DETERMINATION OF BOUNDARY RADIANT HEAT FLUXES BETWEEN THE SURFACE OF A BUILDING CONSTRUCTION AND THE NIGHT SKY

Stanislav Šťastník, Jiří Vala, Radek Steuer

Brno University of Technology, Faculty of Civil Engineering, Veveří 331/95, 602 00 Brno, Czech Republic, e-mail addresses: Stastnik.S@fce.vutbr.cz , Vala.J@fce.vutbr.cz , Steuer.R@fce.vutbr.cz

Abstract:

All radiant heat fluxes between the exterior surfaces of building constructions and the night sky were neglected in the past. However, the application of modern materials and the increasing thermal insulation ability of advanced structures elevate the significance of such heat fluxes. The more precise evaluation of the reciprocal radiant heat transfer between the night atmosphere and the building surface requires knowledge of the spectral emissivity as a function of wavelength. The paper discusses both the quantitative determination of radiant heat fluxes and the measurement of the spectral emissivity of surfaces.

Keywords:

radiative heat transfer, emissivity, thermal emissive power, building physics

INTRODUCTION

Permanent increasing of thermal insulating requirements for external building structures has brought along the series of structural and material changes in their composition. Insulation of objects with help of external contact thermal insulating systems (ETICS) has become ordinary solution. Thus, not everyone realizes that surface layers of insulating system became its strongly loaded part. Great temperature and moisture load of external layers take place due to combination of both climatic effects and building physics' properties of structural layers of ETICS which directly influences the service life of the whole system.

Interaction of climatic effects with modern composition of insulating systems also cause predisposition of insulated facades to appearance of unsightly green incrustation on a façade's surface. Algae growth on a building surface with ETICS is enabled mostly by virtue of night under-cooling of surface layers under the temperature of the ambient air and consequent water vapour condensation on a façade's surface. The source of such periodic phenomena is radiation of thermal energy by the façade's surface. The detailed description of a given topic is comprised in the issues [6] and [7].

It is necessary to know boundary radiant heat fluxes between surface of a building structure and a night sky for more accurate calculation of thermal-moisture processes proceeding in surface layers of ETICS. Unfortunately, this issue has been considerably omitted within building industry so that this paper was created to fill the gap – it deals with measurements of radiative properties of surfaces leading to determination of radiant heat fluxes between surface of a building structure and a night atmosphere.

DASH OF THEORY – DEFINITION AF BASIC QUANTITIES OF RADIATION

As the physics of radiation does not belong to common disciplines of building engineering, the basic used quantities necessary for good orientation in the rest of the paper will be explained and defined in the following chapter. This chapter deals with radiation of real and so-called ideal black bodies and the quantities such as emissivity and spectral emissivity defining thermal radiation of surfaces of real materials. Let us assume that following equations and definitions are valid for bodies and their surfaces which do not transmit the given radiation and entire such radiation impacting on their surface is either reflected or absorbed.

Surfaces of all bodies with non-zero thermodynamic temperature including building surfaces radiate electromagnetic radiation. It has been described by famous Stephan-Boltzman Law; surface emissive power H [W.m-2] can be then expressed

$$H = \varepsilon \cdot \sigma \cdot T^4 \tag{1}$$

where σ is Stephan-Boltzman constant ($\sigma \approx 5{,}67.10^{-8}\ W.m^{-2}.K^{-4}$), T is temperature of radiating surface in Kelvins and ε *[-]* is its emissivity. Emissivity expresses ratio between emissive power H of the given real surface and radiation H_0 of a surface of perfect black body (with emissivity equal to one). It possesses value from 0 to 1 and it is in this form dependent of temperature of radiating surface. Emissivity of surface of a black body equals one.

Surface with such defined “half-space” emissivity, let us say 0.9, does not necessarily have in a perpendicular view intensity of radiation accurate 0.9 of intensity of radiation of black body with the same temperature. It may radiate slightly strongly in this direction. And, vice versa, if we observe it sideways, its radiance may be weaker [1]. In other words, intensity of radiation[1] $I\ [W.sr^{-1}.m^{-2}]$ of radiating surface alters with the angle α *[rad]* measured from normal to the given surface. And what is important: it may alter differently for surfaces made of various materials.

$$I = \frac{dH}{d\omega} = \frac{\varepsilon_\alpha \cdot H_0}{\pi} \tag{2}$$

Where ω *[sr]* is a spatial angle, α *[rad]* is an angle measured from a normal to the surface. Index α expresses emissivity only in a given direction. Then ε_α *[-]* is called directional emissivity. Intensity of radiation of the given surface I is dependent only on the angle α measured from normal. Directional emissivity is usually decreasing function of an angle α. Intensity of radiation of an ideal diffusive so-called “Lambert” surface may be expressed as following:

$$\varepsilon_\alpha \cong \varepsilon_n \cdot \cos\alpha \tag{3}$$

ε_n is directional emissivity in a normal direction to surface. For determination of dependency of directional emissivity of a specific material in a direction, it is possible to measure it approximately by means of infrared spectrometers with special adapter. In our case, however, we will assume that the above mentioned assumption is valid. Thus, we will not further deal with this dependency of emissivity in direction.

Bodies radiate electromagnetic radiation mostly in range of wavelength (4 to 50) micrometers – belonging to infrared range of spectrum[2] – under ordinary temperature conditions. Spectral radiation of perfect black surface with emissivity equal to one $H_{\lambda 0}\ [W.m^{-2}.m^{-1}]$ depending on

---

[1] Note. This paper unconventionally relates intensity of radiation onto surface element! (thus quantities $[W.sr^{-1}.m^{-2}]$) Therefore it is a somewhat local intensity of radiation which can be represented in case of homogeneous surface as intensity of radiation of 1 m^2 of area surface.

[2] Such a body radiation with ordinary temperature is used to be denoted as long-wave radiation and Sun radiation as short-wave radiation in technical literature.

wavelength has been described by Planck's relation for spectral distribution of radiation of a black surface:

$$H_{\lambda 0} = \frac{dI_0}{d\lambda} = \frac{8\pi hc^2}{\lambda^5 \exp\left(\frac{hc}{k\lambda T} - 1\right)}, \tag{4}$$

where: λ is wavelength of electromagnetic radiation *[m]*,
h Planck's constant *6,62618.10^{-34} J.s,*
c light velocity in vacuum *299 792 458 m.s^{-1}*,
k Boltzman constant *1,38066.10^{-23} J.K^{-1}*.

Index *0* at H_0 and $H_{\lambda 0}$ expresses that it means radiation of perfect black surface with emissivity equal to one.

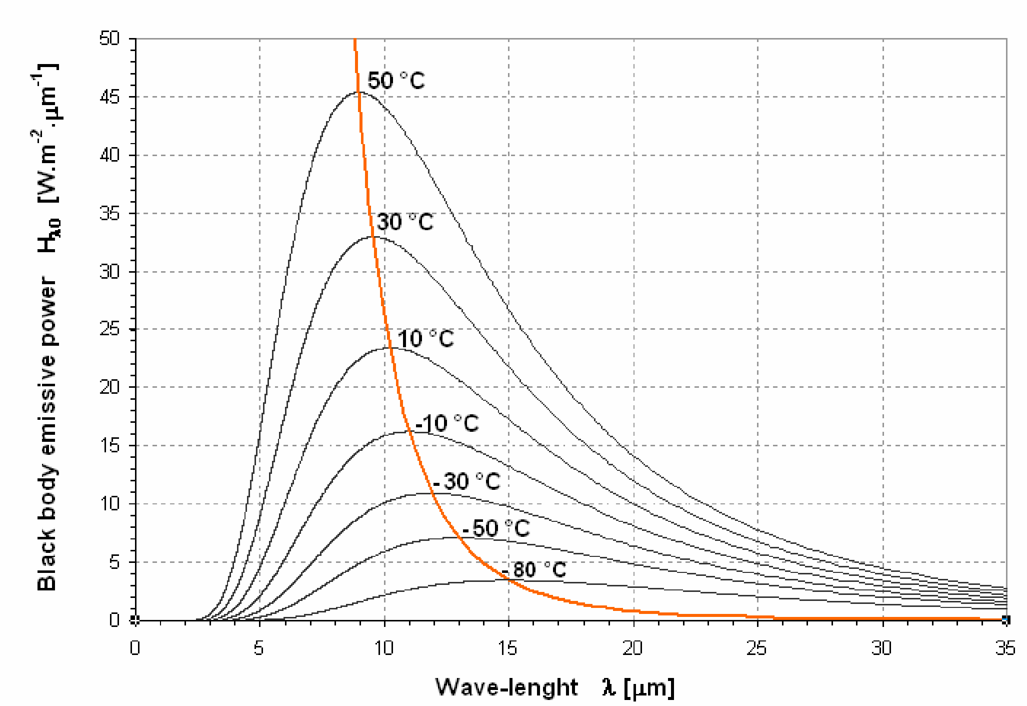

Figure 1: Curves of spectral radiation $H_{\lambda 0}$ of black surface depending on wavelength λ captured for various temperatures. Red line connects maxima of these curves.

To make things even more complicated, let us state that ratio between spectral radiation of real and black body with the same temperature in dependency on wavelength is not constant. We may consider this for accurate calculations of radiation among various surfaces using spectral emissivity ε_λ *[-]* which is the ratio between spectral radiation of the given specific surface and surface of a black body. Then, it holds true that spectral radiation of real body H_λ *[W.m^{-2}.m^{-1}]* is

$$H_\lambda = \frac{dH}{d\lambda} = \varepsilon_\lambda \cdot H_{\lambda 0} \tag{5}$$

In case, we would like to be more precise in the description of a surface of real body, we may use so-called directional spectral emissivity H_λ *[W.m^{-2}.m^{-1}]* for determination of spectral intensity of radiation I_λ *[W.m^{-2}.sr^{-1}.m^{-1}]*

$$I_\lambda = \frac{dI}{d\omega\, d\lambda} = \frac{\varepsilon_{\lambda\alpha} \cdot H_{\lambda 0}}{\pi} \tag{6}$$

For our purposes, we will use simplified assumption from equation (3) that spectral intensity of radiation corresponds to cosine law of radiation. Thus, we will assert that we only need to know for our purposes only spectral emissivity ε_λ.

Spectral emissivity ε_λ has in addition convenient property – it is not on principle dependent on temperature within small temperature range where microstructure of substance does not change. That is why, it is possible to use spectral emissivity measured e.g. at 20 °C for calculation of surface radiation of plasters in range of real temperatures approx. –10 °C up to +50 °C because we do not expect substantial changes in material microstructure of a plaster in this temperature range which would normally have significant effect to value of spectral emissivity.

Further important property of spectral emissivity is the fact that its value (and unit) is according to Kirchhoff's Laws equal to spectral absorption a_λ. Spectral absorption a_λ expresses relation between surface of absorbed compound of spectral radiation and overall spectral radiation impacting onto surface. This equivalence is often used for experimental determination of values of emissivity and spectral emissivity.

$$\varepsilon_\lambda = a_\lambda \tag{7}$$

If we wanted to determine emissivity ε for certain temperature[3] from realized dependency of spectral emissivity $\varepsilon_\lambda(\lambda)$ on wavelength as accurate as possible, we can use the fact that emissivity ε may be expressed also as a ratio of intensity of radiation of a given surface H to intensity of radiation of black body surface H_0:

$$\varepsilon = \frac{H}{H_0} = \frac{\int_0^\infty H_\lambda \, d\lambda}{\int_0^\infty H_{\lambda 0}\, d\lambda} = \frac{\int_0^\infty \varepsilon_\lambda(\lambda) \dfrac{8\pi hc^2}{\lambda^5 \exp\left(\dfrac{hc}{k\lambda T} - 1\right)} d\lambda}{\int_0^\infty \dfrac{8\pi hc^2}{\lambda^5 \exp\left(\dfrac{hc}{k\lambda T} - 1\right)} d\lambda} \tag{8}$$

SPECTRAL EMISSIVITY AND HEAT FLUXES

Energy leaks from bodies by radiation which may manifest as temperature drop of a body in practise. However, bodies usually do not radiate into an empty space but they radiate against surrounding surfaces mutually. They also can partially absorb electromagnetic radiation coming from other surfaces. When the body is completely surrounded with objects with similar emissivity and the same or only slightly different temperature (e.g. as bodies in some room), resulting heat flux among them in negligibly small. When bodies with significantly different temperatures radiate towards each other (e.g. external surfaces against night sky), the influence of difference of their mutual radiant heat fluxes causes implication of heat flux between the bodies.

For easier approach, let us study simply defined case of radiation of horizontal surface against night sky. This model case shows that such loss spectral heat flux from a building surface $q_{r\lambda}$ *[W.m$^-$*

[3] Note: General dependency ε_λ on temperature has been in the following equation neglected. Therefore, temperature for which ε_T is being determined, must fulfil conditions stated two paragraphs higher with respect to measured dependency $\varepsilon_\lambda(\lambda)$.

$^{2}.m^{-1}]$ is equal to spectral heat flux $q_{r\lambda em}$ radiated by a surface with deduction of absorbed compound of spectral heat flux by a surface coming onto a surface from night sky (atmosphere).

$$q_{r\lambda} = q_{r\lambda em} - q_{r\lambda abs} = \varepsilon_{\lambda} H_0 - \varepsilon_{\lambda} q_{r\lambda atm} \tag{9}$$

where: $q_{r\lambda}$ resulting loss spectral radiant heat flux leaving the surface of horizontal surface radiating against night sky $[W.m^{-2}.m^{-1}]$,

$q_{r\lambda em}$ spectral radiant heat flux emitted from a surface $[W.m^{-2}.m^{-1}]$,

$q_{r\lambda abs}$ spectral radiant heat flux from night sky absorbed by a surface $[W.m^{-2}.m^{-1}]$,

$q_{r\lambda atm}$ spectral radiant heat flux impacting on a given surface from night sky $[W.m^{-2}.m^{-1}]$.

If we want to express radiant heat flux q_r $[W.m^{-2}]$ from spectral radiant heat flux $q_{r\lambda}$ $[W.m^{-2}.m^{-1}]$, it is possible to simply integrate equation (8) along the wavelength

$$q_r = \int_0^{\infty} \varepsilon_{\lambda}(\lambda) \cdot \left(\mathrm{H}_{\lambda 0}(\lambda) - \mathrm{q}_{r\lambda atm}(\lambda)\right)\, d\lambda \tag{10}$$

As it is obvious from the above mentioned, it is convenient to carry out experimentally dependency of surface spectral emissivity ε_λ on wavelength for accurate determination of mutual radiant fluxes between night atmosphere and a building surface.

EXPERIMENTAL ASSESSMENT OF SPECTRAL EMISSIVITY

Infrared spectrometer can be used for experimental assessment of spectral emissivity ε_λ. Instead of former spectrometers based on a principle of disperse spectrophotometry, more accurate and faster FT-IR spectrometers based on a principle of Michaelson's wave interferometer and use of Fourier's transformation (which gives the explanation for letters FT in its name) are more often used at present. One such a modern device (Nicolet 380 from a producer Thermo Electron Corporation) is in the possession of Institute of Technology of Building Materials and Elements at Faculty of Civil Engineering, Brno University of Technology. The mentioned device works within the range of wavelengths 1.28 – 28.5 μm – which is relatively suitable range for assessment of spectral emissivity for purposes of above outlined calculations of radiation of building surfaces against night sky.

Necessary equipment for the measurement besides infrared spectrometer is also convenient measuring adapter. Adapters using reflex techniques for measurement resulting from the equation (7) – Kirchhoff's Law – may be used for measuring spectral emissivity. Adapters are adapted for measuring reflectivity of examined surface for a given radiation whereas we come out from our known relation that supplement to one to spectral reflectivity r_λ is equal to spectral absorption a_λ which is equal to spectral emissivity ε_λ from equation (7).

$$\varepsilon_{\lambda} = a_{\lambda} = 1 - r_{\lambda} \tag{11}$$

For the measurement of spectral reflection r_{λ}, two types of adapters can be used– either the adapter with integration sphere, types of which are suitable for accurate assessment of overall "half-space" spectral emissivity, or much cheaper adapter for diffusive reflection can be used; its integration mirror does not embrace all directions of the entire half-space around a testing sample but is seems sufficient due to its smooth surfaces. Description of function of individual adapters and discussion about their suitability for various measurements would apparently produce a separate issue. That is why we only briefly mention that we used adapter for diffusive reflection called PIKE EasiDiff[TM] lent free of charge by company NICOLET CZ.

RESULTS OF THE MEASUREMENT AND AN EXAMPLE OF THEIR PROCESSING

The following graph no. 2 shows an example of measured result of spectral reflectivity r_λ of a testing sample (silicate plaster modified by addition of additive slightly decreasing its emissivity). Displayed curves also document variance of measured values of one sample.

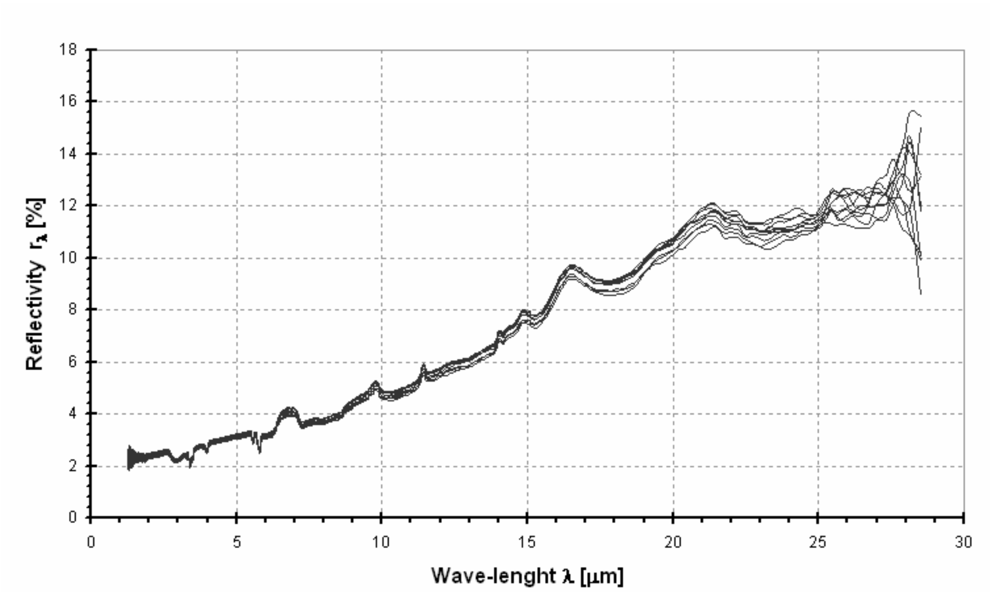

Figure 2: Spectral reflectivity r_λ *measured 10 times at 10 various spots of one testing sample*

The following graph no. 3 shows spectral emissivity ε_λ of the same testing sample obtained from graph no. 2 by means of the equation (11).

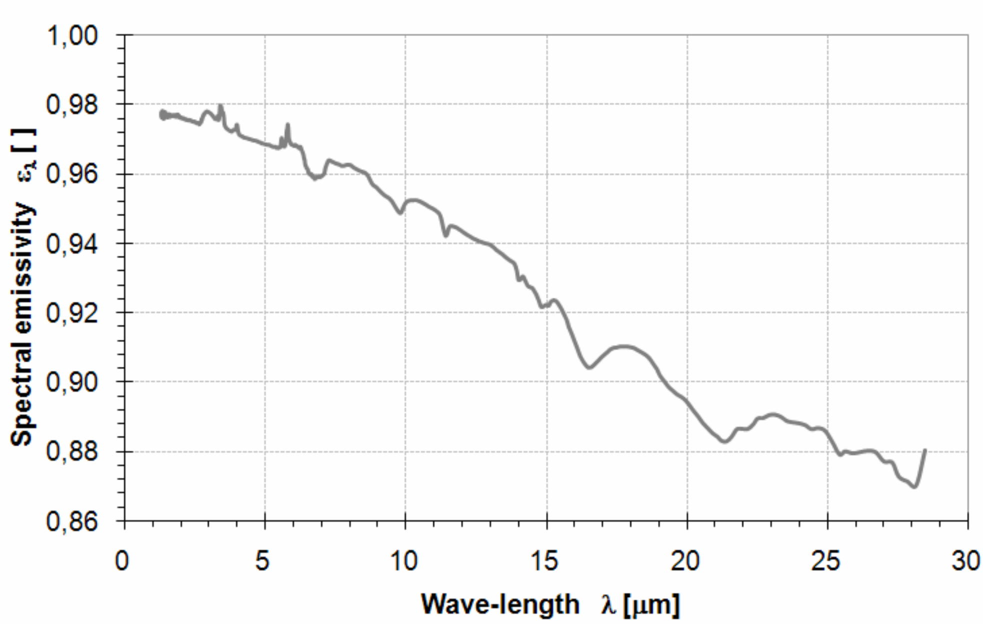

Figure 3: Spectral emissivity ε_λ *obtained as an average from measurement in graph no. 2 and evaluated from the equation (11).*

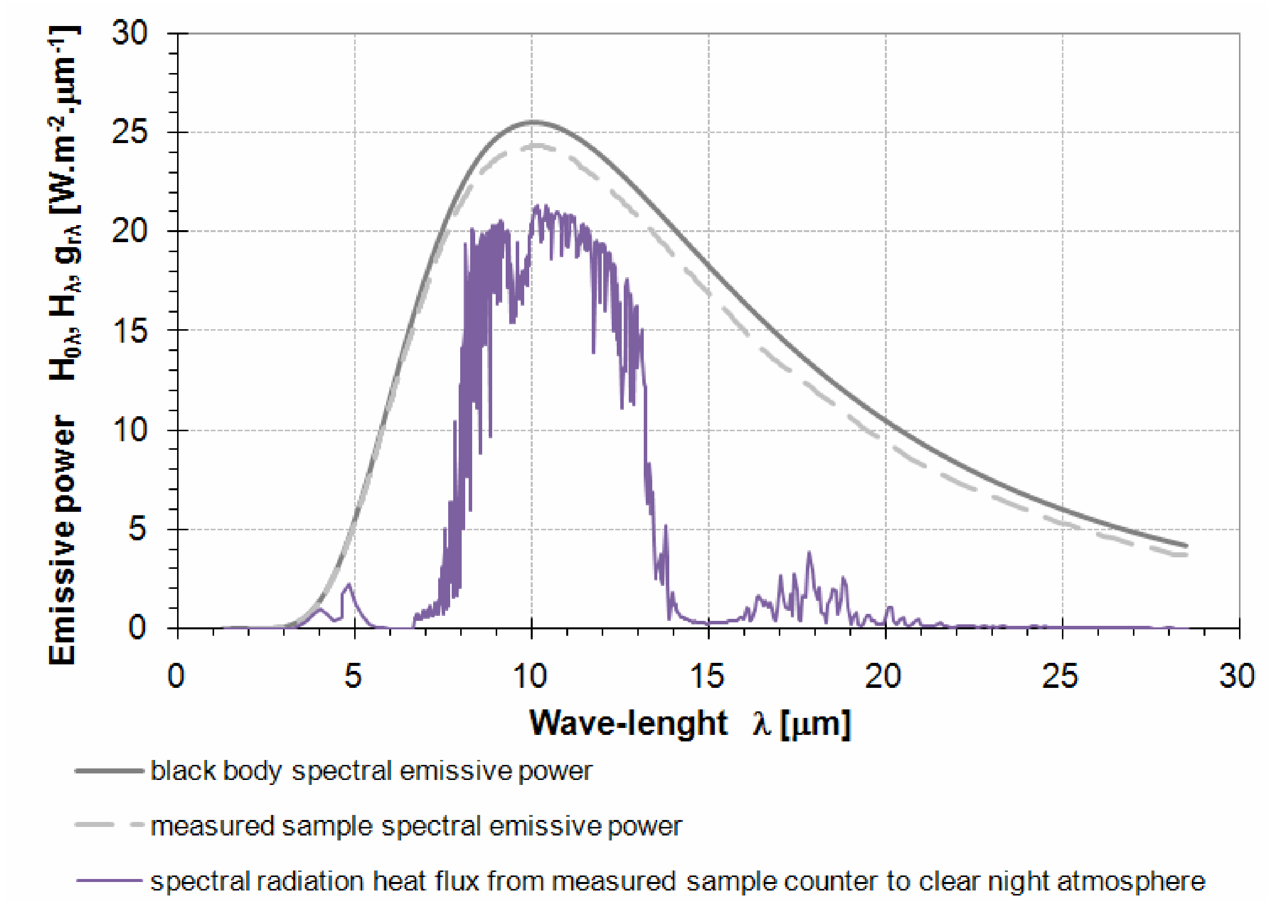

Figure 4: Calculated spectral radiation of black surface $H_{\lambda 0}$, *in comparison with spectral radiation of surface* H_λ *of measured sample and spectral radiant heat flux* $q_{r\lambda}$ *of sample surface oriented horizontally against clear night sky. All three curves of values of spectral surface radiation are calculated for temperature of radiating surface 15 °C.*

Graph no. 4 shows a black curve of spectral radiation $H_{\lambda 0}$ of perfect black body calculated from the equation (4). We can compare it with a red curve of spectral radiation H_λ of a measured sample obtained from the equation (5). The green curve represents resulting spectral radiant heat flux $q_{r\lambda}$ defined by means of the equation (9) for specific state of cloudless summer atmosphere. All three curves of values of spectral surface radiation displayed in the graph are calculated for temperature of a radiating surface 15 °C.

After integration of dependencies of spectral radiation (graph no. 4) over entire range of wavelengths 0 up to +∞ we obtain intensity of radiation of black surface at 15 °C $H_0 = 391\ W.m^{-2}$, intensity of radiation of measured sample surface $H = 364\ W.m^{-2}$ and radiant heat flux of horizontally oriented sample against clear sky $q_r = 105\ W.m^{-2}$.

Overall emissivity for a certain temperature can be determined in accordance with the equation (8) from measured dependency of spectral emissivity on wavelength $\varepsilon_\lambda(\lambda)$. If we wanted to calculate dependency of overall emissivity ε on temperature by means of the equation (8) for temperature interval fulfilling the conditions listed by the equation (8), we can do so – the result is displayed by curve in the graph no. 5. We will see that for small temperature ranges valid for most of building engineering calculations, it has no sense to complicate the calculation with assumption of emissivity being dependent on temperature $\varepsilon(T)$; the assumption for it being a constant value calculated for some average temperature will be also sufficient.

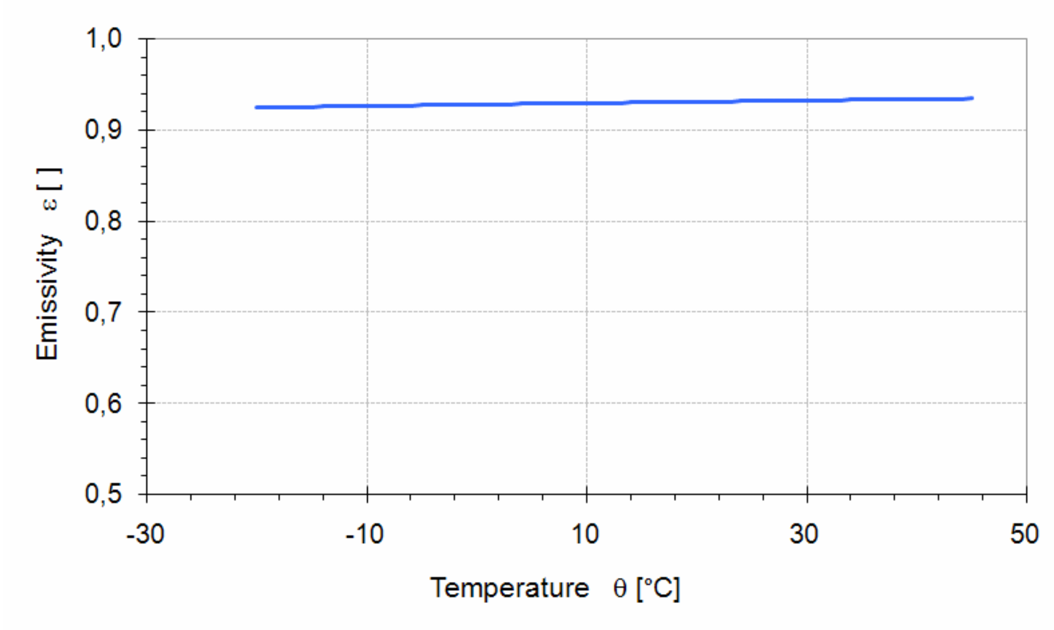

Figure 5: Overall emissivity ε of measured sample (the blue curve) depending on temperature. Calculated due to the equation (8), integrated numerically over the range of wavelengths for which spectral emissivity has been measured.

CONCLUSION

The paper indicates some possibilities of determining spectral emissivity of various surfaces. It can be important for more accurate determination of boundary radiant heat fluxes for some thermal-technical calculations, particularly for determination of radiant heat fluxes between surfaces of building structures and night sky.

This paper has been elaborated with support of grant GA ČR 103/05/H044 and research project No. 1M6840770001 within activities of the CIDEAS research centre. Measurements on the infrared spectrometer was realized by virtue of cooperation and free-of-charge lending of measuring adapter by company NICOLET CZ.

REFERENCES

[1] HOLLAN, J. Zářivé toky a emisivity v praxi. In *Proceedings of Juniorstav 2004*. Brno, VUT v Brně. 2004. ISBN 80-214-2560-1. available online as toky_emi.* in directory: http://astro.sci.muni.cz/pub/hollan/e_papers/prednasky

[2] ŠŤASTNÍK, S.; HOLLAN, J.; STEUER, R. Možnosti určení emisivity materiálů pomocí infračervené termografie. In *Proceedings of Non-Destructive Testing In Engineering Practice 2006*. Brno, VUT v Brně. 2006. p. 181 - 186. ISBN 80-7204-487-7. available online as omitky06.* in directory: http://amper.ped.muni.cz/jenik/LW-infrared

[3] website: Kirtland Air Force Base: http://www.kirtland.af.mil/afrl_vs/

[4] MODEST, M., F. *Radiative Heat Transfer*. 1sted. McGraw-Hill, Inc., 1993. ISBN 0-07-042675-9.

[5] Witt, M. H.: *Heat and Moisture in Building Envelopes*, TU Eindhoven, 2006.

[6] STEUER, R.; ŠŤASTNÍK, S. Růst řas na fasádách s vnějším kontaktním zateplením. In *Proceedings of Tepelná ochrana budov 2007*. Štrbské pleso, Slovakia, VKC Intenzíva s.r.o. 2007. p. 154 - 157. ISBN 978-80-969243-5-6.

[7] ŠŤASTNÍK, S.; BRADÁČ, O.; KMÍNOVÁ, H.; STEUER, R. Projev emisivity na povrchovou degradaci stavebních materiálů. In *Tepelná ochrana budov*. 2005. 2005(2). p. 15 - 16. ISSN 1213-0907.