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The use of infrared radiation in measurement and non-destructive testing.

M. Hain, J. Bartl, V. Jacko

Institute of Measurement Science Slovak Academy of Sciences, Bratislava, Slovakia
e-mail: Miroslav.Hain@savba.sk

Abstract. *Infrared radiation is used in a passive or active way in several types of measuring and testing methods. Advantage of these methods is contactless measurement, usually very fast and without any destructive influence on tested/measured objects. In the contribution several infrared methods and their applications are described, among them infrared thermometry for contactless temperature measurement, infrared thermography for temperature fields measurement and visualisation and at last near infrared reflectography for non-destructive testing of works of art.*

Keywords: measurement, testing, contactless, temperature, near infrared, reflectography

1. Introduction

There is no principal difference between the infrared radiation and other electromagnetic waves like visible light, ultraviolet, X-rays or microwaves. They differ only in wavelength, the boundary between visible and infrared radiation is about 0.7 μm and boundary between infrared and microwave region is about 1000 μm. The whole infrared band can be further divided to three subregions - the near infrared region (0.7-2) μm, middle infrared (2-20) μm and far infrared region (20-1000) μm. As far as sources of infrared radiation (IR) are concerned, there are two principally different groups – thermal and quantum infrared sources. Thermal source of IR is every object with absolute temperature higher than 0 K by the assumption that it’s surface is not perfectly mirroring. Typical source of thermal infrared radiation is for example an incandescent lamp. Energy and spectrum of such thermal sources are determined by Planck’s law of radiation and depend on absolute temperature of the object. Measuring of emitted infrared radiation can be therefore used for determining of object’s temperature without any physical contact with the object. This can be utilised for temperature measurement of moving, distant or very hot bodies. Second group of infrared sources are quantum sources. Typical quantum source of IR is for example light emitting diode (LED) or laser. In spite of thermal sources emitted energy and spectrum of quantum sources doesn’t depend on object’s temperature and radiated energy cannot be used for contactless temperature measurement of the object. It is clear that in the case of infrared temperature measurements we have to take into account also the physical principle of IR generation. By infrared testing methods an object under test is irradiated with infrared radiation and changes in reflected or transmitted radiation are measured and evaluated. This can be utilised for revealing of hidden defects under surface of objects, testing and measurement of thermophysical properties and also for testing of works of art.

2. Physical principles of infrared thermometry and thermography

Object with absolute temperature $T>0$ continuously emits and absorbs electromagnetic energy – thermal radiation. For theoretical derivations it is useful to introduce a special emitting object so-called blackbody, which is absorbing all the energy incident on it. Equation for the theoretical description of the blackbody radiation was derived by Planck [2]:

$$L(\lambda,T) = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \tag{1}$$

where L(λ,T) is spectral radiance (energy emitted from the unit of blackbody surface area into unit solid angle per unit of time and per unit of wavelength), h is Planck's constant, λ is wavelength, k is Boltzmann's constant and c is speed of light in vacuum. Local maximum of spectral radiance depends on the temperature. The displacement of this maximum as a function of temperature is described by Wien's law, which can be derived from Eq.(1) by differentiating dL/d λ=0:

$$\lambda_{\max} = \frac{2898}{T}[\mu m] \tag{2}$$

For example an object at ambient temperature 293 K (20°C) has spectral radiance maximum at around $\lambda_{\max} \approx 10 \mu m$.

Total emittance M(T) – energy emitted by a blackbody to the whole hemisphere per unit time from unit area can be obtained by integrating (1) over hemisphere and over all wavelengths from λ=0 to λ=∞ :

$$M(T) = \sigma.T^4 \tag{3}$$

where $\sigma = 5.67 \,.10^{-8}$ $Wm^{-2}K^{-4}$ is Stefan-Boltzmann's constant.

Generally say, real bodies emit less radiation than a blackbody. The ratio of the real body emission to the emission of a blackbody with the same temperature is called emissivity ε [1], [2]. Its value is between 0 and 1.

3. Applications of infrared thermometry, thermography and developed instrumentation

For the contactless temperature measurement several infrared thermometers were developed in our department. One of the developed thermometers based on a blackened thermopile sensor and designed for industrial applications is on the Fig.1. Infrared thermometer has very fast response with time constant 32 ms, field of view 12°, standard temperature range is (0, 300) °C and resolution 0.1 °C. It has been utilised for example in the technology of aluminium foam production, hydrogen flame monitoring in the project LithoJet and other applications.

Fig.1 Infrared thermometer IRT 711

For high temperature fields measurement and visualization a silicon CCD camera based near infrared thermographic system with digitisation and PC evaluation was developed in our department. System has been radiometric calibrated, for dependence of CCD output signal on absolute temperature of object was derived equation [3]:

$$u = R_\lambda \tau_\lambda \varepsilon_\lambda . \frac{\pi s}{4N^2} . \frac{2hc^2(\lambda_2 - \lambda_1)}{\lambda_c^5} . e^{-\frac{hc}{\lambda_c kT}} \tag{4}$$

where R_λ is spectral responsivity of CCD camera in V/W, $\tau_\lambda = \tau_a . \tau_o . \tau_f$ is total transmittance of optical system (product of transmittance of atmosphere, objective and filter), ε_λ is spectral emissivity of object's surface, s is area of one CCD pixel, N is numerical aperture of the optics, h is Planck's constant, k is Boltzmann's constant, $\lambda_c = \frac{(\lambda_1 + \lambda_2)}{2}$ and λ_1, λ_2 are min. and max. wavelength of CCD spectral band sensitivity.

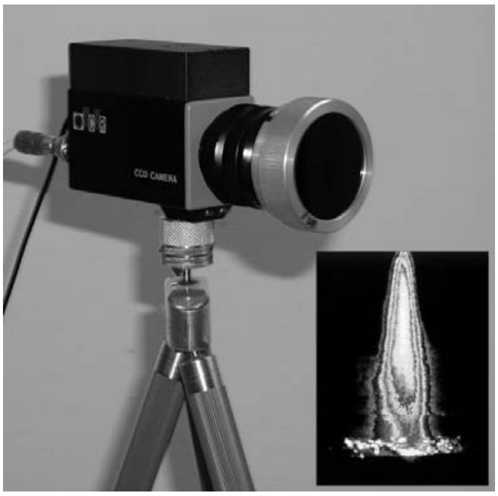

Fig. 2 Near infrared thermographic system

Developed near infrared thermographic system (see Fig.2) is sensitive in the wavelength band (0.8 – 1.1) µm, basic temperature range is (400, 1500) °C . Sensitivity in visible band of silicon CCD chip was cut off by glass filter Schott UG8. Large-scale measuring range was reached by special PC controlled electronic, which allows automatic change of integration time and video gain of the CCD chip. Temperature fields are visualised by means of pseudo-colorised isothermal images. System was used for several scientific and industrial applications like black body radiation uniformity testing, hydrogen flame monitoring (project Litho-Jet), testing of heating elements and other applications.

Even more applications in science, medicine and industry can be covered the middle infrared thermography. Typical band of sensitivity of the middle infrared thermographic system is either (8-12) µm or (3-5) µm. These are so-called atmospheric windows, which have minimal attenuation of infrared optical radiation passing through the atmosphere. We have been using commercial thermographic system NEC TH7102WX in several testing and measuring applications. This thermographic system has spectral range (8,14) µm, measuring temperature range (–20, 500) °C and is based on non-cooled micro-bolometric array. An example of thermography application is testing of thermo-physical properties of buildings (see Fig.3). By the assumption that the building is evenly heated only from the inside (no sun shine from outside), from the thermographic image data can be evaluated information about insulation properties of the building and hot spots show critical areas with bad insulation.

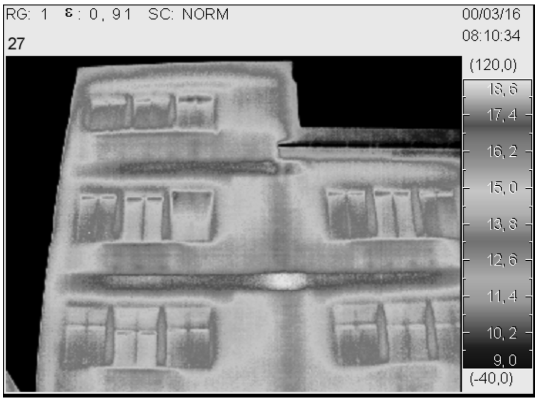

Fig.3 Thermographic image of a front side of a building

4. Near infrared reflectography

Non-destructive testing methods of cultural artefacts are very important tools for restorers and art-historians to get valuable information about works of art without causing any, even local damage of them. Near infrared reflectography is one of them and gives possibility to reveal overpainted pictures, underdrawings, hidden signatures and therefore this method provides information about early composition, development and present state of an artefact under test. It is quite clear that presence of an underdrawing and its relation to the final painting is very important characteristics of artist's technique and can help art-historians to distinguish for example an original picture from a copy. Taking into consideration the fact that the underdrawing is covered by other layers (pigments, varnish), it is obvious that a non-destructive method must be used to reveal the underdrawing without destroying the upper layers of the picture. This method is called infrared reflectography and utilises near infrared light in the band (0.8 – 2) μm. Method is based on the fact that varnish and pigment's layer of a painting absorbs and scatters near infrared radiation less than visible radiation. Near infrared radiation incident on a carbon-based underdrawing is strongly absorbed and therefore infrared light reflected from a picture contains information about presence of an underdrawing. For the reflectance R of a uniform layer of pigment with defined thickness x can be derived formula [4]:

$$R = \frac{1 - R_s\left(a - b \cdot \coth(bSx)\right)}{a - R_s + b \cdot \coth(bSx)} \tag{4}$$

where $a = \frac{S + K}{S}$, $b = \sqrt{a^2 - 1}$

and S is scattering coefficient of the pigment layer; K is absorption coefficient of the pigment layer and R_s is reflectance of the support layer
In the case, if under a pigment layer is a layer of underdrawing, similar equation can be derived:

$$R = \frac{1 - R_U\left(a - b \cdot \coth(bSx)\right)}{a - R_U + b \cdot \coth(bSx)} \tag{5}$$

where R_U is reflectance of the underdrawing.

From equations (4) and (5) follows that infrared light reflected from a picture carries information about the underdrawing. Optical contrast of underdrawing image will increase if

- thickness x of pigment layer decreases
- scattering and absorption coefficients S and K of pigment layer decreases
- difference between reflectance of support layer R_s and underdrawing R_u increases.

Basic configuration of an IR reflectographic system consists from a source of infrared radiation, camera, IR filter, frame-grabber and personal computer . Picture or other work of art under test is uniformly irradiated by source of IR radiation (tungsten lamp) and radiation reflected from picture is detected by near infrared camera coupled with frame-grabber and personal computer. Optimal sensitivity band of the camera for IR reflectography is up to wavelength around 2000 nm. NIR cameras are in most cases based on PbS, InGaAs or PtSi image sensors (CCD, CMOS or vidicon). Many pigments have absorption coefficient small enough also in the band (800 -1300) nm and therefore silicon CCD camera with 800 nm short-wavelength cut filter (Schott UG8) can be used. Filter is used to suppress sensitivity of detector in visible band. Advantage of such solution is besides the relatively low price also high spatial resolution of contemporary silicon CCD arrays (more than 7 millions of pixels). Signal from camera is digitised by frame-grabber and image is than digitally processed in personal computer and after that can be printed or presented on computer screen. Comparing to classical IR photography, the digital IR system has several advantages:

- real-time information about presence of underdrawing
- better quality of IR images due to digital image processing

- possibility to digitally compare infrared and visible images.

Fig. 4a Fragment of the picture under test, image in visible band

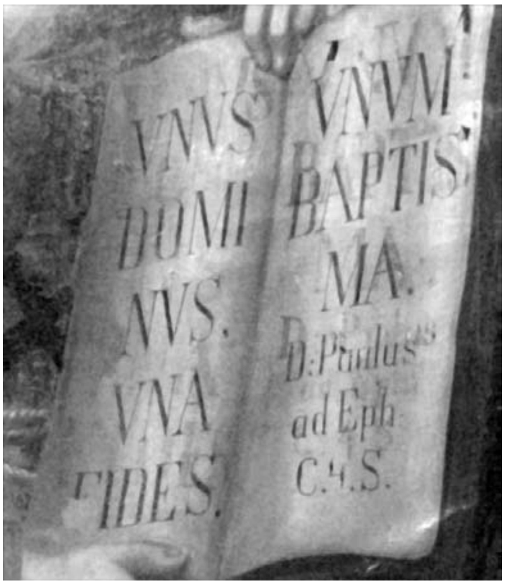

Fig. 4b The same fragment, image in near infrared band with clear visible second scripture under the upper layer

5. Discussion

Infrared measuring and testing methods are very powerful tools for many areas of science, industry, medicine, military and also for cultural heritage preservation. Last years new developments were done in the field of infrared instrumentation (high sensitive array detectors without cooling and high spatial resolution, digital signal processing) and it lead also to improvement and further dissemination of infrared measuring and testing methods in many application fields.

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