtain a clear image. This leads to the need to take into account the dependence of the illumination of the thermal image formed by the lens on the photodetector (Fig. 2) on the distance $2$ to the body whose temperature is measured. The coefficient connecting the luminosity of the body surface and the illumination of its image on the photosensitive surface of the photodetector is described by the expression

$$K = \tau_{ob} \left( \frac{d^2}{4l^2} \right) \left( \frac{l_2}{l_1} \right) 2$$

In thermal imagers of the mid-infrared range of the spectrum, short-focus lenses are used and the decrease in the registered flux by $l_1 > 2$ m, when $l_2/l_1 < 1/30$, is not taken into account.

Thus, the presence of difficult-to-control parameters and characteristics that affect the recorded fluxes of thermal radiation leads to the fact that, during non-contact measurements in production conditions, not the true, but some conditional temperature is determined.

2.2. Investigation of temperature zones with a thermal imager in a laboratory infrared setup

To determine the temperature of the processed cocoons that left the installation and to ensure a uniform temperature in order to maintain the quality of the final product, the infrared field and the processing process were studied using a modern thermal imager, which is shown in Fig. 3.

![Figure 3](image_url)

**Figure 3.** Using thermal imaging to determine the temperature of cocoons during primary processing.

3. Results and discussion

Laboratory experiments were carried out at different temperatures. Thermal fields in the unit during the primary processing of mulberry silkworm cocoons were studied with a thermal imager [6-9]. The temperatures of treated cocoons at the outlet of the unit were studied. The temperatures of treated cocoons at the outlet of the unit were investigated; the images and histograms were obtained, which are shown in Figure 4.
4. Conclusion

As a result of scientific research and experiments, the following conclusions were made.

- As a result of checking the installation with a thermal imager, points of heat loss were identified. These disadvantages are eliminated by filling. The optimal placement of the emitters in the installation has been determined.
- Expansion of functionality and reduction in cost of thermal imaging equipment opens the way to its widespread use in setting up and optimizing various thermal engineering processes in industry.
- Possibility of video recording of the temperature field of the established processes and its subsequent playback allows creating their documented protocols for periodic subsequent control.
- A convincing argument is the quick payback of thermal imaging equipment used to optimize complex heat engineering processes, due to the corresponding savings in expensive energy resources.

Based on the scientific and practical results obtained, the drying process of agricultural products significantly accelerates the drying process with the elimination of defects identified by thermal imaging, serves to improve the quality of the final product and reduce energy consumption, and at the same time allows achieving economic efficiency of the plant. The use of thermal imaging in the improvement of energy-efficient dryers in the food industry, thereby increasing their efficiency and productivity, only serves the benefit of the economy.

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**Figure 4.** Process temperature measurement and histogram of the results of primary processing of silkworm cocoons.
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