Improving the resolution and accuracy of temperature distribution on the surface of microsystems using thermographic methods

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Abstract*: Improvement of thermographic imaging device by using an automatic scanning system as opaque for infrared radiation of a matrix aperture with a window of transparency at the lens of the thermal imaging lens, leads to improvement of the spatial and temporal characteristics of the thermal imager, namely, its separation from the point of view. As a result of the experiments, it was found that the spatial resolution of the improved thermographic method (compared to the standard method of determination) was improved by 15 – 20%, and the spectral resolution by 0.3 – 0.5 μm. According to the results of the analysis of the processed image, the adjusted temperature scale of the thermogram, which, in turn, allowed to increase the accuracy of temperature determination in each accurate image (the temperature distribution error did not exceed 5.5%).*

Keywords: *THERMOGRAPHIC METHOD, THERMAL IMAGER, TEMPERATURE DISTRIBUTION, RESOLUTION, PRECISION, MICROSYSTEMS*

1. Introduction

Today, the development of various components of microsystems (MST), as well as the products and units and systems built on these components, improves the functional and operational characteristics of these devices, while minimizing them. This increases the specific power and performance of both mechanical and electronic components of the MST. This, in turn, leads to a sharp increase in energy (especially thermal) costs, both in individual parts of the device and in general – throughout the device. Such an increase in heat consumption results in a sharp rise in temperature, which in most cases has a negative impact on the performance of the MST devices. (It should be noted that with a sharp increase in temperature, the mechanical components of the MST devices begin to block the movement of tangent elements due to the thermal expansion of the material, which can reach 15 – 25% of the size of the element itself. At the same time, the temperature decreases (up to 2.5 – 3%) the resistance of semiconductor (then, as the resistance of conductors, on the contrary - increases in 9 – 17%) electronic components of MST devices, which leads to their premature failure) [1 – 4].

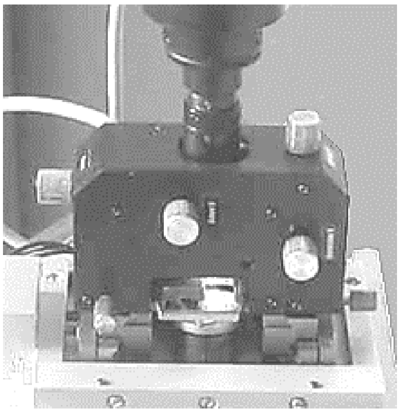
To date, there are and are actively applying a number of methods and means to eliminate (at least reduce) the heat load on the MST device and their components. However, in order to take measures to reduce the heat load, there is an urgent need for rapid monitoring and determination of the temperature distribution over the entire surface of the studied objects operating in dynamic mode.

Among the thermal methods for determining the temperature, the most promising is the thermographic method based on the use of a thermal imaging device. The effectiveness of using this thermographic method is confirmed by the work of many scientists from all over the world, among which the following should be mentioned: Vavilov V.P., Ketkovich A.O., Kurtev M.D., Danilin M.S., Dubitsky L.G., Thomson R.D., Holland S., Bison R., Sakagami T., and many others [5 – 10].

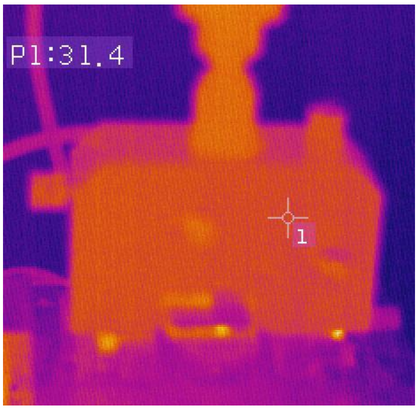
However, in spite of the obtained results, the problem of thermography and MST thermography still remains unsolved in the problem of thermography and determination of the surface temperature containing individual trace elements whose temperature is significantly different from the background temperature (for example, separate structural elements on the background the massive body of the device with a temperature higher than the temperature of these elements). Thus, in the thermographic picture, such elements are not observed due to diffraction by the thermal background radiation of these elements, and, accordingly, their thermal profiles, Fig. 1.

Therefore, improving the resolution and accuracy of the surface temperature determination of MST products by thermographic method is a pressing issue.

The aim of the research is to improve the thermographic method by applying an automatic scanning system in the design of the thermal imager, as well as specialized software, which will improve the resolution and accuracy of the temperature distribution on the surfaces of the elements of MST.



a.



b.

Fig. 1 *Light photograph (a) and thermogram (b) of the measuring unit of the scanning probe nanoscope*

2. The experimental technique

Improvement of the method and device of thermographic imaging has the task of improving the space-time characteristics of the thermal imager, namely, its accuracy and resolution by using an automatic scanning system as opaque for infrared radiation of a matrix diaphragm with a window of transparency up to 100 mm in size and up to 1 mm in size the lens of the thermal imager.

In a modified thermal imager containing a series-coupled registration node in the form of a matrix radiometer and an optical system, which includes an automatic scanning system and an information processing unit. The automatic scanning system gives the possibility of step-by-step movement on a rectangular matrix, which results in obtaining local information of a separate section of the thermal profile of the investigated surface. The optical system also includes a microlens located in front of a transparency window that focuses thermal radiation from an object of observation onto a matrix radiometer [11].

Due to the fact that in the proposed thermal imager there is no multiple reflection of the signal, and there is only a single focusing of the signal when passing through the microlens, the attenuation of the signal and its distortions through diffraction scattering does not occur. In Fig. 2, a block diagram of an improved thermal imager.

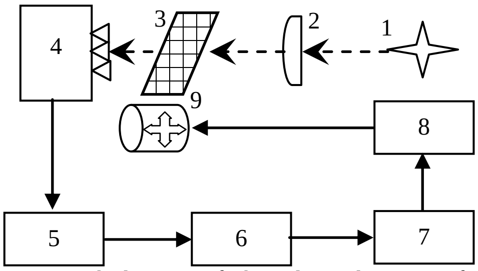


Fig. 2 *Structural diagram of the advanced means of thermographic observation (thermal imager): 1 – object of research; 2 – microlens; 3 – matrix diaphragm; 4 – matrix radiometer; 5 – block of synchronous detectors; 6 – analog-to-digital converter; 7 – microprocessor control device operation; 8 – switching unit; 9 – automatic scanning system.*

The thermal imager consists of a series-connected registration unit in the form of a matrix radiometer 4, an optical scanning system, which includes a matrix aperture 3, made of material that does not transmit infrared radiation with a window for infrared radiation, and microwave radiation conductivity and provides the design of the image on the matrix of the radiometer 4, as well as a processing unit consisting of a block of synchronous detectors 5, analog-to-digital converter 6, plug-in a microprocessor for controlling the operation of the device 7 and switching unit 8, which provides communication of the thermal imager with external control devices, collecting and processing information (eg, PC, industrial computer, etc.).

The imager works as follows. The radiation from the corresponding element of object 1 enters the microlens 2, from which focuses on the conductivity window of the matrix aperture 3 in which focuses on the matrix radiometer 4, which transmits information to the block of synchronous detectors 5. From the block of synchronous detectors 5 information enters the analog-digital converter 6 and further, in digital form, is transmitted to the built-in microprocessor 7 to control the operation of the device, the main job of which is to form an appropriate image matrix and remember it. In parallel, the microprocessor 7 generates a control signal coming through the control driver, which is part of the switching unit 8, to the scanning system 9. The control signal drives the stepper motor of the scanning system 9, which begins to rotate step by step, moving the matrix aperture to the next position. In this case, the matrix diaphragm translates, moving with each subsequent step the window of transparency from left to right in one row. When the end of the row is reached, the scanning system converts the diaphragm to the leftmost position by lowering it one row below. At the moment when the automatic scanning system 9 reaches the maximum value of the position of the transparency window (which corresponds to its maximum position in the lowest line), the microprocessor 7, through the driver of the control unit 8 will switch the scanning system 9 to the initial position (extreme upper – left position) and stop stepper motor 9. After processing by the microprocessor 7, information about the constructed thermographic image, by means of the switching unit 8, may arrive at an external control device, which in turn may carry out Birr and processing the information received, as well as to external control modes imager.

The use of this technical solution automatically maintains the clarity of the image being obtained and its high resolution by keeping the latter in the focal plane of the recording device.

For the experimental testing of the proposed idea, the article used a device Titanium HD 570M (FLIR Systems ATS) with a spectral range of 3.7 – 4.8 μm. Thermographic studies were performed with a recording rate of 1 kHz, a resolution of 160× 128 pixels, and an integration time of 50 μs. The spatial resolution of the camera in the experiments was 220 μm.

The thermal experiment was conducted by thermal imaging examination in several stages: 1 stage – preparation for the experiment, 2 stage – preparation of control means, 3 stage – conducting the study (external and internal thermal imaging and instrumental measurements), 4 stage – analysis and decoding of the obtained results. Each stage was carried out in a specific sequence [12].

Preparation for conducting a thermal experiment. At this point, it is necessary to evaluate the readiness of the object of study for the thermal experiment. Thermal imaging of objects (MST), for example, when put into service, is usually performed during their test run. Shooting is performed with a dynamically operating device on running tests, as it is necessary that there be a temperature pressure - the difference between the temperature of the MST element and the environment. Typically, this temperature pressure should be at least 10 – 15 °C. Such temperature pressure will reveal defects in thermal protection, if any. Then a visual inspection of the MST device is performed and its warming is evaluated. It is desirable that the distance from the shooting point to the subject should be 10 – 30 cm, since at large distances detection of all defects (especially when using thermal imaging with small matrices) is not guaranteed. You also need to snap to the location and navigate to third-party objects. On initial visual inspection, you can make a general idea of the object of study and identify the elements for further detailed thermography. This object evaluation is only preliminary and cannot be independently used to analyze the observations. After visual inspection, reference areas should be selected on the surface of the object. The reference zones are homogeneous areas on the surface of protected structures, with constant temperatures being areas with a relatively isothermal surface [13]. The size of the reference area may be 2 – 10 mm (Fig. 3). In these areas, contact measurements will continue to be made.

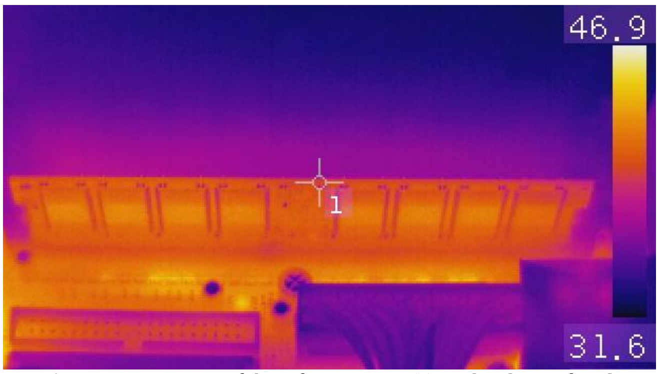


Fig. 3 *Determination of the reference area (1) on the object of study*

The result of the works of this stage is the plan (scheme) of thermal imaging examination, where it is necessary to fix the anchor to the elements of the investigated surface, to determine the shooting points (their place and number), here the distance to the object is indicated, the direction of the shooting, the selected reference areas are marked and areas identified by visual inspection of abnormal (or defective) areas - these may be sites with some unusual design solutions or areas with visually visible defects.

After the general idea of the object of study and the control scheme are defined, they proceed to the inspection and preparation of the equipment [14].

Preparation of controls. This step involves selecting controls based on the temperature range of the detection, the sensitivity, the error of determination, the parameters of the controlled object. Before proceeding directly to thermal imaging control, a series of actions must be taken to reduce errors in temperature detection in the field and to best visualize the thermal image of the object. For this purpose in the thermal imager a number of settings is organized. They can be roughly divided into two classes: settings related to environmental settings and settings that relate directly to the operation of the unit. The settings of the device that set the values of environmental parameters include: ambient temperature; distance to the object of control; air humidity.

Atmospheric conditions in which thermal imaging is controlled affect the passage of infrared radiation from the object to the operator. Therefore, it is desirable to take into account the environmental parameters to reduce errors in determining the actual temperature of the control object. If you set environmental parameters in the corresponding instrument settings menu, the thermal imaging processor will be able to calculate a compensatory correction for external conditions and thus minimize the error in temperature determination associated with attenuation of the IR radiation in the atmosphere. The air temperature and humidity can be determined by a thermogigrometer and the distance by a laser rangefinder. Other settings of the device are already related to the thermal imager and the object of thermal imaging control.

Setting the temperature sub-range of temperature determination. Typically, the thermal imager range (for example, from -40 °C to +600 °C) is broken down into several subbands (for example: from -40 °C to +100 °C, from -10 °C to +300 °C, from +10° C to +600 °C). If you ignore these settings of the device, you can see nothing at all on the screen of the thermal imager (if the temperature of the object is lower than the lower limit of the high-temperature range), and to disable the sensitive elements of the matrix (if a hot object falls into the frame when a low temperature subband is defined) [15].

Set the radiation factor. Since real bodies give less space to their space than an absolutely black body at the same temperature, it is desirable to indicate, in the instrument settings, the radiation coefficient of the material from which the control object is made in order to calculate it and, accordingly, reduce the error in determining the temperature. The value of the radiation factor is usually taken from reference tables or determined experimentally on the spot. According to regulatory documents, it is not recommended to carry out monitoring of an object having an emission factor less than 0.6. In this case, measures are needed to approximate it to 1.0 by painting the surface of the object or other available paths.

Selecting a working palette. Installation of the appropriate palette is required for better visualization of thermal details of the thermal image of the control object. Set of color palettes is a matter of operator's habit and tradition in this or that field of use of the thermal imager. So, if a large temperature range (tens and hundreds of degrees) falls into the frame of the imager, it is advisable to choose a palette with a small number of colors (2 – 3). If an object with a small temperature difference (degrees and tenths of a degree) is considered in the thermal imager, it is better to choose a palette with many colors (up to 8). Specifies the range of displayed temperatures. In most modern thermal imagers this feature is implemented in automatic mode. That is, the upper and lower bounds of the interval itself adjusts depending on the minimum and maximum temperatures of the object that fall into the field of view of the imager. In some cases, you may need to manually adjust the interval, for example, when you need to examine in detail not the entire object with a wide temperature range, but only part of it.

Adjusts focus (sharpness). Sharpening is a very important part of getting a good thermal image. All previous settings discussed can then be corrected in the thermal imaging program (for example, if settings were mistaken at the scene).

To correctly determine the temperature field of the heater with the help of an IR camera, calibration experiments were performed. The resulting calibration curve was approximated by a second degree polynomial. The temperature determination error using a thermocouple was 0.5 °C. The standard deviation was calculated in Altair and was 0.4 °C. The minimum separation temperature difference equivalent to the infrared camera noise is 0.02 °C. Thus, the determined temperature from the test sample corresponded to the surface temperature of the heater directly in contact with the object of study. The relative error in determining the temperature during the calibration step was 3%.

Adjusting the lens image settings. Some models of thermal imagers have the ability to install different lenses with different values of the angles of view. These are the so-called telephoto lenses (narrow-angle) and panoramic (wide-angle). Each time you change the lens, it is recommended that you reflect this in the appropriate settings of the device. Thus, the correction is made to the reading of the device, since the optical system of the imager absorbs IR radiation. Each lens has a construction-dependent absorption correction value. In some devices, this adjustment to the new lens can be implemented automatically. After all the work on preparation for the control and equipment preparation, you can start thermal imaging directly. After the preparation for the control and the devices have been prepared, you can proceed to the stage of thermal control.

Thermal imaging and instrument definitions. At this stage, the geometry of the study object is first determined (the location of the other structural elements of the environment relative to the MCT device is determined) and the distance at which external thermal imaging is taken. It is desirable that this shooting distance remains unchanged. With the help of instruments the temperature and humidity of the environment are fixed. The temperature of the reference zones is then determined, both by the contact method (this is done by means of a contact thermometer) and by the non-contact method (by the thermal imager), and the true coefficient of radiation of the object is established based on these data in the thermal imager menu. Then proceed directly to thermal imaging. External thermal imaging of the object is carried out using the automatic scanning system sequentially left - right and bottom - up, for which the investigated surface is divided into separate sections, arranged in the form of a matrix, Fig. 4.

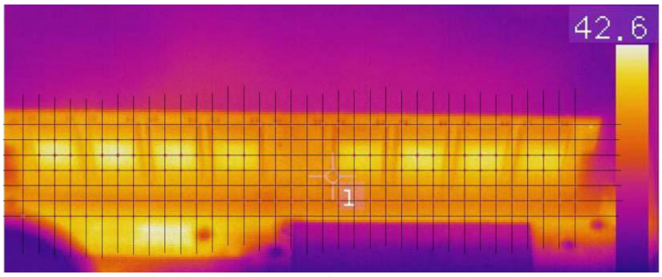


Fig. 4 *Scheme of thermal imaging of the device MCT (control unit optical microsystem positioning)*

Start thermal imaging with the coldest area. Each frame that opens the aperture is accompanied by a photograph. The shooting angle is chosen to be minimal, but in any case it should not exceed 60º. If this condition is not met, the control results may be distorted. After the object has been photographed over the entire surface, you can, if necessary, take a closer look at some areas of doubt. For example, we can do a detailed survey of the overlapping zones of individual colder microdistricts against a hotter surface. It is also advisable to carry out a panoramic thermographic survey of each element of the object.

To maintain the necessary detail and quality overall image of a large object (such as a heat unit, car or airplane), it is advisable to perform panoramic shooting from a not too far distance (in any case, the distance should not exceed 1 – 2 m). In this case, you can take a panoramic shot of each element in a few snapshots, and then create a single overall thermal snapshot of the object during computer processing [16]. At the same time, the quality of the thermal image does not deteriorate, no thermal details are lost, and you can make an overall impression of the defects that are characteristic of the whole object. It should be said that the built-in software of many modern thermal imaging cameras allows directly in the program to "stitch" individual thermograms into a single "panoramic" image, but not always the quality of the "stitched" image remains high.

As a result, after thermal imaging, we will have thermograms of all the elements of the object, "detailed" thermograms of the individual sections of the external elements that protect them, as well as thermograms obtained during the internal shooting. Thermograms obtained during thermal imaging are then computer-processed, analyzed and attached to the thermographic report. In order to make instrumental determinations, one or more typical objects, which maintain a relatively uniform temperature regime under the same environmental conditions, are selected. For these objects, reference areas are selected, which are characterized by homogeneous sections of outer walls with relatively isothermal surfaces. Such sites are characterized by conditional (plane) resistance to heat transfer. You need to log the test data automatically or manually after a certain period of time (eg 0.5 – 1 minute) for several minutes.

After the logging time (usually a few minutes) is over, the results of the determination are processed. Thus, after making instrumental determinations, we will have the values of the temperature at the object under study and outside, the values of the temperatures of the surfaces of the structures inside and outside the PC, the amount of humidity in the study zone, and the values of the density of heat fluxes passing through the protecting structures. The resulting quantitative parameters must be recorded and stored. The results are processed using special software that comes with the equipment, as well as with specialized software packages developed with the help of the authors of the article. Then, based on the obtained instrumental definitions, it is possible to calculate the necessary figures of heat consumption.

Analysis and decoding of the obtained thermograms and interpretation of the determination results. Initially, computer processing of thermograms and identify areas of thermal anomalies – that is, the zone of deviation from the predicted temperature distributions on the surface. In computer processing of thermograms, various built-in functions can be used to isolate and refine anomalous areas – for example, you can set points, lines, rectangles, ovals, and the like, indicating temperatures or temperature deviations. Sometimes the analysis and decryption of thermograms also use the functions of histogram construction (Fig. 5).

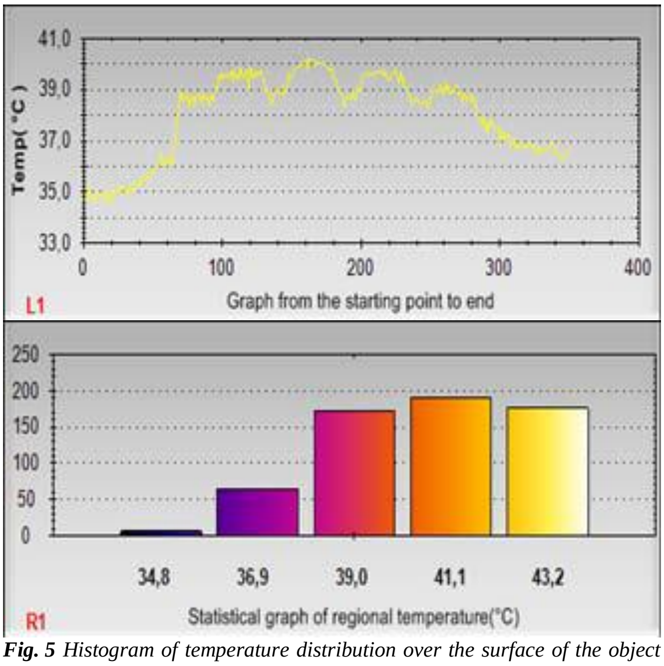


Fig. 5 Histogram of temperature distribution over the surface of the object under study

Thermograms treated in this way give an idea of the presence in the controlled object of anomalous areas (the search for such sites is oriented to the basic idea of work) associated with violations in their manufacture or in operation.

3. Discuss the results of the experiment

According to the results of thermographic studies conducted by the thermographic method before its modification, Fig.6, it is shown that the electronic-mechanical device of micropositioning of the measuring nanosound of the scanning probe nanoscope has an elevated temperature on both its surface, both on mechanical and electronic devices. making it impossible to accurately determine the thermal profile of the individual elements of this device. At the same time, the peripheral mechanical elements of the device had a higher temperature (about 32 °C) compared to the electronic elements located closer to its central part (about 29 °C).

Fig.7 shows the thermograms of the surface of the individual elements of this electronic-mechanical micropositioning device, registered by an advanced thermographic device.

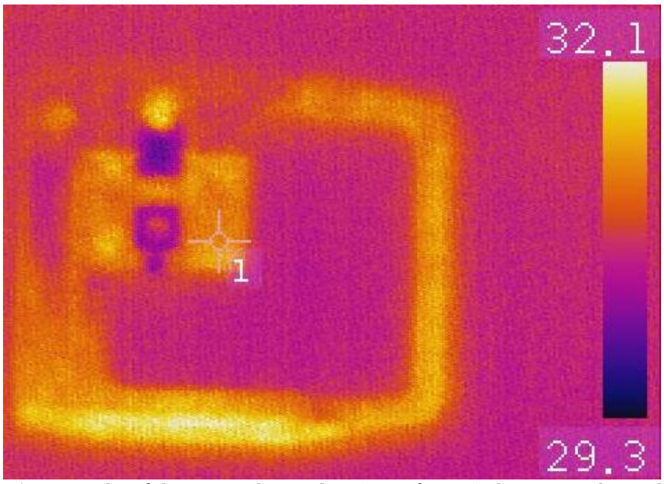


***Fig. 6** Results of thermographic studies (to perfection) electron-mechanical micropositioning device of measuring nanosand of scanning probe nanoscope with specified reference point (mark 1)*

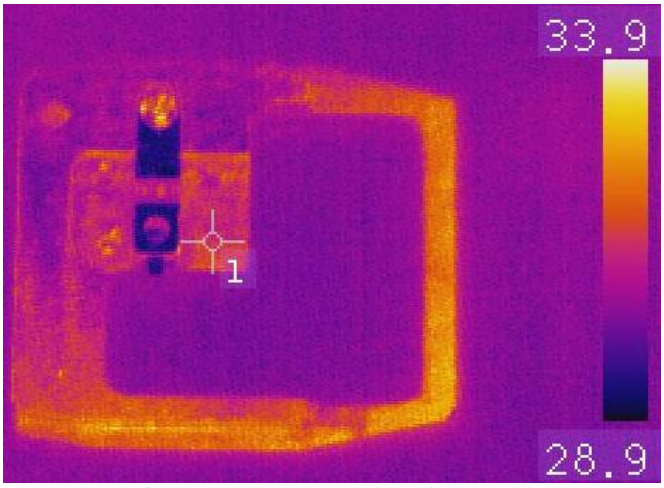


***Fig. 7** Results of thermographic studies (after refinement) of the electronic-mechanical micropositioning device of the measuring nano-probe of the scanning probe nanoscope with the specified reference point (mark 1)*

As can be seen from Fig. 7, after receiving the thermogram by an improved thermographic device, we have a clearer image of the object under study, whose spatial resolution (compared to the standard method of determination) is improved by 15 – 20%, and the spectral resolution by 0.3 – 0.5 μm. Examining the thermogram visualization (Fig.7), one can see a clear separation of the thermal effect on the piezochips (having a lower temperature) and the mechanical elements of the device (fixed higher temperature heating), which is not observed on the thermogram with Fig.6.

According to the results of thermal imaging diagnostics, the number of high-energy centers of temperature rise was determined. The number of such centers was automatically determined using a software algorithm implemented in the MatLab environment.

According to the results of the analysis of the processed image, the temperature scale of the thermogram was also adjusted, which, in turn, allowed to increase the accuracy of determining the temperature in each accurate image. Thus, the temperature distribution error determined by the authors of the algorithm article did not exceed 5.5%.

At the same time, the high spatial resolution of the proposed advanced thermographic method in the experiments made it possible to trace the evolution of the surface temperature field distribution in certain areas of the surface of individual elements of the MST device. This made it possible to analyze the temporal thermal characteristics and to determine the temperature gradients on the surface of the object under study.

3. Conclusion

It has been proved that the improvement of the thermographic imaging device by using the automatic scanning system as an opaque for infrared radiation of a matrix aperture with a window of size from 100 μm to 1 mm at the inlet of the lens of the imager, leads to the improvement of its spatial and temporal characteristics, namely accuracy and resolution.

Experimental studies have shown the high efficiency of using an advanced thermographic method to obtain a high-precision thermographic image of the investigated high-resolution MST devices.

It was found that the spatial resolution of the improved thermographic method (compared to the standard method of determination) was improved by 15 – 20%, and the spectral resolution by 0.3 – 0.5 μm. According to the results of the analysis of the processed image, the adjusted temperature scale of the thermogram, which, in turn, allowed to increase the accuracy of temperature determination in each accurate image (the temperature distribution error did not exceed 5.5%).

The data obtained can further be described by semi-empirical dependencies and used to describe the local and integral heat transfer characteristics between the elements of the MST devices.

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