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Selected interpretations of infrared thermal research for the needs of building industry

The introduction to the article includes a general interpretation of infrared display system. Thermal display of buildings will be analyzed in a comparative-qualitative approach.

Chapter II presents a detalied interpretation of the formulas applied at thermal research. chapter III quotes the kinds of errors performed at remote temperature measurements by means of single-band or double-band infrared devices.

The sources of uncertainty of remote temperature measurements, elementary applications and evaluation of thermovision in building industry have been included in the final part of this.

1. *Introduction*

Insufficient thermal insulating power of walls is the cause of frost penetration of buildings, which in turn leads to moisturization and the drop of thermal insulating power of bulkheads [1].

The faults of thermal insulation, leaks in the casing of a building, as well as heat leakage bridges are easy to detect by means of thermographic equipment. The use of thermal display of the outer walls temperature field combined with the point measurement of the heat flux is the basis for determination of the volume of heat lost by walls [2].

A thermographic system's capability of accomplishing thermal images within real time, which comprise accurate values of the temperatures of the observed surface, is its fundamental trait [3].

An infrared display system consists of a camera which records the electromagnetic energy radiated out by an object within the infrared band of the spectre and processes it to an electronic video signal. Thus, the infrared radiation energy of the object will be radiated out into the medium, for instance the atmosphere, next it will reach the measuring system, pass through the lens, fall onto a single infrared radiation detector, matrix in the focal plane, or a sensor, to be processed to an electric signal. The first generation infrared recording systems, which are generally provided with a single detector, require a scanning mechanism and are convetionally referred to as infrared scanning rediometers — IRSR.

The instantaneous standard output data of each thermogram are represented by a matrix data of an order of $20-60k$ elements [3].

IRSR is a real bidimensional temperature sensor. It enables accurante surface temperature measurements also in the presence of strong spatial temperature gradients and heat fluxes with a spatial resolving power which depends on the applied plate. As yet the potential of the IRSR has been used to a considerably small extent in the context of quantitative applications, at convecting heat exchange measurements in particular. Infrared thermography may be successfully applied in convecting heat fluxes measurements, both at steady and transient states [3].

Thermal display of buildings for the needs of thermorenovation will be analyzed in the following approaches:

— comparative and quantitative,

— qualitative [4].

Thermogram comparative and quantitative analysis consists in indication of the spots of augmented temperature of the surface of a bulkhead. Thermogram quantitative analysis, presenting distribution of temperatures, calls for surface emissivity to be determined.

In order to obtain data for the needs of thermorenovation it is necessary to combine the thermal display of a bulkhead with a measurement of the heat flux that penetrates it, at an optional point of the bulkhead [5]. Thermovision display may be carried out for selected fragments of walls — measurements of the temperature of inner surfaces and outer walls by use of a portable thermovision camera. Research of the insulating power of the walls of apartment buildings by means of the thermovision method will be carried out for both new buildings and those that have been is use for long.

A camera interface in which analogue signal carrying information on the temperature of an object is changed into a digital form and sent to the computer, is a necessary element of the thermographic images processing system [6].

Thermal images superimposed with visible band images will be used thermogram interpretation. Image processing methods pertain to both the thermal part and the optical one; they differ from one another according to defferent amount of information in both the images.

Economization on energy to be looked for in building industry on the basis of technological and economic analyses makes it necessary to correctly evaluate the actual insulating traits of outer coats of buildings. Thermovision research provides a chance of such an overall evaluation. Localization of the spots of augmented heat diffusion is an immediate effect of the said research. However, thermogram quantitative analysis comes up against many difficulties which question the possibility of e.g. the overall heat-transfer coefficient of bulkheads or the heat fluxes they lose, to be determined on the foregoing basis.

The object of this article is to provide a tentative comparison of measuring and computing methods suggested by different authors for quantitative evaluation of the properties of constructing bulkheads, and to point out the method that suits best the actual functional model of a bulkhead.

2. *Interpretation of elementary formulas applied in thermal research*

Infrared rediation is an electromagnetic one emitted from the surface of a body within the range of wavelength $\lambda = 0.7 - 1000$ µm, the volume of emitted photon energy amounting to [7]

$$E = h\frac{c}{\lambda}$$

where:

$h = 6.63 \times 10^{-34}$[Js] — Planck constant
$c = 3 \times 10^{8}$ [m/s] — speed of light
λ[m] — wavelength of radiation emitted within IR band.

IR band has been roughly divided into the following ranges [7], [8]:

NIR $= 0.7 - 3$µm — near infrared,
MIN $= 3 - 6$µm — medium infrared,
FIR $= 6 - 15$µm — far infrared,
XIR $= 15 - 1000$µm — extreme infrared.

In accord with the Boltzman-Stefan law, distribution of intensity of IR radiation from a homogenous surface of a black body corresponds to distribution of temperatures of the surface.

Thus the emitted energy will be defined by the following equation:

$$E = \delta \cdot T^{4}$$

where:

T — temperature of black body [K],
δ — Stefan-Boltzman constant equal to $5.67 * 10^{-8}$[W/m^{2}K^4].

Overall heat-transfer coefficient u (in literature often marked by k) is a significant quantity characterizing the thermal properties of walls of buildings.

In [1] the so called estimated values of coefficient u have been analyzed; they have been obtained on the following basis:

- measurement of heat flux by use of a calibrated thermometer. In the case in question value of coefficient u will not be obtained for entire surface, but just for measuring points,
- temperature distribution measurement on the outer and inner surface of a bulkhead, the following measuring conditions having been satisfied:

1) determined thermal motion through the bulkhead and temperature stability during measurement,

2) temperature differences between outer and inner side of the bulkhead should amount to at least 10 K,

3) a few hours before measurement and during measurement of the temperature of walls, they should not be exposed to strong thermal impact.

The value of coefficient u cannot be obtained on the basis of „visual observation of frost penetration symptoms". Such observations are helpful merely at forecasting the overestimated value of coefficient u, yet its value may be determined only by means of measurements.

Temperature of the surface of a wall depends on its heat conduction, emissivity, and the conditions heat is abstracted from it. The volume of heat conducted by the wall is proportional to the difference of temperatures between temperature of the air inside the building t_i and temperature of ambient air t_e. Density of heat flux penetrating through the surface of the wall may be determined by the following equation:

$$q = u(t_i - t_e)$$

where: u — bulkhead heat-transfer coefficient, referred to the cross-sectional area the heat flux passes through.

For given area A^i, temperature v_e^i, the volume of lost heat will be calculated from the following formula:

$$Q_i = \gamma \cdot v_e^i \cdot A^i$$

where:

$$\gamma = \frac{q_r}{v_e^r}$$

q_r — density of heat flux measured in a determined heat datum point,
v_e^r — temperature of outer surface of the wall at the datum point,
v_e^i — temperature of the isothermal field of the outer surface of the wall,
A^i — isothermal field.

In [9] the overall heat-transfer coefficient has been interpreted thus.

At a steady state, the same volume of heat passes through a flat wall at all sectors of the path.

Thus the following equation may be written:

$$Q = h_i F(t_w - t_1)\tau = \lambda F(t_1 - t_z)\tau / s = h_e F(t_z - t_0)\tau$$

where:

Q — heat volume,
h_e — convective heat-transfer coefficient on the outer surface of the wall,
h_i — convective heat-transfer coefficient on the inner surface of the wall,
F — surface area,
τ — time,
t_w — indoor temperature,
t_z — outer temperature of the wall,
t_1 — inner temperature of the wall,
t_0 — ambient temperature,
s — thicknees of the wall,
λ — thermal conductivity

After particular temperature drops have been summed, the following will be obtained:

$$Q = uF\tau(t_w - T_0)$$

where: $1/u = 1/h_i + s/\lambda + 1/h_e$

If outside the building air moves merely due to thermal currents, convective heat-transfer coefficient h_e for a flat wall may be accepted in accordance with [9].

Therefore:

$$h_e = 9.8 + 0.07(t_z - t_0)$$

After transformations the following will be obtained:

$$u = [9.8(t_z - t_0) + 0.07(t_z - t_0)^2]/(t_w - t_0)$$

In order to determine overall heat-transfer coefficient u, it is necessary to measure ambient temperature, outer temperature of the wall and indoor temperatures [9].

For analyses of thermovision measurements of heat emission of surfaces the authors of [10] apply the standard overall heat-transfer formula:

$$u = \frac{1}{Ri + R + Re}$$

where:

Ri — heat take-up resistance [m²K/W],

R — thermal resistance of a bulkhead, calculated on the basis of thermovision research,

Re — local heat take-up resistance.

The thermal resistance of the bulkhead will be calculated through comparison of the heat flux penetration through the bulkhead and through environment, in accord with the following formula:

$$R = \frac{(Ri + Re)(tp_i - tp_e)}{(t_w - t_z) - (tp_w - tp_z)}$$

where:

Ri, Re — see the foregoing,

tp_w, tp_z — indoor and outdoor temperature of the bulkhead obtained by means of thermovisin measurements,

t_w — indoor temperature,

t_z — outdoor temperature on the day of the measurement.

On the basis of the calculated overall heat-transfer coefficient, volume of heat emitted by the bulkhead will be computed for calculating conditions out of the following formula:

$$Q^0 = uA(t_i - t_e)$$

where:

A — area of the bulkhead,

u — overall heat-transfer coefficient,

t_i, t_e — calculating temperatures, according to PN [10].

Once temperature of the surface of the wall has been obtained alongside ambient and indoor temperatures, certain measures of quality factors of a building's insulating power may be created [8].

Therefore:

$$T_i = \frac{v_i - t_e}{t_i - t_e}$$

where:

v_i, t_i — temperature of the inner surface of the wall and temperature of the indoor air,

t_e — ambient temperature.

In his own analyses Jaworski has taken it for granted that the volume of heat conducted by the casing of a building is proportional to the difference of ambient and indoor temperatures, area of the casing and its type, which is accounted for by the volume of the overall heat-transfer coefficient u [8].

Density of heat flux is not a homogeneous function within area A, due to heterogeneity of temperatures of the area $t_i(x, y)$ $t_e(x, y)$ or heterogeneity of the bulkhead $k(x, y)$.

The analyzed density of heat flux will be expressed by the following formula:

$$q = u(t_i - t_e)$$

Further on the following assumptions have been made [8]:

— analyzed area A of the bulkhead in homogeneous in respect of material, therefore within the area $u=$const.,

— in order to determine the volume of lost energy, parameters have been accepted not to be dependent on time. This pertains chiefly measured inner and outer temperatures. Besides, it has been taken for granted that inner temperature does not depend on coordinates. Thus the indoor temperature stratification effect has been disregarded.

— after the assumption of heat flux being independent of time has been taken into account, alongside its continuity and monotonicity having been maintained, it might be taken for granted that flux is proportional to the outer temperature of the casing.

I.e.:

$$q^i = u \cdot v_e^i$$

If at point r of the casing it is possible to adequately measure the density of the flux:

$$q^r = u \cdot v_e^r$$

substituting u for the foregoing equation, volume of the heat lost by area A of the bulkhead will be obtained.

Therefore:

$$Q^i = \frac{q^r}{v^r} \cdot A^i \cdot \sum_{i=1}^{i=n} v^i$$

Note that v_e^i stands for distribution of outer temperature on the surface within given area A^i of the bulkhead covered by thermogram, in which overall heat-transfer coefficient u is constant out of definition. Once all isothermal areas A^i of the casing of the building have been summed up, volume of heat lost from walls will be obtained at the moment thermographic measurements for a given outer temperature have been carried out.

In the building in question one should determine on the basis of documentation, homogenous — according to insulating power, equal to u — areas A, which should be followed point measurements of q^r in the preceding period and at the time thermogrames are being carried out. That quantity, together with the thermogram and the range of respective temperatures, will be included as data in the programme that is meant to carry out the assigned estimation of the volume of lost heat from the part of the casing covered by the thermogram.

While applying this method it is not necessary to know the exact value of the wall emissivity coefficient. At an assumed inner temperature, with a given actual course of outer temperature, it is possible to estimate the energy lost by the walls within a given time [8].

In his own work Kisielewicz maintains that the relationship of local thermal resistances for stationary flux at optional points 1 and 2, equals to the quotient of local differences of outer temperatures of the surface of the wall at those points and outer temperature [11].

I.e.:

$$\frac{R_1}{R_2} = \frac{t_1 - t_e}{t_2 - t_e}$$

where:

R_1, R_2 — total thermal resistances of the wall at points 1 and 2,
t_1, t_2 — temperature of the surface of the wall at points 1 and 2,
t_e — temperature of ambient air.

3. *Remote temperature measurement errors of the researched objects*

In [12] errors of remote temperature measurements by means of single of double-band infrared equipment have been divided into:

- methodological measurement errors,
- errors of a device's electronic path,
- calibrating errors.

Methodological measurement errors, generated by disturbances in the input channel before detector, do not occur at research carried out under the conditions that are identical to a device's calibrating ones. Under such conditions temperature measurement errors are determined by the resultant of errors of electronic path from detector up to microprocessor, and calibrating errors.

In our discussion it should be taken for granted that methodological measurement errors generated by:

— reflected thermal radiation of the environment,
— estimating errors of effective emissivity of an object,
— changes of self-radiation of optical elements,
— limited temperature resolution of the camera,
— atmospheric influence,

may be determined for known measuring conditions with the use of the mathematical model.

A typical correcting model of the influence of environmental reflected radiation is based upon the assumption that environment may be approached as a black body of a homogenous temperature distribution. At selected applications there occurs an environment of heterogeneous temperature distribution, or temperature changes in the course of the research.

Effictiveness of correction of the influence of optical elements radiation depends on indications of a single thermoelement. Measurements with the use of the latter make it possible to accurately specify the temperature of the single element, whereas the temperature of the other optical elements may be quite different.

Digital path cameras are usually provided with image processor, which makes it possible to average even up to several images. The use of the image averaging effect enables to considerably improve the temperature resolution of a camera, yet, on the other hand, it lowers the speed of measurements.

Medium-wave cameras which make it possible to correct the influence of limited atmospheric transmission make use of atmospheric transmission models working well for a typical atmosphere, yet much worse under the conditions that differ from typical ones [13].

In modern thermovision cameras it is possible to partly correct the influence of reflected environmental radiation, radiation emitted by the optical system, limited temperature resolution, as well as the influence of limited atmospheric transmission [13].

Electronic path errors are generated by:

— detector noises that not been eliminated,
— unstability of the cooling system,
— fluctuations of amplification of the preamplifier and other electronic systems,
— limited transmission band of the detector and electronic systems,
— limited resolution and nonlinearity of analogue and digital processors , etc.

The influence of electronic path errors upon the accuracy of measurements may by determined by:

— time stability measurement,
— temperature stability measurement,
— specification of camera's errors under optimum measuring conditions.

Calibrating errors result from limited accuracy of determination of a device's calibrating characteristics. They occur due to:

— limited accuracy of the standard,
— limited number of calibrating points,
— errors of the applied interpolation algorithm.

Accuarcy of black bodies applied at calibration of infrared equipment amounts to approx. 0.4 per cent. Calibration to be carried out for a sufficiently large number of measuring points alongside the use of typical interpolation algorithms make it possible to obtain calibrating errors not exceeding the foregoing value. Therefore the said errors may be regarded as small and as such — disredarded [12].

4. *Sources of uncertainty of temperature measurement of objects in question and elementary applications of thermovision in building industry*

Thermovision cameras enable remote and quick measurments of temperature distribution on the surface of researched objects. Uncertainty of temperature measurements comparises a number of elements. Some of them will be determined on the basis of a statistical distribution of the results of a series of measurements and might be characterized by standard deviation. Other elements will estimated on the basis of assumen probability distributions.

The uncertainty model of temperature measurements by means of thermovision cameras is based on the assumption that there are two groups of sources of uncertainty, i.e. external and internal ones.

The former includes the limited accuracy of determination of effective:

— emissivity of an object,
— ambient temperature,
— atmospheric transmission.

The latter includes limited:

— temperature resolution of the camera,
— resolution and linearity of digitalization systems,
— time satability of the camera,
— temperature stability of the camera,
— camera's own errors under optimum measuring conditions [12].

Elementary applications of infrared thermography for the needs of building industry comprise:

— detection and localization of the spots of augmented heat losses or refrigeration losses,
– localization of warm and cold water pipes,
— specification of the quality of materials used for construction,
— evaluation of the refrigerating quality of sub-assemblies and systems [4].

Thermivision camera assisted research may pertain to search for water leaks from underfloor heating installation. The bulk of wet part of concrete floor is characterized by augmented heat conduction. Procedural methodology comparises a raise in temperature of indoor air and analysis of changes of temperature field on the surface of the floor. In the process of interpretation of thermograms informing on the state of heat condution and local floor moisturization, it is particularly significant to eliminate:

— the influence of differences of emissivity of the surfaces in question,

— the influence of differences of radiation reflected by the environment;

— it is also necessary to acquire a complete knowledge on the structure of the floor [15].

5. *Final remarks*

Thermal analyses for the needs of building industry make up the only practical basis for a complete actual thermal evaluation of inner bulkheads of buildings. On the basis of designing calculations or random measurements by means of overall observations they make is possible to substitute for the evaluations of insulating properties of bulkheads which do not comply with actual state [11].

Considerable interest in the research in question occurs at the time of intensive thermo-modernizing activities in building industry, as well as at the time of auditing works.

Quantitative evaluations included herein are based chiefly upon a simplifying assumption in which stationary character of boundary conditions pertaining to:

— temperature changes in time, and

— eliminating the causes of measuring inaccuracies has been taken for granted.

In order to make the method create a possibility of generation of results, close to real values, it is necessary to observe practical measuring instructions, which minimize the influence of non-stationary temperature courses.

Methods of quantitqtive evaluation of thermal insulating power of construction bulkheads, based on thermovision research, might be generally divided into two kinds:

a) absolute — evaluation is based on calculations resulting form measured values of temperatures of the air and surface of a bulkhead,

b) relative — measurements are meant for comparison of the results thereof, for example with:

— designed standard bulkhead,

— measuring standard bulkhead,

— point of reference at which temperature measurement has been taken by means of the classical method (measurement of density of heat flux, or the point of reference is a place whose thermal characteristics are known).

In absolute methods a remarkably large number of potential measuring errors is to be dealt with. Most of them have been discussed or pointed out in the earlier chapters of this article. In Polish and foreign literature experimental research concerning the accuracy of analyzed methods is presented in an encyclopaedic way. This is why, consideration being taken of the present state of knowledge and experience in the line, one might claim that relative methods make it possible to better present quantitative specifications of bulkheads, getting rid of artificial assumptions, eliminating the need to assume calculating conditions or estimate emitting properties.

Relationship of thermal processes in a bulkhead within a given time span is of primary importance for the values of thermovision measurements. A fraction of a second is enough to record a thermovision image. A large area image will be obtained in the course of a very fast study. On the other hand, however, instantaneous camera recorded distributin of surface temperatures results not merely from the insulating properties of a bulkhead; it is also an effect of a certain history of changes of temperature on either side the bulkhead, its accumulating properties, radiation observed by the bulkhead, etc. Thus instantaneous, random measurements of distribution of surface temperatures, will merely comply with stationary assumptions. Therefore it should be taken for granted that at homogenous insulating properties of the surface of a bulkhead, local temperature differences will approximately (no regard being taken of deeper layers of the bulkhead and their share in accumulation) comply with differences in thermal insulating power of particulary places. Thus, if the referential insulating power of a bulkhead is known at the reference point (e.g. arrangement of layers compliant with the desing, or heat flux measured within a long time span and them averaged), it is possible — on the basis of thermovision temperature differences — to estimate approximate insulating properties of the bulkhead within particular areas. However, in order to specify the value of the measuring error, it is necessary to carry out a series of comparative measurements, associated with classical investigations into thermal insulating power of bulkheads.

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Wybrane interpretacje badań termicznych w podczerwnieni dla potrzeb budownictwa

Streszczenie

Na wstępie pracy przedstawiono ogólną interpretację układu zobrazowania w podczerwieni. Obrazowanie termalne budynków analizowane jest w ujęciu porównawczo-jakościowym i ilościowym.

W rozdziale drugim przedstawiono szczegółową interpretację wzorów stosowanych w badaniach termicznych. Natomiast w kolejnym rozdziale przytoczono rodzaje błędów zdalnego pomiaru temperatury za pomocą jedno lub dwu pasmowych urządzeń podczerwieni.

Źródła niepewności zdalnego pomiaru temperatury, podstawowe aplikacje i oceny termowizji w budownictwie ujęto w końcowej części pracy.

Збигнев Пясек

Избранные интерпретации тепловых исследований в тепловой инфракрасной области спектра для потребностей строительства

Резюме

В самом начале работы представлена общая интерпретация системы получения изображений в тепловых ИК-лучах. Тепловые изображения зданий анализированы справительно-качественным и количественным способами.

В главе второй представлена подробная интерпретация формул применяемых в термических исследованиях. В следующей главе приведены виды ошибок дистанционных измерений температуры при помощи приборов действующих в одном или двух областях длины ИК-лучей.

Источники неопределенности дистанционных измерений температуры, основные применения и оценки термовизии в строительстве представлены в последней части работы.