INFLUENCE OF THE OBJECT'S EMISSIVITY ON THE ACCURACY OF INFRARED TEMPERATURE MEASUREMENT

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Abstract: *This paper aims to explain importance of emissivity in non-contact measurement. The significance and methods of contactless temperature measurement, as well as the physics of non-contact measurement, are presented. Non-contact temperature measurement method is based on the laws of radiation. The temperature value that will be measured by this method depends on the temperature and the emissivity of the object. To understand the importance of emissivity for accurate temperature measurement, first of all the term of emissivity is explained more closely. Furthermore, the parts of the laboratory equipment, which was used to experimentally determine the influence of the object's emissivity on the accuracy of temperature measurement, are explained. The body with known emissivity was heated and its temperature was measured using an infrared sensor. In order to predict impact of emissivity of body on accuracy of temperature measurement emissivity was varied from 0.7 to 1.0 by the software. Six body's temperature points were used for analysis. The measured temperature values are shown, as well as the deviations of the measured temperature from the actual body temperature. The graphical representation is given for a better understanding of the measurement error caused by used wrong value of body emissivity.*
Key words: *non-contact temperature measurement, emissivity, black body laws, infrared sensor*

1. INTRODUCTION

Temperature measurement has a great importance in everyday life as well as in industry, medicine, military and many other fields. It can be determined only indirectly by measuring changes of other states. Temperature measurement methods can be grouped into two major categories: contact and non-contact. "In contact measurements, the temperature measuring instrument is brought into direct contact with the object or medium whose temperature has to be measured."[1] Anybody whose temperature is above the absolute zero radiates energy in a certain spectrum of electromagnetic waves. The operation of the temperature measuring device without direct contact is based on radiation laws. These devices measure the amount of energy that is emitted from an object whose temperature we want to determine.

[1] SELECTION OF THE MOST EFFICIENT TEMPERATURE MEASURMENT METHOD BASED ON DESIRED RESPONSE TIME AND EXPERIMENTAL RESULTS (Laban, Rudonja, and Gojak)

There are several reasons why non-contact temperature measurement is important. Infrared thermometers enable easier measurement of moving parts and they enable temperature measuring from a distance. The temperature of machines can be detected while they're in operation, without need to estimate whether it is safe to work on a machine. There is no risk of contamination and no mechanical effect on the surface of the object. Also, sometimes object whose temperature is measured have very high temperature, which makes contact methods impossible or dangerous.

2. NON-CONTACT TEMPERATURE MEASUREMENT METHODS

The most common infrared thermometer types are spot infrared thermometers, infrared scanning systems and infrared thermal imaging.
Spot infrared pyrometer measures the temperature at a spot on a surface (a relatively small area determined by the Distance: Spot ratio). Usually a visible red dot is projected on the centre of the object whose temperature is being measured.
Infrared scanning systems scan a larger area using an infrared imaging camera.
Infrared thermal imaging cameras are infrared radiation thermometers that measure the temperature at many points over a relatively large area. They generate a two-dimensional image - thermogram, where each pixel representing a temperature.

3. PHYSICS OF MEASUREMENT

3.1. Black body radiation

In the heat transfer by radiation, the term black body is introduced, which represents idealized physical body. A black body has the following characteristics[2]:

- It is an ideal emitter, it emits as much or more thermal radiative energy than any other body at the same temperature;
- It is an ideal absorber, it absorbs all incident radiation that reaches its surface, regardless of wavelength and direction;
- It is a diffuse emitter, the energy is radiated isotropically, independent of direction;

3.2. Stefan–boltzmann law

The Stefan–Boltzmann law describes the energy radiated from a black body in terms of its temperature. Stefan–Boltzmann law states that the total energy radiated across all wavelengths, per unit surface area of the black body, is proportional to the fourth power of the black body's thermodynamic temperature *T*.

$$\dot{E}_b = \sigma \cdot T^4 \quad \left[\frac{W}{m^2}\right] \tag{1}$$

where $\sigma = 5{,}67 \cdot 10^{-8} \quad \left[\frac{W}{m^2 K^4}\right]$ is *Stefan–Boltzmann* constant

[2] Cengel Yunus Heat transfer

When the apparent temperature [3] is calculated, the sensor is detecting the amount of energy emitted from the body, as well as the energy that is reflected from the surface of the body. When the body reflects energy from a source of radiation with a higher temperature, the apparent temperature that is being read will be greater than the actual temperature. In the opposite case, if the body reflects energy from another source of radiation of lower temperature, the apparent temperature will be lower than the actual one.
In contactless temperature measurement it is very important to determine the sensor detection area[4] as well as the central point of the object whose temperature is measured. The detection area must not include the environment around object whose temperature is measured.

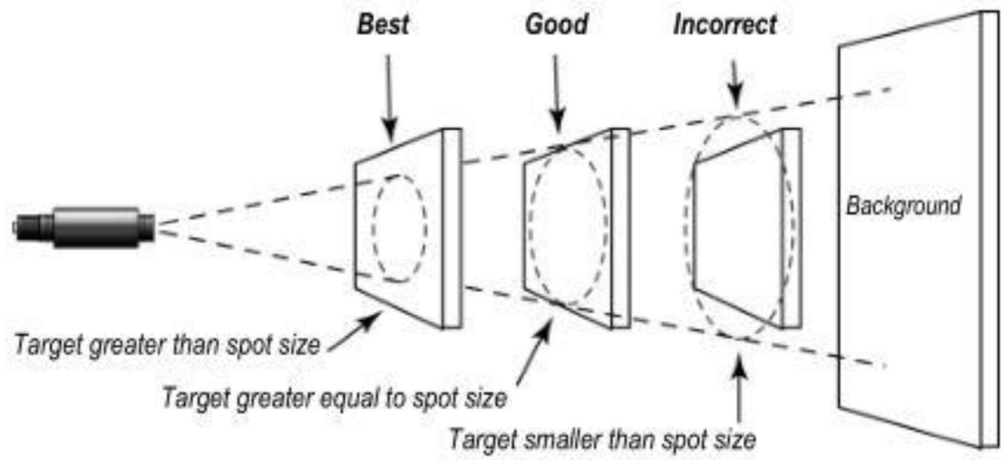

Figure 1: Proper sensor placement

The environment's temperature is called background temperature. This is temperature of the objects facing the surface whose temperature has to be measured. If the observed opaque surface has an emissivity of 0.95, then it reflects 0.05 radiation energy from environment. Some infrared thermometers have settings that include background impact (background temperature). The amount of ambient radiation depends on background temperature and background emissivity. As the background temperature is lower, it is more problematic for precise measurement.

4. EMISSIVITY

Real bodies radiate less energy than a black body at the same temperature. Emissivity determinates how much radiation object emits compared to a black body at the same temperature (the ratio of the energy radiated from the real body to the energy radiated from a black body at the same temperature):

$$\varepsilon = \frac{\dot{E}(T)}{\dot{E}_b(T)} \qquad (2)$$

Spectral emissivity of the real body is:

[3]Temperature that infrared thermometer reads, doesn't have to be same as actual temperature
[4] The spot size (field of view) is usually defined as the radius of 90% to 95% of the radiation energy.

$$\varepsilon_\lambda = \frac{\dot{E}_\lambda(T,\lambda)}{\dot{E}_{\lambda,b}(T,\lambda)} \quad (3)$$

The emissivity of a surface depends on the material, nature of the surface, temperature of the surface, wavelength and angle. It is a dimensionless number between 0 and 1. An ideal black body would have emissivity ε = 1. In reality there is no ideal black body.
If the spectral emissivity of the body depends only on the temperature, not wavelength, the observed body is called the grey body. At the same temperature and for the entire spectrum of radiation, the grey body radiates less energy than black body. It means that emissivity of gray body is constant for whole range of wavelengths, i.e. $\varepsilon = f(T)$, for the known temperature $\varepsilon = \text{const}$.

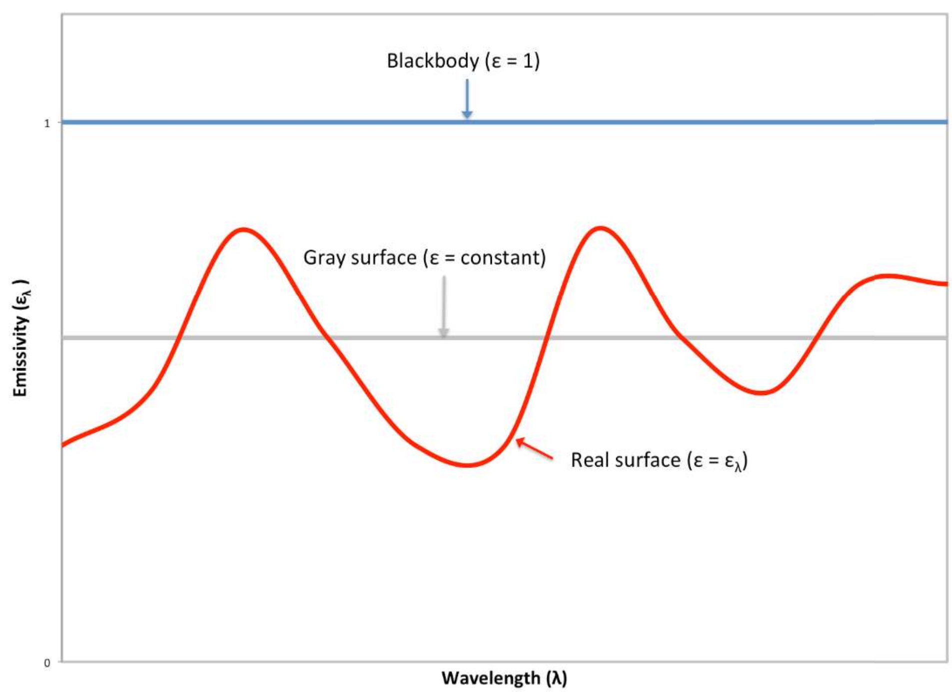

Figure 2: Comparison of the radiation energy of the real, grey and black body

The surface energy flow, or the energy radiated from the unit surface of the grey body at the given temperature *T*:

$$\dot{E}_b = \varepsilon \dot{E}_{b,\lambda} \quad (4)$$

$$\dot{E}_b = \varepsilon \sigma T^4 \left[\frac{W}{m^2}\right] \quad (5)$$

5. LABORATORY EQUIPMENT

5.1. Source of thermal radiation

Figure 3: Source of thermal radiation

In experiment as a source of thermal radiation FLUKE Calibration 4180 Precision Infrared Calibrator was used. Its target has 152.4 mm diameter. Calibrator's nominal emissivity is 0.95. This black body operates in temperature range 35°C to 500°C. Time needed for stabilization is about 10 minutes.

Display accuracy is changed depending on temperature:

$\pm 0.35°C$ at $35°C$

$\pm 0.50°C$ at $100°C$

$\pm 0.70°C$ at $200°C$

5.2. Infrared sensor

For temperature measurment infrared sensor Raytek RAYTXSLTSF was used. Sensor has operating temperature range from -18°C to 500°C and it's spectral response is 8 to 14 μm. Object's emissivity is adjustable form 0.1 to 1.0 by the softwer of infrared sensor. Because of that, it is possible to adjust the sensor so that the temperature measurement is as precise as possible. For known emissivity of object infrared sensor has error of ± 1 % of reading or ± 1.4°C (2.5°F), whichever value is greater.

Figure 4: Infrared sensor

For accurate measurement of temperature by the infrared sensor it is important to calculate sensor spot size, i.e. diameter of the measurement area. There are more ways for accomplishing this. One of them is by using optical resolution given by the manufacturer. For this sensor optical resolution is 33 : 1. That gives proportion between Distance (D) to Target Spot Diameter (S) from whom spot size can be calculated:

$$D : S = 33 : 1 \quad (6)$$

Another way is using optical diagram, diagram for determining the target spot diameter, at given distance between the target object and infrered sensor, also given by the manufacturer (Fig. 5).

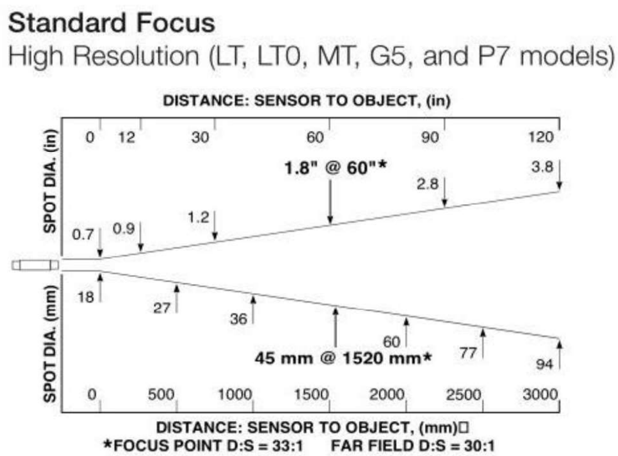

Figure 5: Optical diagram

5.3. Hart

The HART protocol allows the transmission of information. It is used to connect an infrared sensor and a computer. The transmission of information is bi-directional. It is possible to monitor the temperature change in time on the computer, but also the parameters can be changed in order to make the measurement of temperature as precise as possible. The figure 7 shows how it is connected in the installation.

5.4. Infrared sensor power supply

In order for the sensor to work, it is necessary to have a constant 24V supply. Figure 6 shows the device used for this purpose. The way infrared sensor power supply and HART adapter need to be connected is shown on scheme given by the manufacturer on Fig. 7.

Figure 6: Infrared sensor power supply

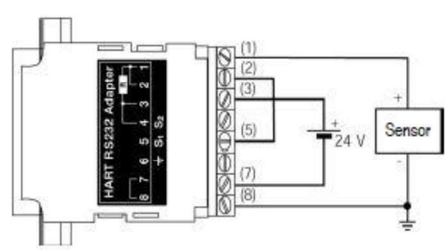

Figure 7: HART adapter and infrared power supply

6. MEASUREMENT PROCEDURE

The main goal was to show the impact of emissivity of body on accuracy of temperature measurement. The installation used for this purpose consists of a source of radiation, an infrared sensor and equipment that should enable the proper operation of the sensors and the reading of data. This equipment includes: 24V constant power, HART adapter and computer with installed software.
Body whose temperature was measured is a source of radiation (FLUKE Calibrator). Body's emissivity was known, its value was 0.95. The body was heated and its temperature was measured using an infrared sensor. Measured temperature values were in the range of 50-300°C with a step of 50°C, giving six points for analysis.
In order to predict impact of emissivity of body on accuracy, body's emissivity was varied from 0.7 to 1.0 in sensor setup by the software for each of the six selected temperature points.
The objectives of this measurement are to determine how much the temperature that the infrared sensor displays deviates from the actual temperature of the body when emissivity setup doesn't match object real emissivity. By measuring six different temperatures, the influence of temperature increase on emissivity is included.
In this experiment, the largest radius of the detection area that infrared sensor had was 9 cm, while the radius of the black body's is 15 cm. The whole procedure was performed three times, first at a distance of one meter, then at two and finally at three meters. Distance is very important because when it changes also changes the sensor detection area (spot size).
From the distance sensor's spot size was calculated by using expression (6):

Table 1: Sensor's spot size

Measuring distance [m]	Spot size [cm]
1	3
2	6
3	9

2. RESULTS AND DISCUSION

Table 2: Temperatures measured with different emissivity

	Temperature [°C]					
Emissivity	50	100	150	200	250	300
0.7	57.10	119.60	181.27	241.97	303.00	365.07
0.8	53.73	110.53	166.90	222.77	278.83	335.33
0.9	51.03	103.03	155.30	207.63	259.27	311.63
1	48.87	96.93	145.63	194.67	243.07	292.03

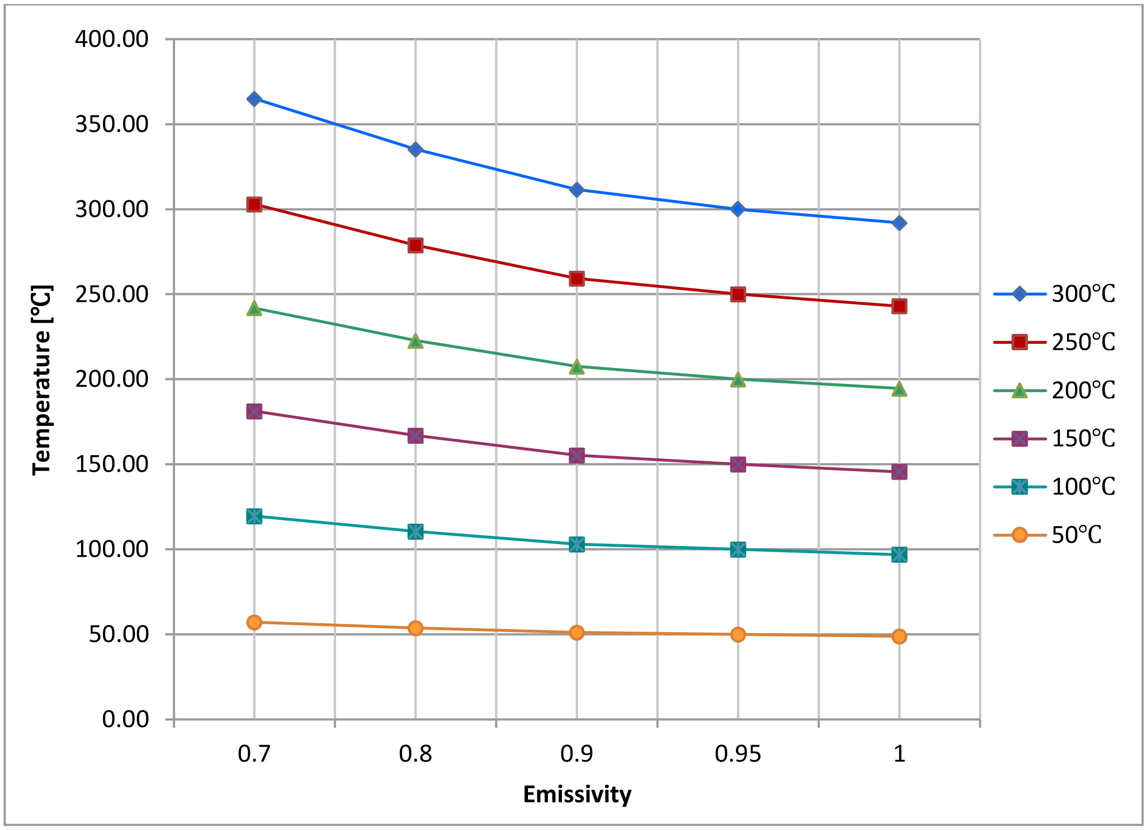

Figure 8: Dependence of the body's measured temperature on change of emissivity

Table 3: Temperature difference from measured to real temperature

	ΔT - temperature difference [°C]					
Emissivity	50	100	150	200	250	300
0.7	7.1	19.6	31.3	42.0	53.0	65.1
0.8	3.7	10.5	16.9	22.8	28.8	35.3
0.9	1.0	3.0	5.3	7.6	9.3	11.6
1	1.1	3.1	4.4	5.3	6.9	8.0

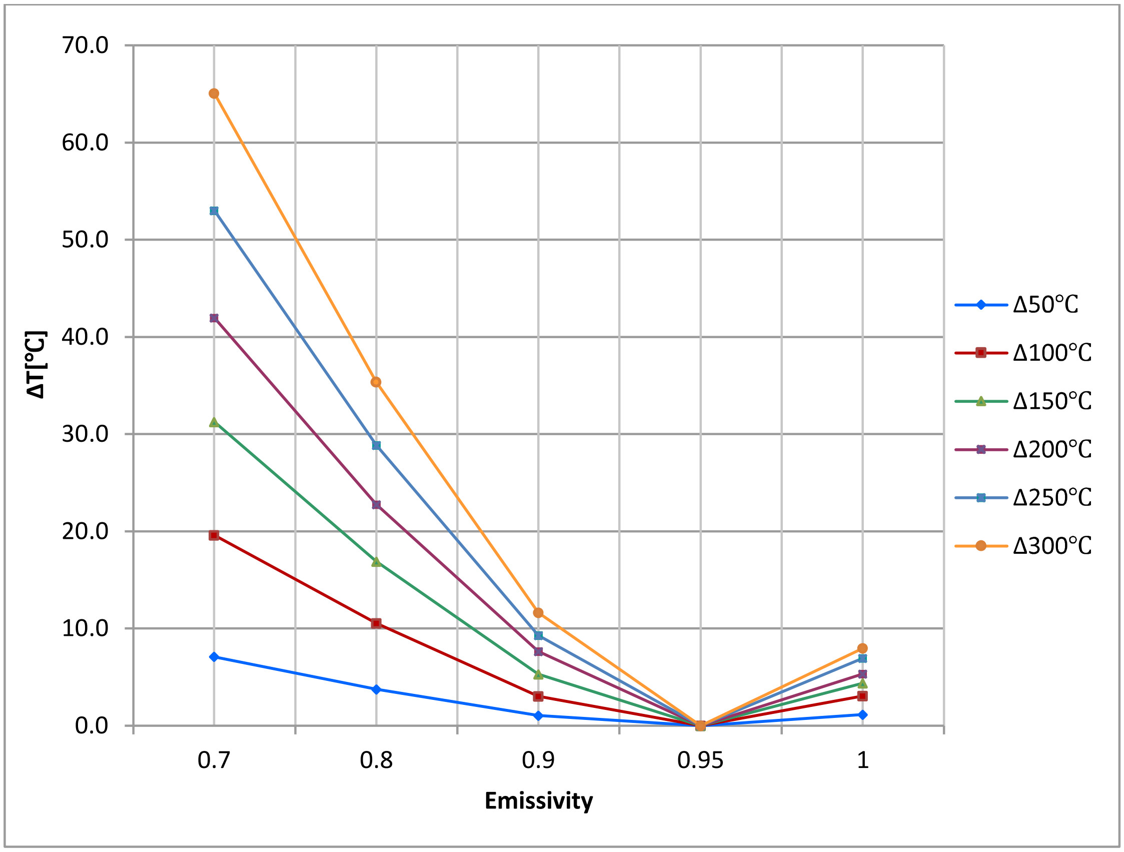

Figure 9: Deviation of the measured temperature from the actual temperature

Analyzing the values of the body's temperature, measured by the infrared sensor, it can be noticed that the emissivity has a great influence on the accuracy and precision of the measurement. With the rising difference in emissivity between infrared sensor setup and real emissivity of the object, error in measuring temperature kept growing (Figure 8). The mentioned temperature difference indicates the importance of the emissivity setting when temperature is measured with non-contact measurement. It is necessary that the emissivity of the object and the infrared sensor setup coincide, otherwise the measurement is not correct.

With increasing temperature, incorrect emissivity values have more influence at the accuracy of the measurement, which can be seen at all three measuring distances. When comparing the measured temperatures presented in the tables, it can be concluded that with temperature increase incorrect object's emissivity value of the infrared sensor results in a larger error (Figure 9). By adjusting the object's emissivity in infrared sensor setup to 0.7 instead of 0.95, at every 50C°, the temperature reading error increases by about + 11°C. On the other hand when the emissivity is set to 1 the temperature reading error increases by + 1.3°C at every 50 °C.

Since the emissivity of an object affects how much energy object emits, emissivity also affects sensor's temperature calculation. The infrared sensor can't determine the emissivity of the object, therefore it can't calculate object's actual temperature. Infrared sensors read the apparent temperature of the object, which is a function of the emissivity and temperature of the object.

If two objects of equal temperatures are observed, one with high emissivity, other with low, regardless that they have actual temperature equal, the infrared sensor will display different values of apparent temperatures. This happens because the object which has lower emissivity radiates less energy, and therefore the infrared sensor will read it's apparent as lower than the temperature of body with higher emissivity.

On the other hand, if two objects with same emissivity were observed, but different temperatures, a higher apparent temperature would have object with a higher actual temperature. By non-contact temperature measurement, the actual body temperature can be determined only when the emissivity of the body is known.

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