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The use of contactless methods in the study of metallic stock surface temperature

***Abstract**. Maintaining a process in the appropriate temperature range is a basic requirement imposed by process engineers, especially in metallurgy. Commonly known temperature measurement methods use mercury thermometers, thermocouples, and resistance and vapour pressure thermometers. However, these methods have a major drawback, namely the inability to be used in situations where the temperature of an object being measured exceeds 1200 °C. These problems have been solved by the use of the contactless measurement method. Thermovision is not only a temperature measurement, but also the capability to detect potential threats that can lead to unplanned downtimes in production, as well as diagnostics being widely applied in various fields of industry and research. This paper presents the measurements of metallic charge temperature both under actual and laboratory conditions. The investigation described herein cover only a part of the possibilities offered by the use of the thermovision camera in industry.*

Streszczenie.** Utrzymanie procesu w odpowiednim zakresie temperaturowym jest podstawowym wymogiem stawianym przez technologów zwłaszcza w hutnictwie metali. Powszechnie znane są pomiary temperatury za pomocą termometrów rtęciowych, termoelementów, termometrów oporowych i manometrycznych. Jednakże metody te mają zasadniczą wadę, a mianowicie brak możliwości zastosowania ich w sytuacjach gdzie temperatura mierzonego obiektu przekracza 1200 °C. Problemy te rozwiązano stosując pomiary metodą bezstykową. Termowizja to nie tylko pomiar temperatury, to także możliwość wykrywania potencjalnych zagrożeń, które mogą doprowadzić do nieplanowanych przestojów w produkcji, to także diagnostyka w szerokim zastosowaniu w różnych dziedzinach przemysłowo-naukowych. W niniejszej pracy zostały przedstawione pomiary temperatury wsadu metalowego w warunkach rzeczywistych jak i pomiar w warunkach laboratoryjnych. Przedstawione badania to tylko fragment możliwości, jakie daje zastosowanie kamery termowizyjnej w przemyśle.* ***(Badanie temperatury powierzchni wsadu metalowego metodą bezstykową).

Keywords: contactless temperature measurement, metallic charge, thermovision.
Słowa kluczowe: bezstykowy pomiar temperatury, wsad metalowy, termowizja.

The background of contactless measurement methods

There are many temperature measurement methods differing in the operation principle, the measuring range and typical applications. Generally known and widely applied temperature measurement methods use mercury thermometers, thermocouples, and resistance and vapour pressure thermometers. All the above-mentioned instruments have, however, several drawbacks, namely [1]:

- they can only be used to determine the temperature within a narrow measuring range,
- the obtained signal cannot usually be used in technological process recording, control or automation systems, with the exception of thermocouples,
- an additional difficulty in conducting measurements with these types of sensors is the need for placing the instrument inside the heated body, which often poses great difficulties (an invasive measuring method).

Instruments that are free from these drawbacks are pyrometers and thermovision cameras, as used for contactless temperature measurement. These instruments measure temperature based on the temperature radiation emitted by the body or medium being examined, in the range of both visible radiation and part of infrared radiation.

Thermovision cameras and pyrometers have a number of advantages that qualify them to be included in a group of universal instruments. First of all, they do not introduce any interference in the measured temperature field and also can be used for an unlimitedly high temperature. They have low thermal inertia, high accuracy, and the signal obtained from these instruments is usually suited to operating with the systems of recording, control and automation of technological processes.

During thermovision temperature measurement, in addition to the radiation emitted by the object under examination, also radiation coming from the environment and the atmosphere gets into the camera, which interferes with the measurement. This situation is schematically illustrated in Figure 1, where the particular symbols have the following meaning: ε - emissivity of the examined object; τ - transmittance of the atmosphere; W_{refl}, W_{obj}, W_{atm} - fluxes of radiation emitted by the environment, the examined object and the atmosphere, respectively; T_{refl}, T_{obj}, T_{atm} - ambient temperature of the examined object and the atmosphere [2,3]. Thus, the total flux of infrared radiation which reaches the camera is described by the equation:

$$W_{tot} = \varepsilon \cdot \tau \cdot W_{obj} + (1-\varepsilon) \cdot \tau \cdot W_{ref} + (1-\tau) \cdot W_{atm} \quad (1)$$

In the infrared detector, the radiation flux W_{tot} is converted into voltage, which, after appropriate calibration, is recorded as a temperature map of the object under examination.

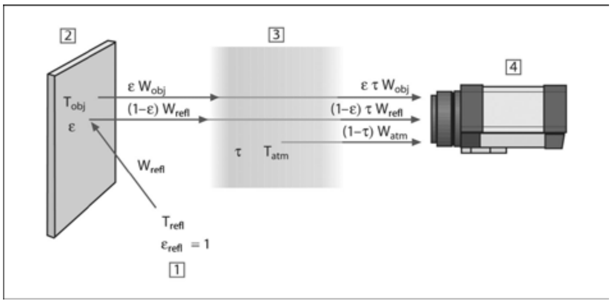

Fig. 1. Schematic of temperature measurement using the thermovision camera: 1 - environment, 2 - examined object, 3 - atmosphere, 4 - thermovision camera [2,3].

Obtaining the accurate results of temperature measurement using a thermovision camera requires compensation for the influence of radiations sources that interfere with the measurement. In most of modern cameras, the compensation for those interferences is performed automatically after data on the emissivity of the examined object, ambient temperature, distance from the examined object and the relative humidity of the atmosphere have been entered by the user.

In terms of history and technology, thermovision systems can be divided into the following categories [4]:

- optomechanical systems using point detectors - the first generation,
- linear thermovision scanners,
- systems using slot matrices - the second generation,
- systems cooled thermoelectrically (the Peltier effect), with a Sterling pump or liquid nitrogen,
- non-cooled systems - the third generation,
- stationary or portable systems,
- short-wave systems (operating in the wavelength range of 3µm-5µm),
- long-wave systems (operating in the wavelength range of 8µm-14µm),
- variable received wavelength range systems - the fourth generation.

The most important element of a thermovision camera is the detector, or a matrix of detectors, depending on the type of camera. The detector is the most technologically advanced part of the camera, which converts the energy of infrared radiation into another physical quantity, such as voltage, resistance variation, or an electric charge.

As has already been mentioned, cameras can be divided into short- and long-wave ones. This division is closely related to the type of detectors, and these, in turn, to the natural division of the atmosphere radiation pass band. For some wavelength ranges (1.2-1.3µm; 1.5-1.8µm; 2.1-2.5µm; 3.2-4.2µm; 4.4-5.9µm; 7.5-14µm), called "atmospheric windows", the transmittance of infrared radiation is relatively high (Fig. 2) [5,6].

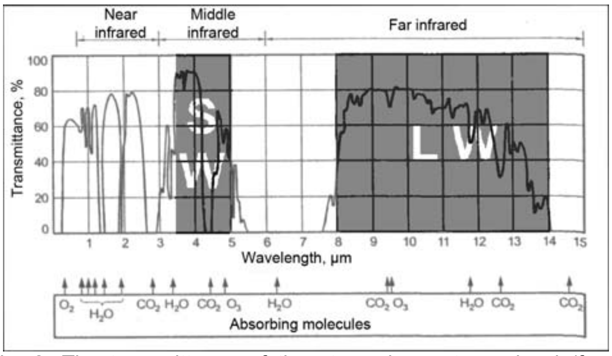

Fig. 2. The transmittance of the atmosphere at sea level (for a distance of 1 nautical mile) [6,7].

Thermovision measurements are used in all instances, where on the basis of the values and distribution of temperature on the surface of the examined object, its technical condition can be assessed. Such a measurement is done remotely and in a contactless manner. Therefore, it is safe and convenient. Thanks to such examinations it is possible to prevent any failures from occurring and to detect manufacturing defects.

Listed below are just some of the applications of the thermovision technique in industry. It should be noted that this is a relatively new field of research, which is constantly being developed and improved, so it can have new applications.

In the case of industrial power engineering, the thermovision is used when:

- testing the thermal insulation of the walls, ceilings and windows of buildings [3, 8, 9, 10]
- examining the thermal condition of working medium discharge channels [11, 12, 13, 14]
- examining the hotplate temperature distribution [15, 16]
- performing the diagnostics of electric equipment [11, 17, 18, 19]
- examining industrial hall walls, utility and heating boilers, and other thermal equipment [20, 21, 22]
- testing heat pipelines for technical condition [23]
- locating underground heating elements [24]

In the metallurgical industry and foundry engineering, the thermovision technique is used for all kinds of heat loss assessment, e.g. [25, 26]:

- assessment of the condition of furnace lining,
- determination of the temperature distribution on furnace shells,
- determination of the temperature distribution on the metal sheet surface in the manufacturing process,
- carrying out the diagnostics of industrial chimneys.

Temperature measurement by the contactless method

Testing methodology and scope

The investigation was divided into two stages. Preliminary tests were carried out under laboratory conditions for a square 25x25 mm-cross-section and 45 mm-high metal sample. The main element of the measuring stand was an electric furnace, as shown in Fig. 3.

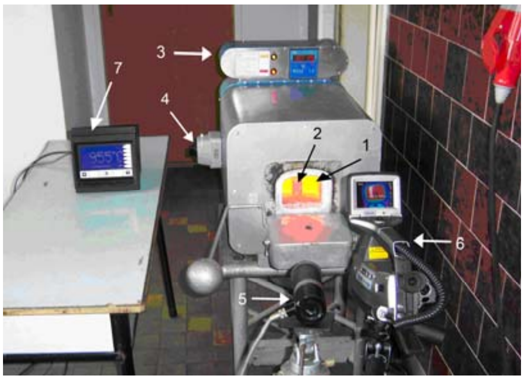

Fig. 3. View of the apparatus and the measuring stand on the furnace chamber side: 1 - chamber furnace, 2 - test sample, 3 - furnace program selector, 4 - furnace power switch, 5 - pyrometer head , 6 - thermovision camera, 7 - pyrometer.

After heating the electric furnace up to a temperature of 500 °C, the sample was placed in the furnace, then, after the sample temperature equalized with the furnace temperature, temperature measurements were started in the temperature range of 500 to 1000 °C with a step of 100 °C. The measurements were done using a ThermaCAM P65 thermovision camera supplied by FLIR Systems and a point pyrometer, model RAYSHHTCF1. Tables 1 and 2 list the measurement data and the equipment specifications.

Table 1. Measurement data.

Measuring distance	1.20m
Ambient temperature	25°C
Pyrometer accuracy	±5°C
Camera accuracy	±2°C
Emissivity (emission factor)	0.85 µm

Table 2. Technical specifications of the ThermaCAM P65 thermovision camera.

Detector type	Focal Plane Array (FPA), non-cooled microbolometric
Thermovision resolution	320 x 240 pixels
Detector operation band	7.5 - 13 µm
Temperature measurement range	-40°C to +2000°C
Measurement accuracy	± 2% of reading or ± 2 °C

Another series of measurements were carried out in real conditions in one of the Polish steelworks. The following measurements were done with the thermovision camera:

- the temperature of electric converter steel tapping,
- temperature of square billets on the continuous steel casting machine,

- the temperatures of slabs prior to rolling and plate after rolling.

The examination was conducted with a ThermaCAM P65 thermovision camera by FLIR Systems, at different production levels. The photographs taken with a Kodak V603 digital camera represent the examined objects. The measurements are presented in the order corresponding to the production cycle.

The condition for determining the surface temperature of the metal charge is to adopt the proper emissivity parameter. In the case of laboratory testing, it amounted to 0.85, while for the real measurements it was 0.65 for liquid steel and 0.8 for metal stock in the form of slabs and plates after rolling.

The conducted investigation and its results

Due to space limitations, the paper contains only selected examples of thermograms from the measurements carried out.

Laboratory testing

Measurement no. 1 - Furnace temperature indication: 1005 °C.

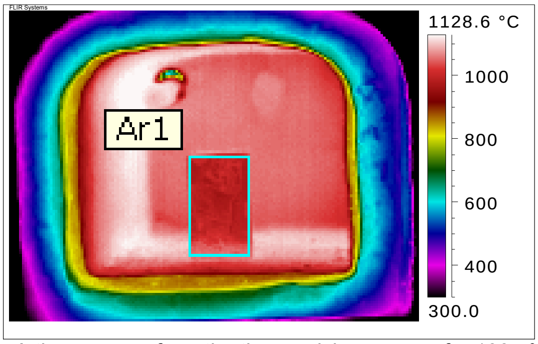

Fig. 4. A thermogram from the thermovision camera for 1005 °C.

Table 3. A summary of measurement data from figure 4 .

Object Parameter	**Value**
Emissivity	0.85
Object Distance	1.2 m
Label	**Value**
Ar1: Max	1068.9 °C
Ar1: Min	955.5 °C
Ar1: Average	996.4 °C
Pyrometer indication	990 °C

Examination on an industrial facility - Steelworks

Measurement no. 2 - Steel tapping

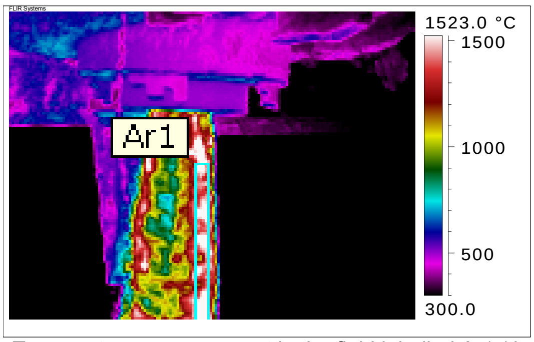

Fig. 5. Temperature measurement in the field labelled Ar1 (the area with the highest temperature).

Table 4. A summary of measurement data from figure 5 .

Object Parameter	**Value**
Emissivity	0.60
Object Distance	10.0 m
Label	**Value**
Ar1: Max	1812.5 °C
Ar1: Average	1459.4 °C

Measurement no. 3 - Measurement of the strip in the zone of water-cooled stretching and straightening rolls

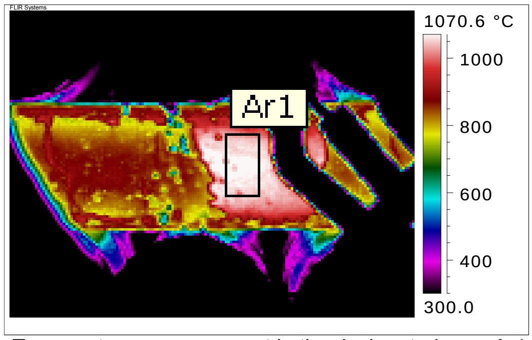

Fig. 6. Temperature measurement in the designated area Ar1.

Table 5. A summary of measurement data from figure 6 .

Object Parameter	**Value**
Emissivity	0.80
Object Distance	1.5 m
Label	**Value**
Ar1: Max	1081.9 °C
Ar1: Min	992.8 °C
Ar1: Average	1055.3 °C

Measurement no. 4 - Temperature measurement on the roller table; the upper part and the lateral part after cutting are examined.

The photograph is a close-up view of the measurement area shown in the thermogram (the blue square).

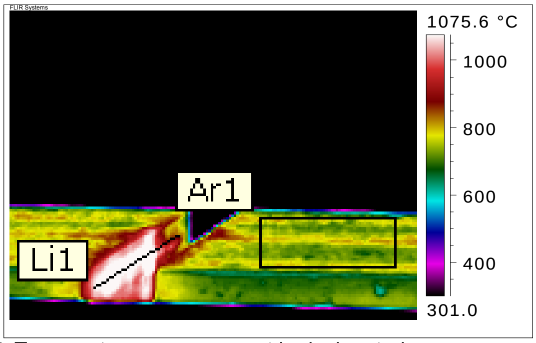

Fig. 7. Temperature measurement in designated areas.
Ar1- the upper surface of the metal billet, and LI1- the line along the cutting surface section

Table 6. A summary of measurement data from figure 7 .

Object Parameter	**Value**
Emissivity	0.80
Object Distance	5.0 m
Label	**Value**
Li1: Max	1134.0 °C
Li1: Min	818.1 °C
Li1: Max - Min	315.8 °C
Ar1: Max	816.8 °C
Ar1: Min	671.8 °C
Ar1: Average	744.0 °C

Examination on the industrial facility - Plate Rolling Mill

Measurement no. 5 **-** Temperature measurement through the pusher furnace loading window. The photograph shows a close-up view of the area visible in the thermogram.

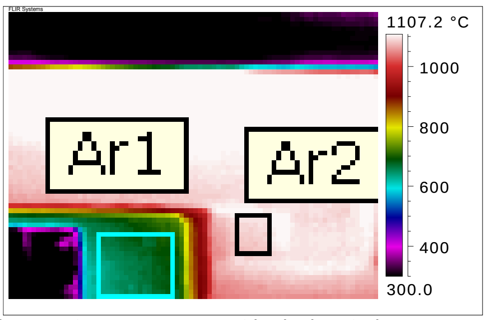

Fig. 8. Temperature measurement in designated areas.
Ar1- billet entering the furnace, and Ar2 - billet located in the central part of the furnace

Table 7. A summary of measurement data from figure 8 .

Object Parameter	Value
Emissivity	0.80
Object Distance	10.0 m
Label	**Value**
Ar1: Max	706.3 °C
Ar1: Max - Min	79.8 °C
Ar1: Average	666.9 °C
Ar2: Max	1111.2 °C
Ar2: Max - Min	37.8 °C
Ar2: Average	1087.3 °C

Measurement no. 6 - Billet in the heating (pusher) furnace. Examination done through the (revision) window in the side furnace part.

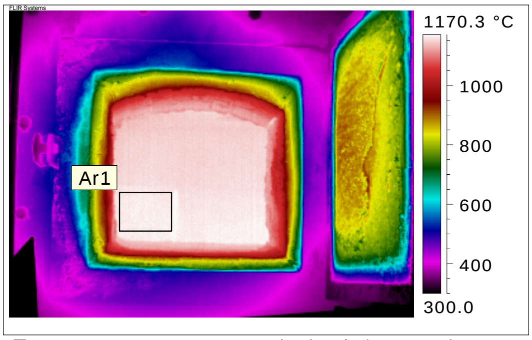

Fig. 9. Temperature measurement in the Ar1 area - the contours of a heated-up billet slightly visible.

Table 8. A summary of measurement data from figure 9 .

Object Parameter	Value
Emissivity	0.80
Object Distance	3.0 m
Label	**Value**
Ar1: Max	1170.8 °C
Ar1: Min	1151.9 °C
Ar1: Max - Min	18.9 °C
Ar1: Average	1161.9 °C

Measurement no. 7 - Metal stock leaving the heating chamber; the measurement done through the unloading window.

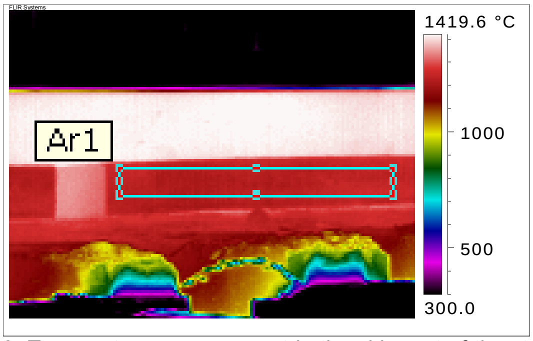

Fig. 10. Temperature measurement in the side part of the stock in the area Ar1.

Table 9. A summary of measurement data from figure 10 .

Object Parameter	Value
Emissivity	0.80
Object Distance	10.0 m
Label	**Value**
Ar1: Max	1263.6 °C
Ar1: Min	1200.4 °C
Ar1: Max - Min	63.3 °C
Ar1: Average	1227.9 °C

Measurement no. 8 - Temperature measurement of metal stock leaving the pusher furnace.

The closing lock of the unloading window and the examined stock on the roller table immediately after leaving the furnace are visible in the photograph.

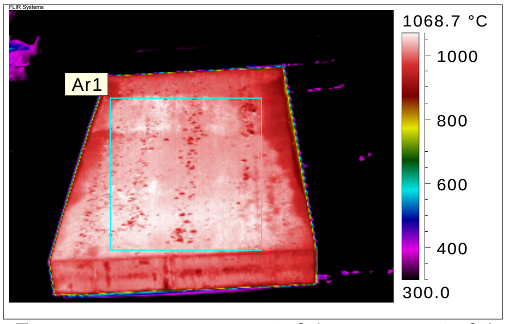

Fig. 11. Temperature measurement of the upper part of the metal stock , the area Ar1.

Table 10. A summary of measurement data from figure 11.

Object Parameter	Value
Emissivity	0.80
Object Distance	4.0 m
Label	**Value**
Ar1: Max	1084.1 °C
Ar1: Min	878.9 °C
Ar1: Max - Min	205.2 °C
Ar1: Average	1031.5 °C

Measurement no. 9 - Temperature measurement of the stock before descaling.

The photograph shows the same stock from the side perspective.

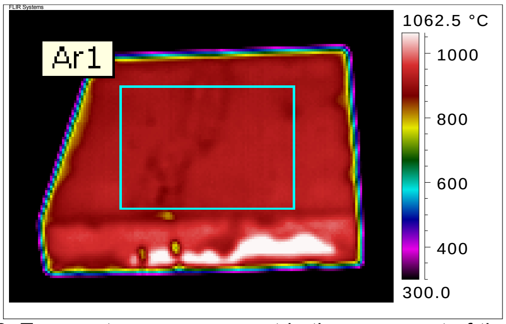

Fig. 12. Temperature measurement in the upper part of the stock, in the area Ar1.

Table 11. A summary of measurement data from figure 12.

Object Parameter	Value
Emissivity	0.80
Object Distance	10.0 m
Label	**Value**
Ar1: Max	942.6 °C
Ar1: Min	866.9 °C
Ar1: Max - Min	75.7 °C
Ar1: Average	913.0 °C

Measurement no. 10 - Temperature measurement on the stock surface immediately after descaling.

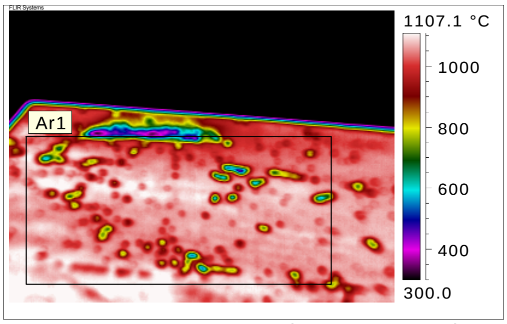

Fig. 13. Temperature measurement of the upper part of the stock.

Table 4. A summary of measurement data from figure 13.

Object Parameter	Value
Emissivity	0.80
Object Distance	3.0 m
Label	**Value**
Ar1: Max	1135.9 °C
Ar1: Min	390.8 °C
Ar1: Max - Min	745.1 °C
Ar1: Average	1017.0 °C

In all examinations, the ThermaCAM program was used for the analysis of thermograms. The results obtained using the pyrometer are contained in within the minimum and maximum range of the thermovision camera (Table 3). The obtained temperature difference between the pyrometer reading and the average value from the thermovision camera is 6.4 ºC. The reporter that allowed results to be obtained in the appropriate format in the form of tables with the average values of temperature in selected areas on the examined objects.

Table 13 summarizes all measurements made within the scope of the present study.

Table 13. A summary of investigation results.

No.	Description of the conducted process	Average temp. [°C]	Place of examination
1	A sample heated in the electric furnace	996.4	Laboratory
2	Steel tapping	1459.4	Steelworks
3	Measurement of the strip in roll zone II	1055.3	Steelworks
4	Temperature on the roller table	744	Steelworks
5	Temperature measurement through the furnace loading window	1087.3	Plate Dept.
6	Examination done through the window in the side furnace part.	1161.9	Plate Dept.
7	Measurement done through the furnace unloading window	1227.9	Plate Dept.
8	Temperature measurement of stock leaving the pusher furnace	1031.5	Plate Dept.
9	Temperature of stock before descaling.	913	Plate Dept.
10	Temperature of stock after descaling.	1017	Plate Dept.

The table shows that the highest temperature measured in the Steelmaking Department, which is1459 °C, was recorded during steel tapping, whereas in the Rolling Mill Department, the examined stock attained the highest temperature when being measured through the furnace unloading window. It amounted to1227.9 °C.

Summary

The investigation has shown that the use of the contactless method for measuring metal stock temperature allows any irregularities on the stock surface to be monitored and detected. This is true in particular to plastic working processes, including the rolling process, where it is essential to maintain the desired profile temperature. Any deviations lead to an uneven temperature distribution, which, as a consequence, will affect the quality of products and semi-finished products. Due to the high temperature of metallurgical processes, the temperature measurement under industrial conditions is difficult to accomplish. For this reason, the thermovision technique makes a prospective subject of research. The investigation carried out within this paper shows that the results of laboratory measurements made using a thermovision camera are close to the measurement results obtained from a pyrometer, which proves the correctness of the methodology adopted for the investigation.

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