36. Energy performance of a ventilated façade by simulation with experimental validation / Aparicio-Fernández C. et al. // Applied Thermal Engineering. 2014. Vol. 66, No. 1–2. P. 563–570. doi:10.1016/j.applthermaleng.2014.02.041

37. Kolosov A. E., Sivetskii V. I., Kolosova E. P., Lugovskaya E. A. Procedure for analysis of ultrasonic cavitator with radiative plate // Chemical and Petroleum Engineering. 2013. Vol. 48, No. 11–12. P. 662–672. doi:10.1007/s10556-013-9677-9

38. Klychnikov R. Yu., Ezerskii V. A., Monastyrev P. V. Tehniko-ekonomicheskaia otsenka termomodernizatsii zhilyh zdanii. Moscow: ASV, 2011. 176 p.

39. Zaitsev D. V., Klymchuk O. A., Balasanian H. A. Analiz osnovnykh sposobiv termomodernizatsii budivel ta metodyka yikh vprovadzhennia // Visnyk Natsionalnoho tekhnichnoho universytetu «KhPI». Enerhetychni ta teplotekhnichni protsesy u ustatkuvannia. 2015. Vol. 17. P. 156–160.

40. Borys G. Selected directions of increasing efficiency in supporting thermomodernization in buildings from public funding // Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu. 2015. No. 397. P. 68–77. doi:10.15611/pn.2015.397.05

41. Ickiewicz I. Building thermomodernization and reducing air pollution // Ecological Chemistry and Engineering S. 2013. Vol. 20, No. 4. P. 805–816. doi:10.2478/eces-2013-0056

42. Wciślik S. Energy efficiency and economic analysis of the thermomodernization of forest lodges in the Świętokrzyski National Park // EPJ Web of Conferences. 2017. Vol. 143. P. 2144. doi:10.1051/epjconf/201714302144

43. Kryk B. Rachunek korzyści ekologicznych z inwestycji termomodernizacyjnych na przykładzie spółdzielni mieszkaniowych województwa zachodniopomorskiego / Account of environmental benefits from thermomodernization investment on the example of cooperative housing of West Pomeranian Voivodeship // Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu. 2016. No. 454. P. 92–101. doi:10.15611/pn.2016.454.08

44. Basinska M., Koczyk H., Kosmowski A. Assessment of Thermo Modernization Using the Global Cost Method // Energy Procedia. 2015. Vol. 78. P. 2040–2045. doi:10.1016/j.egypro.2015.11.204

45. Fanti M. P., Mangini A. M., Roccotelli M. A simulation and control model for building energy management // Control Engineering Practice. 2018. Vol. 72. P. 192–205. doi:10.1016/j.conengprac.2017.11.010

46. Adamczyk J., Dylewski R. Analysis of the sensitivity of the ecological effects for the investment based on the thermal insulation of the building: A Polish case study // Journal of Cleaner Production. 2017. Vol. 162. P. 856–864. doi:10.1016/j.jclepro.2017.06.123

47. Yeromin A. V. Systema kompleksnoi termomodernizatsii budivel i sporud za Yerominym: pat UA 121347 U, MPK F24D3/00, F16L59/00. Publ. 27.11.2017, Bull. No. 22.

48. Yeromin A. V. Sposib kompleksnoi termomodernizatsii budivel i sporud za Yerominym: pat UA 121348 U, MPKF24D 3/00, F16L59/00. Publ. 27.11.2017, Bull. No. 22.

ВЫБОР И ОБОСНОВАНИЕ НАПРАВЛЕНИЙ ПОВЫШЕНИЯ ЭНЕРГЕТИЧЕСКОЙ ЭФФЕКТИВНОСТИ УКРАИНСКИХ ЗДАНИЙ И СООРУЖЕНИЙ

Проанализированы имеющиеся организационные и технические решения по повышению энергетической эффективности украинских зданий и сооружений, а также обозначены нерешенные проблемы в этой сфере. Отмечено, что сложность реализации технической процедуры модернизации трубопроводов системы центрального водяного отопления препятствует повышению энергетической эффективности украинских зданий и сооружений. Не меньшей проблемой является необходимость «грубого» вмешательства в уже существующие ремонты, сделанные внутри зданий и сооружений.

Ключевые слова: термомодернизация зданий и сооружений, фасадная теплоизоляция, модернизация трубопроводов системы центрального водяного отопления.

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INCREASING THE ACCURACY OF THE NON-CONTACT TEMPERATURE MEASUREMENT IN THE CASE OF ENERGY AUDITS OF DIFFERENT OBJECTS

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Визначено чинники, що впливають на точність проведення енергоаудиту за допомогою тепловізорів. Оцінено ступінь впливу кожного фактору, що впливає на результат вимірювання, та сумарну методичну похибку від одночасної дії усіх впливаючих факторів. Запропоновано способи підвищення точності проведення енергоаудиту, які дозволять зменшити методичну похибку шляхом зменшення ступеня дії впливаючих факторів на точність проведення енергоаудиту.

Ключові слова: *енергоаудит за допомогою тепловізорів, матричний приймач випромінювання, коефіцієнт випромінювання, точність вимірювання.*

1. Introduction

In conditions of high energy costs, with a large share of energy-consuming buildings, energy conservation is one of the priority tasks for development of the municipal economy in accordance with the Law of Ukraine «On Energy Saving» [1]. Increasing the energy efficiency of buildings and facilities begins with an energy audit that identifies sources of heat loss, shortcomings in thermal insulation, thermal bridges, insufficient insulation density

and other construction defects. According to the results of the energy audit of the building, an energy passport is compiled [2, 3].

To determine the thermal characteristics of thermal protection of buildings, enclosing structures are examined using such means of measuring technology as thermal imagers, pyrometers, anemometers, heat flow meters, contact thermometers and moisture meters. Among the listed means of measuring technology, only a thermal imager allows to visualize the temperature fields of the survey object. For thermal inspections, in accordance with DSTU B EN 13187:2011 [4], the actual temperature of the enclosing structures should be measured with an error of not more than ±10 % or ±0.5 K.

Thermal imagers used for thermal inspection of enclosing structures, in accordance with DSTU B V.2.6-101:2010 [5], must comply with the following metrological characteristics:
– the range of measured temperature from minus 30 °C to 40 °C;
– resolution of temperature not more than 0.2 °C;
– the main absolute error of temperature measurement is not more than ±2 °C.

2. The object of research and its technological audit

The object of this research is the process of thermal inspection of enclosing structures using a thermal imager. A significant drawback of thermal imaging energy studies is the presence of a significant methodological error. The reason for this is a large number of factors affecting the process of measuring the temperature of the surfaces of objects in thermal imaging diagnostics.

According to DSTU 2820-94 [6], a thermal imaging device is a means of thermal imaging intended to perceive the thermal radiation of the objects under investigation with the subsequent formation of their adequate images suitable for observation with the naked eye.

A thermal imaging converter (a receiver of thermal radiation) is a thermal imaging device designed to generate a thermal information signal in a form that is convenient for transfer, further conversion, processing, storage, but not suitable for immediate perception by the observer [6].

Thermal imagers with electronic scanning have recently become widely used, the characteristic feature of which is the absence of optical-mechanical scanning of the image and the presence of matrix (multi-element) radiation receivers [7, 8]. The optical system of the matrix thermal imager forms the image of the object of research and directs its radiation to the matrix receiver [9, 10]. To form an image of the temperature fields of an object, it is necessary to have a temperature contrast between the object and the background [10, 11].

Matrix radiation receivers can be cooled and uncooled. There are thermal and photoelectric radiation detectors. Thermal receivers of radiation include bolometric, pyroelectric, thermoelectric and pneumatic. The work of bolometric receivers is based on a change in the electrical resistance of the measuring transducer when heated by infrared radiation. Pyroelectric receivers use the pyroelectric effect, which consists in the appearance of a charge on the faces of a crystalline element when it is heated [11]. In thermoelectric radiation detectors, the electromotive force arises from the thermoelectric effect. In pneumatic receivers, the change in the gas pressure in the chamber is measured as a result of heating of the sensitive element under the influence of the radiation flux [10].

Among the heat receivers, the most widely used are uncooled bolometric matrixes on vanadium oxide, with a tendency to transition to matrices based on materials containing silicon. Such matrices do not require cooling, their spectral range is in the range from 8 to 14 μm [12, 13].

Photovoltaic radiation receivers include converters with an external photoelectric effect (photoemission and photoelectron multipliers), with an internal photoelectric effect (photoresist) and photovoltaic converters (photodiodes and phototransistors).

In photoemission receivers of radiation, the electric signal corresponds to the number of electrons emitted by a solid body under the influence of incident photons and applied to a photocell by a constant voltage [10, 14]. In photoresist receivers, under the influence of radiation, the excitation of electrons in the valence band and impurity levels increases, the electrons pass into the conduction band. This causes an increase in electrical conductivity, which corresponds to the signal of the receiver [10, 15]. Photodiodes and phototransistors are receivers of radiation with *p-n* junctions in which the flux of incident photons causes a change in the potential barrier at the transition inside an inhomogeneous conductor, an additional carrier concentration in the *n*-layer is created when the transition is illuminated [16, 17]. The spectral range of such matrices is from 3 to 5 μm and from 8 to 12 μm [8, 12].

In practice, when the number of matrix elements becomes large, one resorts to the technique of multiplexing and reading information based on the use of [16–18]:
– devices with charge transfer (charge communication device (CCD));
– charge injection devices (CID) on complementary metal-oxide semiconductors (CMOS).

CID and CCD are based on fast charge reading [10]. The principle of operation of charge-coupled devices is based on the use of a metal-insulator-semiconductor structure in the form of a matrix of photosensitive elements [7, 10]. From the CCD matrix, the image is read by transferring charges along each line to the output register representing the column of CCD elements used in the multiplex mode. Information from the CCD array can be transferred to the memory array and then multiplexed by the output CCD register [10]. The CCD matrix makes it possible to obtain a complete image of the temperature field of an object located at a temperature exceeding 0 K [12]. The MOS capacitor is the simplest CDI [17]. The principle of operation of devices with charge injection is similar to the principle of CCD operation, but differs in the formation of a video signal. In FDI, a current appears in the substrate, proportional to the number of received photons, due to the injection of charges that make up the video signal.

The structural scheme of the matrix thermal imager of the last (third) generation is shown in Fig. 1 [8, 9]. The image of the object is formed by the optical system on the matrix radiation receiver. The most common thermal imagers with matrices with a resolution of 320×240, 640×480 and 1024×768 pixels (up to 106 or more sensitive elements) [12]. The matrix is cooled and thermostabilized by a thermal stabilization unit. Preamplifiers amplify the signal of each sensitive element of the matrix radiation receiver, then the signal goes to the multiplexer [8, 9].
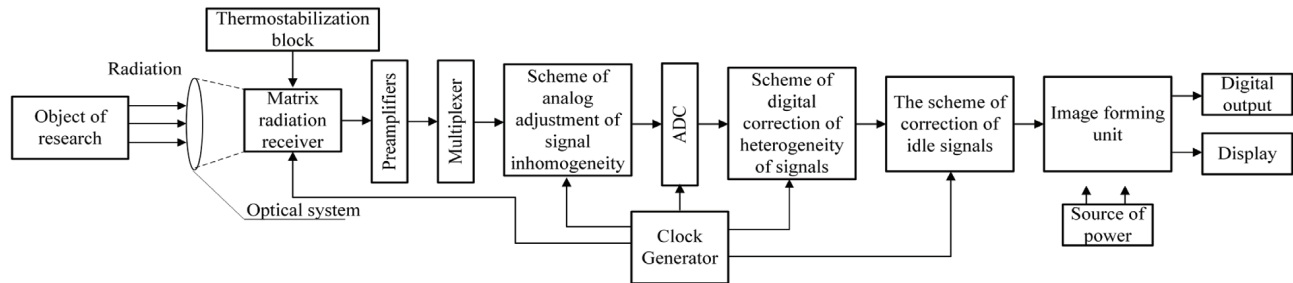
Fig. 1. The structural scheme of the modern thermal imager

The signals from the multiplexer are routed to the analogue circuit for correcting the signal inhomogeneity, then they are converted by an analog-to-digital converter. After the analog-to-digital converter, the signals are fed into the digital signal irregularity adjustment circuit and then to the correction circuit of the idle matrix receiving elements (replace the signal at the location of the dead cell interpolated between adjacent ones). The corrected signal is fed to the imaging unit with microprocessor image processing and then to the digital output and the display [8, 9]. To synchronize the described processes in the thermal imager, a clock generator is used. As a power source, a rechargeable battery is usually used.

Examples of infrared and photometric images of equipment obtained in experimental studies with the Fluke Ti25 thermal imager are shown in Fig. 2, 3.

Advantages of the matrix thermal imager are small dimensions, sensitivity in several spectral ranges, simplicity in operation and reliability.

The matrix thermal imager allows to instantly obtain the thermogram of the surveyed object with a high spatial resolution (up to 106 sensing elements) and a temperature resolution of up to 0.01 °C (with an error of measuring the temperature to ±1 °C).

A significant disadvantage of such thermal imagers is their high cost (from 500 to 20,000 c. u. and more). Also, drawbacks include the presence of non-photoactive areas (gaps between pixels), which reduce the quality of the image.

3. The aim and objectives of research

The aim of research is reducing the methodological errors in measuring the temperature of enclosing structures with the help of a thermal imager. This will improve the accuracy and quality of energy audits of buildings.

To achieve this aim, it is necessary to solve such problems:

1. To determine the factors having an influence on the accuracy of the energy audit using thermal imagers.

2. To estimate the methodical error of thermal imaging energy surveys depending on various influencing factors.

3. To find ways to improve the accuracy of the energy audit, allowing to minimize the methodological error.

4. Research of existing solutions of the problem

The analysis of the principle of action of thermal imagers allows to proceed to an assessment of the factors affecting the accuracy of the energy audit.

When energy audits of objects using thermal imagers, the operator should take into account the following factors, according to [19–22], as the most influencing the measurement error in thermal imaging diagnostics [8–10]:

– emissivity of the enclosing structures of the investigated building (characterized by an integrated radiation coefficient) is one of the most significant factors and is described in [23];
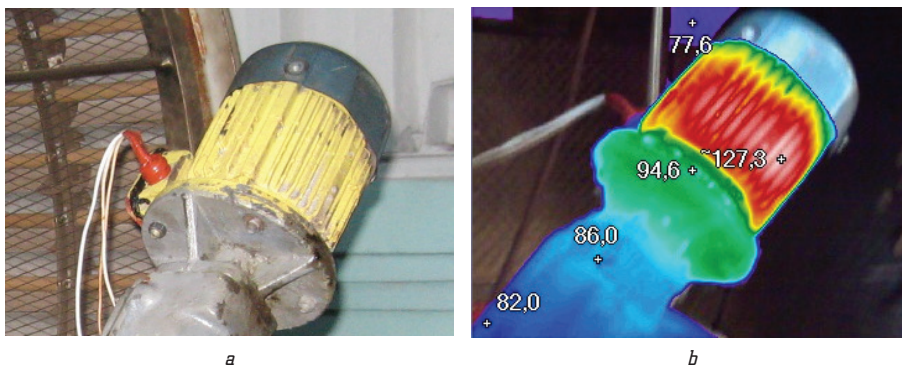

Fig. 2. The image of the electric drive, obtained by the Fluke Ti25 thermal imager:
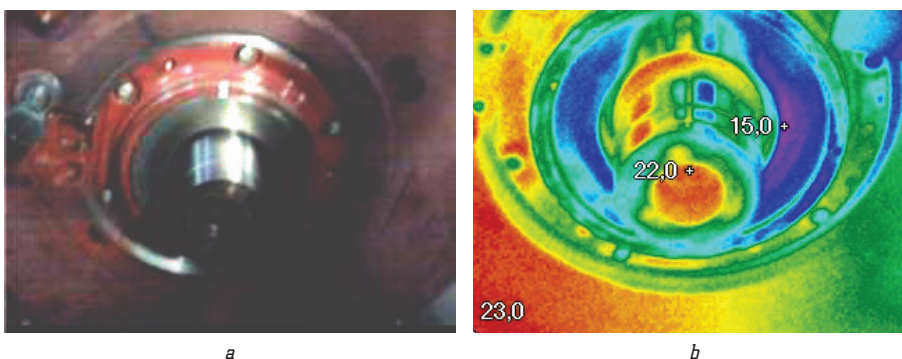*a* – photometric; *b* – infrared

Fig. 3. Image of the test bench for the bearings, obtained by the Fluke Ti25 thermal imager:
a – photometric; *b* – infrared

– inclination angle of the optical axis of the thermal imager relative to the normal to the investigated surface of the object of investigation (in [9, 24] it was shown that the radiation coefficient of non-planar surfaces is different at different points);

– parasitic reflection of thermal radiation, solar radiation and convective heat fluxes;

– composition of the environment through which radiation passes (dust, gases, water vapor) [25];

– contamination of the surface of the optical system;

– meteorological conditions (wind, atmospheric precipitation, etc.) [23];

– metrological and technical characteristics of the thermal imager (spectral characteristic, temperature sensitivity, temperature resolution, spatial resolution, etc.) [9, 10];

– temperature of the device body, environment, etc.

Let's consider in more detail the factors influencing the accuracy of the measurement result, as well as the existing methods for increasing the accuracy of contactless temperature measurement during energy audits.

5. Methods of research

Thermal imagers are graded by the emissivity of an absolutely black body and determine the radiation temperature, which is lower than physical, because it depends on the emissivity of the object of research.

Emissivity is described by the emissivity coefficient (thermal radiation), which characterizes the ability of the investigated object (in the case of considered outer surfaces of the enclosing structures) to emit electromagnetic energy. Emissivity depends on the wavelength, temperature and physical and chemical properties of the object (material, aggregate state and surface quality) [9, 10]. Because of this, it is impossible to calibrate thermal imagers on real objects.

The emissivity coefficient ε_T of the surface material of the enclosing structure (the integral coefficient of thermal radiation or the blackness degree) makes it possible to find its true temperature T and is determined from the following relation:

$$\varepsilon_T = \frac{B_T}{B_{0T}},$$

where B_T – the total energy brightness of the investigated object at temperature T, B_{0T} – the total energy brightness of an absolutely black body at the same temperature.

The total energy brightness of an absolutely black body at absolute temperature, according to the Stefan-Boltzmann's law, is determined by the expression [25, 26]:

$$B_{0T} = \sigma \cdot T^4,$$

where σ – the Stefan-Boltzmann constant, equal to $5.67 \cdot 10^{-8}$ W/m²K⁴.

Radiation temperature is the conditional temperature of a real body, numerically equal to the temperature of an absolutely black body, at which their integral energy brightnesses are equal [27, 28]:

$$B_T = \varepsilon_T \cdot B_{0T} = B_{0T_r}.$$

In accordance with the Stefan-Boltzmann law [29]:

$$\varepsilon_T \cdot \sigma \cdot T^4 = \sigma \cdot T_r^4.$$

The true temperature of the enclosing structures is always greater than the radiation temperature ($0 < \varepsilon_T < 1$) and is determined by the formula:

$$T = T_r \cdot \sqrt[4]{\frac{1}{\varepsilon_T}}.$$

Knowing the value of the integrated coefficient of thermal radiation, it is possible to determine the actual temperature of the outer enclosing structure from the radiation temperature.

The most common models of thermal imagers are used to measure temperatures in the range from minus 50 to plus 650 °C, the most expensive models allow to measure temperatures up to 2500 °C.

The emissivity influence is inaccurate in determining the integral coefficient of thermal radiation, which in turn leads to a significant methodological error. Moreover, this error can significantly exceed the instrumental error of the thermal imager itself.

The error in determining the actual temperature of the exterior surfaces of buildings by their radiation temperature is found by the formula [28]:

$$\Delta T_\varepsilon = -\frac{1}{4} T \cdot \frac{\Delta \varepsilon_T}{\varepsilon_T}.$$

The choice of the emissivity coefficient ε_T of the object according to the available specialized directories can be made with an error of not less than ±10 %, and sometimes up to ±50 %.

Thus, a 10 % error in the determination ε_T entails a 2.5 % error in the measurement of the object temperature by an infrared pyrometer and a thermal imager [22].

The emissivity coefficient ε_T depends on the chemical composition of the body, the shape of the object, the wavelength, the temperature, the state of the surface of the radiator (roughness, degree of oxidation, the presence of any films and coatings on it) and the viewing angle.

It should be taken into account that the emissivity with increasing wavelength λ decreases for metals (Fe, Ni, Co, Ag, Cu). The graphical dependence of the spectral coefficient ε(λ) is shown in Fig. 4 [22].

For dielectrics, the spectral coefficient increases with increasing wavelength. With increasing temperature, the integral coefficient for dielectrics decreases due to the growth of the refractive index of the material, and the maximum of the spectral radiation shifts toward short wavelengths [10].

The inclination angle of the optical axis of the thermal imager relative to the surface of the object of investigation affects the integral emissivity [25]. The graphical dependence is shown in Fig. 5. Curve 1 characterizes a dielectric with a refractive index of 1.5 (Fig. 5), curve 2 is a dielectric with a refractive index of 2; curve 3 is a dielectric with a refractive index of 4 and curve 4 is a metal. For metals, Lambert's law [10] is valid in the observation angle range from 0 to 40°, and for dielectrics from 0 to 60°. At large angles, the integral emission coefficient for dielectrics immediately tends to zero, for metals, after some increase, also tends to zero. In [24], studies were carried out which showed that the error due to the influence of the observation angle of the thermal imager on the error of the measured temperature does not exceed 1 %.
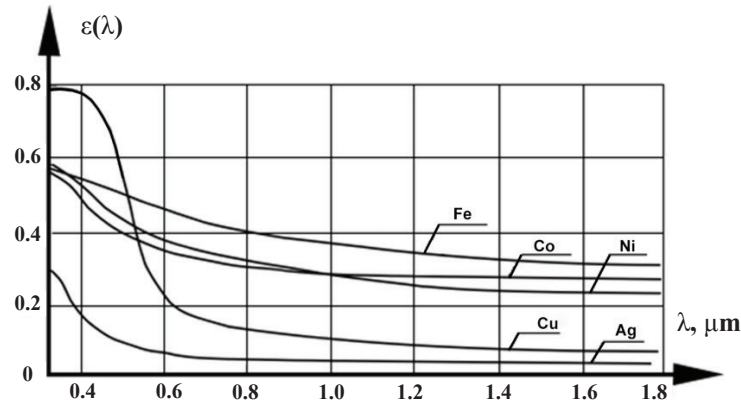
Fig. 4. The spectral emissivity of some metals

The smaller the emissivity of the object of research, the greater its reflectivity. Parasitic radiation from the environment of nearby objects, mainly with the same temperature, light sources and the sun (in the case of being in the sun's rays) distorts the measurement result. The object of research reflects thermal radiation from neighboring objects with a different temperature, which affects the measurement result because of the difficulty in detecting radiation due to reflection. And if the temperature of the surrounding objects is substantially higher or lower, then the influence will be significant (in [30], studies have been performed that showed an error in the determination of more than ±50 %). But in the cold season, the ambient temperature is usually below the surface temperature of the outer enclosing structures by no more than 5 °C. This leads to a small error in determining the temperature with a thermal imager to −0.5 % [21].
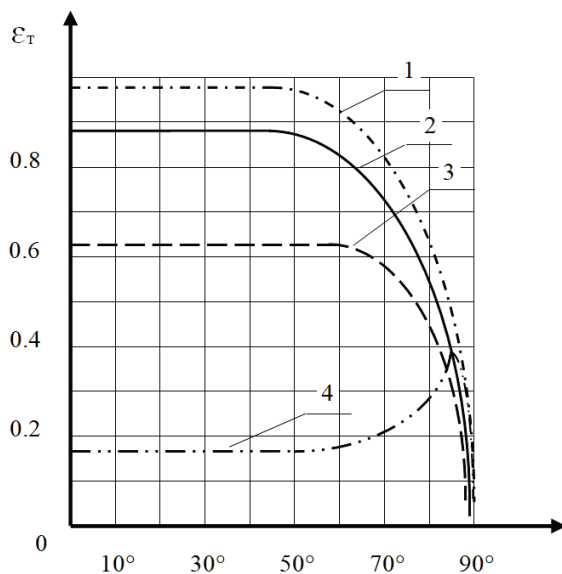

Fig. 5. Dependence of the integral coefficient of radiation from the observation angle

Convective air currents can influence the result of temperature measurement with the help of a thermal imager by replacing the adjacent layer of air with a new layer, with a temperature different from the temperature of the investigated object. Moreover, the greater the difference between the surface temperature of the investigated object and the ambient temperature, the stronger the heat transfer effect [19]. The result of measuring the surface temperature can be underestimated by about half at a wind speed of 5 m/s relative to the windless weather.

Water vapor, carbon dioxide, dust, smoke in the air and pollution of the optical system absorb some of the energy emitted by the object of research. Atmospheric precipitation cools the surface of enclosed structures and largely dissipates infrared radiation. The measurement error, due to the influence of the medium through which radiation passes, increases with increasing distance to the object of investigation. Thus, at distances up to 2 m (ambient humidity up to 60 %), the error in determining the surface temperature of an object can reach 3 % [30, 31].

6. Research results

The analysis of the main factors influencing the accuracy of the energy audit makes it possible to estimate the total methodical error in their simultaneous action:

$$\delta \approx \pm\sqrt{2.5^2 + 1^2 + 0.5^2 + 3^2} \approx 4\ \%.$$

Methods for increasing the accuracy of energy audit, allowing to reduce the degree of simultaneous impact of the main influencing factors:

– the radiation coefficient ε_T is determined experimentally: the temperature is measured by the contact method, then, changing the values of the radiation coefficient ε_T in the instrument settings, the temperature values measured by the contact method and the contactless temperature are equal;

– the reference factor determines the radiation coefficient;

– the surface of the investigated object is subjected to additional processing to increase the radiation coefficient: paint is applied, various films are subjected to machining, etc.;

– it is necessary to periodically clean the surfaces of the optical system of the pyrometer and the thermal imager;

– obstacles between the optical system of the pyrometer (thermal imager) and the surface of the investigated object should be avoided;

– the medium through which radiation passes must be transparent;

– the background temperature, in most cases, corresponds to the ambient temperature, which is advisable to measure with a thermometer in advance;

– it is possible to reduce the effect of radiation from other objects by isolating or isolating them, in this case the reflected background temperature will be equal to the ambient temperature [7, 19];

– since a significant part of the measurements are conducted in the open air, it is advisable to change the location to take into account the possible influence of the sun on the intensity of the infrared radiation of the object of research [19, 30];

– it is recommended to conduct energy audits of buildings in the early morning or late evening, take into account the presence of wind, and in the presence of wind at a speed exceeding 1 m/s, the measured temperature values are multiplied by the correction factors [31];

– measurements must be made taking into account the dependence of the radiation coefficient ε_T on the inclination angle of the optical axis of the thermal imager (pyrometer);

– measurements should be guided by the spatial resolution of the thermal imager (resolution of the matrix; the more pixels, the better);

– to reduce the error due to changes in the temperature of the body of the device, various methods and means of temperature compensation must be used. Such methods and means include: an electrical shunt made of copper or nickel, a bimetallic compensator and the introduction of a software correction for the temperature of the body of the device, measured by a digital temperature sensor.

7. SWOT analysis of research results

Strengths. Among the strengths of this work include the allocation of factors that have the greatest impact on the thermogram of the object and the accuracy of measuring the temperature of the surface of the enclosing structure with a thermal imager. Results are obtained on the evaluation of the influence degree of each influencing factor on the measurement result and the total methodical error from simultaneous influence of all influencing factors is estimated.

Weaknesses. The weaknesses of this research are due to insufficient experimental studies. In order to eliminate this drawback, further experimental surveys of various objects should be carried out using experimental design methods (to search through various combinations of influencing factors while simultaneously affecting the measurement process). When conducting experiments, it is necessary to monitor the thermodynamic temperature of the investigated object by contact means for measuring temperature, which will allow to estimate the actual measurement error and the quality of the obtained thermogram.

Opportunities. Additional opportunities to reduce the methodical error in measuring the temperature of enclosing structures using a thermal imager are opened in the development of methodological recommendations for performing measurements based on the results obtained during experimental studies. Carrying out an energy audit with less error makes it possible to increase the energy efficiency of buildings, and thus to reduce the cost of their heating.

Threats. Threats in implementing the results are often associated with inadequate qualification of personnel performing energy audit, which is expressed in the incorrect interpretation of the thermograms obtained during inspection of the enclosing structures (false shortcomings in thermal insulation, «cold bridges», etc.). And, accordingly, to the wrong recommendations to eliminate the identified shortcomings.

SWOT analysis of research results allows to identify the main task of reducing the methodological errors of temperature measurement with a thermal imager. The solution of this problem is development of a methodology for performing measurements by a thermal imager on the basis of the recommendations suggested in this paper.

8. Conclusions

1. The factors influencing the accuracy of the energy audit using thermal imagers are determined:
– inaccuracy in determining the integral coefficient of thermal radiation;
– observation angle of the thermal imager;
– reflectivity of the object of research;
– influence of the medium through which radiation passes, etc.

2. The total methodical error of thermal imaging energy surveys (up to 4 %) is estimated. The assessment is carried out based on the results of an analysis of the factors influencing the accuracy of the energy audit.

3. Methods for improving the accuracy of the energy audit are found, which make it possible to minimize the methodical error by reducing the degree of influence of factors influencing the accuracy of the energy audit. The proposed methods for increasing the accuracy consist in simultaneously taking into account the main influencing factors and allow estimating the methodical error of thermal imaging energy studies when they are combined.

References

1. Pro enerhozberezhennia: Law of Ukraine No. 74/94-VR from July 1, 1994 / Baza danykh «Zakonodavstvo Ukrainy» // Verkhovna Rada Ukrainy. URL: http://zakon3.rada.gov.ua/laws/show/74/94-%D0%B2%D1%80?lang=uk
2. DBN V.2.631:2006. Konstruktsiibudynkiv i sporud. Teplova izoliatsiia budivel. Kyiv, 2006. URL: http://online.budstandart.com/ua/catalog/doc-page?id_doc=6919
3. DSTUNBA.2.25:2007. Nastanova z rozroblennia ta skladannia enerhetychnoho pasporta budynkiv pry novomu budivnytstvi ta rekonstruktsii. Kyiv: Minrehionbud Ukrainy, 2008. 44 p.
4. DSTU B EN 13187:2011. Teplovi kharakterystyky budivel. Yakisne vyiavlennia teplovykh vidmov v ohorodzhuvalnykh konstruktsiiakh. Infrachervonyi metod. Kyiv: Minrehionbud Ukrainy, 2011. 33 p.
5. DSTU B V.2.6-101:2010. Metod vyznachennia oporu teploperedachi ohorodzhuvalnykh konstruktsii. Kyiv: Minrehionbud Ukrainy, 2010. 84 p.
6. DSTU 2820-94. Teploviziini systemy. Terminy ta vyznachennia. Introduced: 1996-01-01. Kyiv: DerzhstandartUkrainy, 1994. 27 p.
7. Vavilov V. P. Infrakrasnaya termografiya i teplovoy kontrol. Moscow: Spektr, 2009. 544 p.
8. Skripal A. V., Sagaydachnyi A. A., Usanov D. A. Teplovizionnaya biomeditsinskaya diagnostika: handbook. Saratov, 2009. 118 p.
9. Osnovy infrakrasnoy termografii / Afonin A. V. et al.; ed. by Nyuport R. K., Tadzhibaev A. I. Saint Petersburg: Izdatel'stvo PEIPK, 2004. 240 p.
10. Gossorg J. Infrakrasnaya termografiya. Osnovy, tekhnika, primenenie. Moscow: Mir, 1988. 416 p.
11. Levshina B. C., Novitskiy P. V. Elektricheskie izmereniya fizicheskikh velichin. Izmeritel'nye preobrazovateli: handbook. Leningrad: Energoatomizdat, 1983. 320 p.

12. Sizov F. F. IR-photoelectronics: photon or thermal detectors? Outlooks // Sensor Electronics and Microsystem Technologies. 2015. Vol. 12, No. 1. P. 26–52. doi:10.18524/1815-7459.2015.1.104447

13. Uncooled infrared detectors toward smaller pixel pitch with newly proposed pixel structure / Tohyama S. et al. // Optical Engineering. 2013. Vol. 52, No. 12. P. 123105. doi:10.1117/1.oe.52.12.123105

14. Osnovy teplovideniya / Korotaev V. V. et al. Saint Petersburg: NIU ITMO, 2012. 122 p.

15. Izmerenie elektricheskikh i neelektricheskikh velichin: handbook / Evtikhiev N. N. et al. Moscow: Energoatomizdat, 1990. 352 p.

16. Fizicheskie osnovy poluprovodnikovoy fotoelektroniki: handbook / Voytsekhovskiy A. V. et al. Tomsk: Izdatel'skiy Dom Tomskogo gosudarstvennogo universiteta, 2013. 560 p.

17. Sopryazhenie datchikov i ustroystv vvoda dannykh s komp'yuterami IBM PC / ed. by Tompkins U., Uebster J. Moscow: Mir, 1992. 592 p.

18. Ilyushin V. A. Mnogoelementnye fotopriemnye ustroystva i teplovizory: handbook. Novosibirsk: Izdatel'stvo NGTU, 2003. 57 p.

19. Proshkin S. S. K voprosu o tochnosti izmereniya temperatury s pomoshh'yu teplovizora // Vestnik mezhdunarodnoy akademii kholoda. 2014. Vol. 1. P. 51–54.

20. Vavilov V. P., Larioshina I. A. Metodicheskie pogreshnosti teplovizionnogoenergoaudita stroitel'nykh sooruzheniy // Vestnik nauki Sibiri. 2012. Vol. 5, No. 6. P. 49–53.

21. Vavilov V. P. Pessimisticheskiy aspekt teplovizionnogoenergoaudita stroitel'nykh sooruzheniy // Defektoskopiya. 2010. Vol. 12. P. 49–54.

22. Frunze A. V. Metodicheskie pogreshnosti energeticheskikh pirometrov i sposoby ikh minimizatsii // Metrologiya. 2012. Vol. 7. P. 19–38.

23. Enyushin V. N., Kraynov D. V. O vliyanii izluchatel'noy sposobnosti poverkhnosti issleduemogo obekta na tochnost' izmereniya temperatur pri teplovizionnom obsledovanii // Izvestiya KTASU. 2013. Vol. 1 (23). P. 99–103.

24. Golofeeva M. A., Levinskiy A. S., Tonkonogiy V. M. Povyshenie tochnosti izmereniya temperatury s pomoshh'yu priborov infrakrasnoy tekhniki // High technologies in machine engineering. 2016. Vol. 1 (26). P. 14–18.

25. Levinskiy A. S., Golofeeva M. A., Ryabushenko Yu. A. The improving the accuracy of temperature measurement through devices of the infrared technology // Technologes of informations are in education, science and production. 2016. Vol. 2 (13). P. 153–158.

26. Ivanova G. M., Kuznetsov N. D., Chistyakov V. S. Teplotekhnicheskie izmereniya i pribory: handbook. Moscow: Izdatel'stvo MEI, 2005. 460 p.

27. Kulakov M. V. Tekhnologicheskie izmereniya i pribory dlya khimicheskikh proizvodstv: handbook. Moscow: Mashinostroenie, 1983. 424 p.

28. Oleynik B. M., Lazdina S. I., Zhagullo O. M. Pribory i metody temperaturnykh izmereniy: handbook. Moscow: Izdatel'stvo standartov, 1987. 296 p.

29. Preobrazhenskiy V. P. Teplotekhnicheskie izmereniya i pribory: handbook. Moscow: Energiya, 1978. 704 p.

30. Polyakov V. S. Primenenie teplovizionnykh priemnikov dlya vyyavleniya defektov vysokovol'tnogo oborudovaniya // Metodicheskie ukazaniya po kontrolyu oborudovaniya teplovizorami. Leningrad: PEIPK, 1990. 57 p.

31. Galanov E. K., Filatov M. K. Metrologicheskie voprosy izmereniya temperatury poverkhnostey beskontaktnym metodom IK pirometrii // Opticheskiy zhurnal. 2009. Vol. 76, No. 3. P. 44–47.

32. Gobrey R. M., Chernov V. F., Udod E. I. Diagnostirovanie elektroustanovok 0.4–750 kV sredstvami infrakrasnoy tekhniki. Kyiv: KVITS, 2007. 374 p.

ПОВЫШЕНИЕ ТОЧНОСТИ БЕСКОНТАКТНОГО ИЗМЕРЕНИЯ ТЕМПЕРАТУРЫ ПРИ ЭНЕРГОАУДИТЕ РАЗЛИЧНЫХ ОБЪЕКТОВ

Определены факторы, влияющие на точность проведения энергоаудита с помощью тепловизоров. Оценена степень влияния каждого влияющего фактора на результат измерения и суммарная методическая погрешность от одновременного воздействия всех влияющих факторов. Предложены способы повышения точности проведения энергоаудита, позволяющие уменьшить методическую погрешность путем уменьшения степени воздействия влияющих факторов на точность проведения энергоаудита.

Ключевые слова: энергоаудит с помощью тепловизоров, матричный приемник излучения, коэффициент излучения, точность измерения.

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