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Use of infrared camera in energy diagnostics of the objects placed in open air space in particular at non-isothermal sky

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A B S T R A C T

The important task of the energy sector is to look for the ways of increasing energy efficiency of energy installations. This can be achieved by reducing heat losses. The thermovision technique is a very useful tool in this area. Owing to thermovision inspections it is possible to find the places with excessive heat losses as well as to determine them quantitatively. During the thermovision measurements it is necessary to know the temperature of the surroundings of considered object. A considerable group of energy installations are the objects placed in open air space. In such a case the surroundings constitute the ground and sky which are usually of different temperatures. During infrared inspections only one ambient temperature has to be entered into the camera system. The aim of this work was to develop a method for determination of equivalent ambient temperature representing thermally the surroundings of the object exposed to open air space. The use of long-wave infrared camera for sky temperature measurement has been proposed to carry out this task. Additionally, it has been proposed to use the aforementioned measurement results for the determination of total sky radiation temperature which is useful for radiative heat losses calculation.

1. Introduction

Thermovision examination of different contemporary objects (overhead pipelines, buildings, industrial installations, and others) is a very effective and modern tool used in the process of their energy evaluation. The infrared camera measurement results allow us to recognize the temperature distributions on outer surfaces of the considered objects or to find the places with excessive heat losses from examined objects as well as faults of thermal insulation [1,2]. Knowledge of the temperature distribution on the external surface is necessary for the calculation of heat losses from the considered objects into the environment. In the calculation procedure for the determination of the annual heat losses the method based on the concept of a one-off infrared camera measurement of the considered object can be applied [3]. Knowledge of the heat losses from the analysed objects is the basic element in the elaboration of energy audits or recommendations for improving the technical operation manners of these objects (pipelines, buildings, thermal installations, and others) in terms of energy or exergy efficiency [1–8].

The result of the temperature measurement by means of the infrared technique is influenced by many parameters, especially by emissivity of the examined surface, the temperature of the surrounding elements and others. The scale of this influence depends on reciprocal configurations of values of measurement parameters [9–13]. The principle of the infrared camera measurement is based on the determination of radiative heat flux emitted from the considered surfaces. In most cases the emissivity of the examined object is less than 100%, thus the total radiation heat flux coming from the tested surface consists of two parts. The first part presents the self-emission heat flux whereas the second part is the radiation flux which comes from surrounding elements and is reflected by the surface under consideration.

Generally, the surrounding of the objects exposed to open air space consists of two surfaces: hypothetical sky surface and ground surface [13,14]. Normally, the temperature values of these elements are different. Moreover, very often the celestial vault is not isothermal [15,16]. Thus, a problem arises with the proper determination of the ambient temperature for objects which are to be found in open air space. The aforementioned ambient temperature value should be entered into the measuring system of the IR camera during the thermovision inspection as well in the process of working out of the measurement results.

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Nomenclature

D	diameter, m
$\dot{e}_{\lambda}(\lambda, T)$	spectral density of black body self-emission (hemispherical spectral emissive power [17]) for temperature T, resulting from Planck's law, W/(μm m^2)
$\dot{e}$	density of black body emission (emissive power [17]) in spectral range $\lambda' \div \lambda''$ of infrared camera, W/m^2
$\dot{e}_S$	thermal sky emission within pyrgeometer spectral range irradiating unit horizontal surface, W/m^2
$\dot{e}_{tr}$	unit flux of thermal radiation within complete spectral range, W/m^2
F	area of surface, m^2
$\dot{h}$	unit radiosity of surface, W/m^2
N	number of spherical bands of celestial vault
r	reflectivity of surface
s_T	experimental standard deviation of temperature, K
T	temperature, K
$\overline{T}$	average value of temperature, K
T_{at}	temperature of atmospheric air, K
T_{cm}	sky temperature measured by infrared camera, K
$\overline{T}_{cm}$	average value of sky spherical band temperature measured by infrared camera, K
u	standard uncertainty of measurement, K, W/m^2
u_c	combined uncertainty, K, W/m^2
U	expanded uncertainty, W/m^2

Greek symbols

α	tilt angle—angle between zenith and normal direction of considered surface, °
σ	radiation constant, $5.67 \cdot 10^{-8}$ W/(m^2 K^4)
ε	emissivity of surface
Θ	zenith angle, ° or rad
λ	wave length of thermal radiation, μm
λ', λ''	spectral limits of infrared camera operation, μm
φ	configuration factor

Subscripts

at	atmospheric air
c	combined uncertainty
cm	infrared camera measurement
d	differential or local
D	statistical dispersion of measurement results
ec	equivalent parameters dealing with IR camera measurement
G	ground
i,j	i-th or j-th surface or element
p	pyrgeometer or its spectral range
S	sky

Abbreviations

CF, CFs	configuration factor, -s
FOV	horizontal angle of infrared camera view (Field Of View)
IR	infrared
LW	long-wave

A novel method for the determination of the equivalent temperature in the case of non-isothermal multi-element surroundings has been developed in the work. The main principle of this method is the conversion of multi-element and non-isothermal surroundings into one-element isothermal surroundings while at the same time keeping the thermal radiation influence of the ambient elements on the radiosity of the examined surface at a constant level. A method of radiosity and configuration factors [14,17–19] in a modified form has been employed in this operation. The modification consists in the formulation of radiosity balances for the spectral range, limited to the operational spectral range of the IR camera.

The sky temperature measured in the so-called “atmospheric window” by means of the LW IR camera is also useful for the calculation of total radiation flux emitted by the celestial vault. For the purpose of the above-mentioned flux calculation, it is necessary to add up radiation fluxes emitted within all active bands and windows which can be distinguished for the atmospheric air in full spectral range of its thermal radiation, i.e. $0 \div \infty$μm. Analysis of the Planck's law indicates that for temperature values typically occurring in the atmosphere, the thermal radiation of the atmospheric air for wavelength below 4 μm is negligibly small and can be omitted [14,20]. Thus, the heat exchange within the atmospheric window has a significant share in the total potential heat losses into the environment. Therefore, the knowledge of the sky temperature measured with the use of LW IR camera is very useful for the calculation of radiation heat losses from the considered object into the surroundings.

Due to a very strong influence of sunny radiation on the thermovision measurement results, it is reasonable that such measurements should be carried out during the nights [21–23]. In the case of clear sky, its temperature is relatively low and diversified whereas during cloudy nights this temperature is much higher and quite uniform along the zenithal angle [24,25]. During the day, the clouds attenuate sunny radiation but at nights they increase the intensity of sky thermal radiation [16]. During the nights, due to lack of sunny radiation, the sky emission is similar to isotropic model of radiation [26]. Further considerations comprising theoretical analyses and infrared measurements in open air space will deal only with fairly stable and symmetrical sky thermal conditions. The skies with irregular and moving clouds will not be considered.

The method of determining thermal radiation of the sky on the basis of infrared camera measurement results has been successfully verified [20]. In the process of verification of the proposed method, the results obtained with the use of the IR camera have been compared with the results obtained by means of the pyrgeometer. The verification results are quite satisfactory.

Summing up, the purpose of this work was to develop a functional thermovision measurement technology applicable in the energy evaluation of the objects and installations placed in multi-element and non-isothermal surroundings, in particular the objects exposed to open air space.

2. Description of the influence of the surrounding temperature on the results of the thermovision temperature measurement

2.1. Configuration factors

Elementary (differential) configuration factor deals with a relation between two differential area elements $\mathbf{d}F_1$ and $\mathbf{d}F_2$, Fig. 1, and is