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The Design Concept of the Laboratory Heater for Studying the Effect of Surface Topography to Emissivity

Abstract

Remote temperature sensing and thermal imaging systems [1, 2] are invaluable tools in various fields of science and technology. The fact that radiation is a function of object surface temperature makes it possible for remote temperature measurement systems to calculate this temperature. However, to measure temperature accurately with IR system, it is necessary to know emissivity. Emissivity is one of the major sources of error in radiometric measurements. Generally, emissivity is not constant as it depends on several parameters: temperature, viewing angle, wavelength, contamination or roughness. The article presents a laboratory heater which can be used to measure the thermal emissivity ε depending on the sample surface topography.

Keywords: temperature control, PID control, laboratory heater, emissivity, surface topography.

1. Introduction

Emissivity describes the object's ability to emit thermal radiation. Normally, object materials and surface treatments exhibit emissivity ranging from approximately 0.05 to 0.99. A highly polished surface falls below 0.1 while an oxidised or painted surface has much higher emissivity.

Generally, emissivity is not constant as it depends on several parameters: temperature, viewing angle, wavelength, contamination or roughness [3, 4, 5]. All total radiative properties of materials can only be regarded as a function of viewing angle and temperature. Spectral emissivity as a function of wavelength decreases for metals, increases for dielectrics and it is band - like for gases, liquids and same solids. A general characteristic, which is independent of the kind of material, is the variability of emissivity according to surface roughness. Emissivity increases with the increase of roughness. In particular the emissivity of metal, which is usually low, can considerably increase with roughness. Classification of emissivity models has been created under Fresnels's equation, Kirchhoff's low, Drude free electron theory (optically smooth surfaces) as well as applying bidirectional reflectance function (BRDF), geometric optics, and electromagnetic scattering theory (rough surfaces).

Before 1980 roughness analysis had been based on 2D measurements, which had given two-dimensional characteristics of the surface. During the last decades many scientists and constructors became convinced that the third dimension should be added to the analysis. At present, 3D analysis of the surface geometry is widely accepted [6,7]. Today, there are many methods for available for geometric and surface topography measurements: contact and non-contact, micro and nanoscale approaches.

Measurement based on light has many advantages as compared to traditional profilometers, like short measurement time with a vertical resolution close to the Atomic Force Microscopes (AFM). We have tested the application of white light interferometry for this purpose – optical surface profiler Veeco NT1100 and the sample images of the measured surface topography are shown in Figure 1.

The Veeco NT1100 is an optical profiler providing three-dimensional surface profile measurements without contact. It is able to work both in a vertical scanning mode and in a phase-shifting (PSI) mode, which is important to achieve maximum vertical measuring range and maximum resolution. The maximal horizontal resolution that can be achieved in both modes with a 50 times magnifying objective is 167 nm. In the PSI mode it is possible to reach a vertical resolution of 0.1 nm. The apparatus includes an automatic moving table which allows to measure surface mosaics as large as 100 × 100 mm.

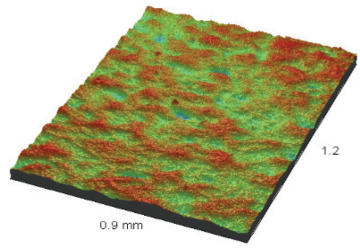

Fig. 1. The sample images of surface topography, measurement area 0.9×1.2 mm

2. The concept of a laboratory heater

The concept of a heater laboratory device (Fig. 2) used for measuring the coefficient of thermal emissivity ε depending on the surface roughness of the sample is shown in Figures 2 – 4. The purpose of the device is to heat the metal samples of different surface topography to a certain temperature and then the observation using thermal imaging camera takes place. By keeping the temperature constant in the time unit, it can be possible to determine the correlation between emissivity ε and the roughness of the surface of the sample.

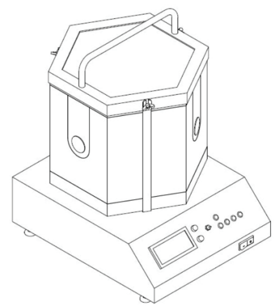

Fig. 2. The general view of the concept of a laboratory heater

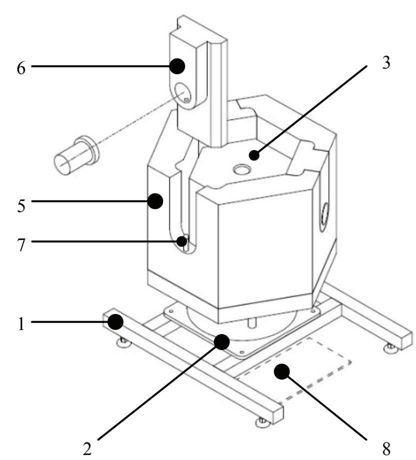

Fig. 3. The view of the most important elements of the device

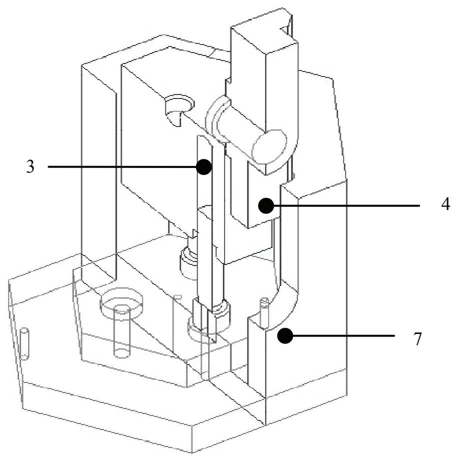

Fig. 4. The cross-section view of a heating element

In Figure 3 and Figure 4 the view of the most important elements of the device is shown. The presented device consists of the following components: framework – 1, rotary base – 2, accumulation core – 3, patron heater – 4, cover of thermal insulating – 5, insert for fixing the sample – 6, temperature sensors – 7, controller – 8.

The thermal insulation shielding of the accumulation core jointly with the heater is mounted to a rotary base. The use of a movable body allows you to change the position of each sample, relative to the observer without the need to replace them during the test. Three cylindrical metal samples may be fixed into the heater, with the use of inserts which can ensure easy exchange. The shape of the inserts and the cover of thermal insulating eliminate thermal bridges. The accumulation core is made of aluminum alloy PA6. Its task is to hold constant heat even if the heaters are stopped, thus eliminating the temperature oscillations on the surface of the samples. A laboratory heater is intended for operation in the temperature range to 250°C. The thermal insulation and inserts are made of a material having overall heat transfer coefficient U = 0.14 W/m^{2}K. In order to reduce heat transfer to the outer of the device, the accumulation core and the cover of thermal insulation are separated by an air-gap. The inner side of the cover is coated the reflective lining.

3. The control of the heater

The purpose of the controller is to control the supply voltage of the heaters in order to hold the constant desired temperature which is defined by the user. Information about the status of the unit, the heating power and the temperature of the samples are displayed on the LCD.

The control system of the laboratory heater can be divided into the following parts (Fig. 5):

- power supply,
- temperature measuring system with sensors PT1000,
- microcontroller system,
- device interface,
- the power control system.

The control system uses a microcontroller ATmega 16 ATMEL [8]. The high-performance, low-power Atmel 8-bit AVR RISC-based microcontroller combines 16KB of programmable flash memory, 1KB SRAM, 512B EEPROM, an 8-channel 10-bit A/D converter, and a JTAG interface for on chip debugging. The device supports throughput of 16 MIPS at 16 MHz and operates between 4.5 – 5.5 volts.

To ensure maximum usability of the ADC microcontroller, sensor PT1000 was connected in a Wheatstone bridge (Fig. 6) whereby by appropriate selection of the resistors, it is possible to set start point of the measurement range. To ensure maximum usability of the ADC microcontroller, sensor PT1000 was connected in a Wheatstone bridge [9], whereby by appropriate selection of the resistors, it is possible to set start point of the measurement range. The analog signal is amplified by operational amplifiers.

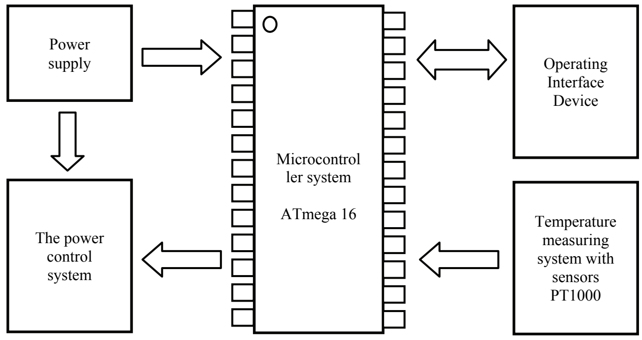

Fig. 5. The diagram of the laboratory heater control

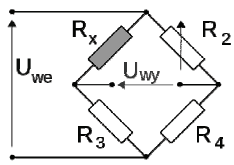

Fig. 6. Wheatstone bridge [9]

Known characteristics of PT1000 sensor and the characteristics of output voltage depend on the input resistance (which was determined experimentally). It allows the development of system calibration software. The uncertainty of the measured temperature is ± 0.1°C. A sensor placed inside the accumulation core allows you to monitor the current temperature inside the heater. A sensor placed inside the accumulation core allows you to monitor the current temperature inside the heater, which allows to implement PID regulator inside the program the microcontroller. The simplest form of PID regulator is the relationship:

$$ster = K_p \cdot X_b + \left[\frac{X_p + X_b}{T_i} + T_d \cdot \left(X_b + X_p \right) \right], \qquad (1)$$

where:

K_p – gain,
T_i – integration time,
T_d – derivation time,
X_b – the control deviation at time t,
X_p – the control deviation at time t–1.

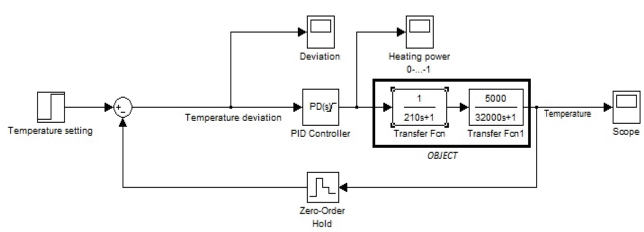

Fig. 7. Model of simulation - in Matlab Simulink

To choose the correct coefficients of PID the regulator requires the knowledge of the characteristics of the controlled object. For this purpose, before the stage controller programming, the temperature dependence as a function of time $T=f(t)$ was determined. Based on these characteristics the transfer function of an object was calculated. To speed up the process of programming the microcontroller and matching the PID regulator, the control system model created in Matlab Simulink are presented in Fig. 7 by means of a number of simulations have been carried out properly selecting the controller parameters. Matlab Simulink is a block diagram environment for multidomain simulation and Model-Based Design. It supports simulation, automatic code generation, and continuous test and verification of embedded systems [10].

The theoretical graph of the temperature as a function of time for the set parameters of PID regulator is shown in Figure 8.

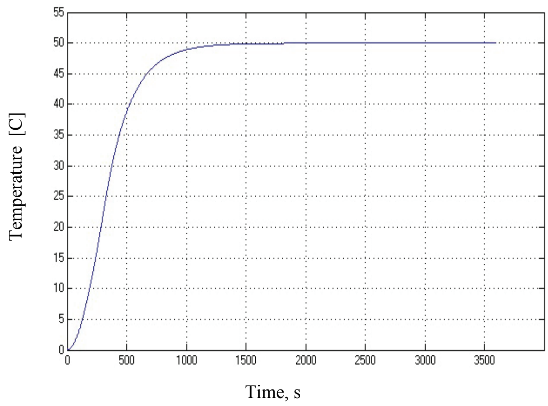

Fig. 8. The theoretical graph of the temperature for the set parameters of PID regulator

The output value of the PID controller implemented in the microcontroller represents the ratio of the PWM duty cycle and this is used to power heaters. Others PT1000 temperature sensors are placed into a sample. Information about the current temperature of each sample and the set temperature are displayed on the LCD. This device is also equipped with LEDs with the task to inform the user about reaching the set temperature for storage core and test samples.

4. The example of the experiment using a developed heater

The simple experiment was carried out using a constructed heater in order to validate his work. When the experiment was prepared and the nitrogen boride sample was heated to temperature from 50 to 250 °C in steps of 25 degrees. The sample was observed using the infrared camera FLIR T620 [11] (Fig. 9).

In order to determine the emissivity of the sample it was used as a reference the emissivity of tape , which is glued to the surface of the sample. The emissivity of the tape was assumed: $\varepsilon = 0.96$.

The emissivity was determined according following algorithm [2]:

- Stick on the object's surface a piece of material (sticker) of high and accurately known emissivity (e.g. ε = 0.95) and of good thermal conductivity, or paint of it with special paint of known and high emissivity.
- Heat up the object to a temperature at least 50°C higher than the ambient temperature.
- Set up the camera spot point on the part of object with sticker (or previously painted).
- Set on the camera the know emissivity of the sticker (or the paint) and measured earlier values of atmospheric temperature, the ambient temperature, the camera-to-object distance and atmospheric humidity.
- Read to spot point temperature of the area of know emissivity.
- Move to spot point outside the area of known emissivity.
- Change the parameter of the object emissivity, in the camera and read the spot point temperature until the same as the clean of known emissivity.

The similarly algorithm is also presented [12, 13]. The obtained results are presented in Table 1. The uncertainty of the emissivity was determined by the method presented in [14, 15] and the relative uncertainty did not exceed 7%.

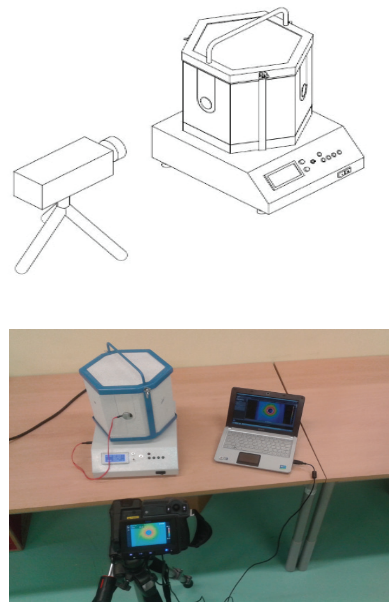

Fig. 9. The setup of the experiment

Figure 10 shows a sample thermogram in which we can see the temperature on the test surface without the tape and with the tape.

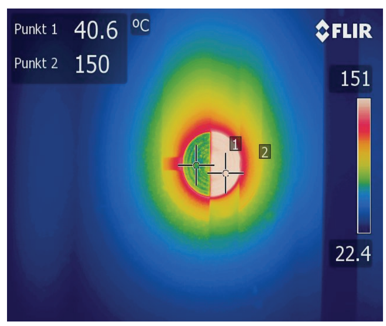

Fig. 10. The example of a thermogram

Tab. 1. The results of the experiment

Set temperature, °C	Temperature Measured, °C		
	Core temperature PT1000	Thermal Camera FLIR T620 (Tape ε = 0,95)	Determined emissivity ε
50	48.0	49.0	0.44
75	75.0	75.0	0.38
100	101.0	100.5	0.38
125	126.0	125.5	0.38
150	150.0	149.5	0.37
175	175.0	175.5	0.36
200	205.0	202.5	0.35
225	228.0	226.5	0.36
250	261.0	256.0	0.35

5. Conclusions

The concept of a heater laboratory device used for measuring the coefficient of thermal emissivity ε depending on the surface roughness of the sample was presented. The simple design of the device and the developed control set enable to test the samples under reproducible conditions. It was one of the objectives of the project.

To measure the temperature accurately with IR system, it is necessary to know emissivity. Emissivity is one of the major sources of error in radiometric measurements. Generally, emissivity is not constant as it depends on several parameters: temperature, viewing angle, wavelength, contamination or roughness. Emissivity increases with the increase of surface roughness.

The next investigations will be performed in order to choose the specific roughness and surface topography parameters which define the correlation between surface topography and its emissivity.

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