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MEASUREMENTS OF HETEROGENEOUS HEAT STREAMS PERMEATING THROUGH DAMAGE TO REFRIGERATED BODIES

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Abstract – This paper presents a description of the author's method of determining the heat flux penetrating the partition on the basis of a thermographic image. The method is based on a comparison of the temperatures of two areas, one of which is a heat-loaded area with a known heat flux (measured in this case by means of a heating box) and the other control area that was not heat-loaded. Based on preliminary tests, a "calibration" of the method based on differential measurements was carried out using a thermographic camera. Two areas were observed with a thermographic camera, one of which was thermally loaded with various heat fluxes and temperature increases were observed using a thermographic camera in relation to the surface temperature of an identical reference plate but not thermally loaded. As a result of "calibration", a relationship arose that linked the temperature difference with a registered thermographic camera to the heat flux measured with the heating box. The new method was validated by making subsequent series of measurements, this time with models of heat bridges that most often occur in refrigerated bodies and after determining the heat flux, the calculated values were compared with the results of measurements with a heating box.

Key words – heat bridge, heat flux density, refrigerated body, thermography

INTRODUCTION

For the measurement of heat flux density, heat flux density meters are commonly called heat meters. They are commonly used to measure the heat loss of buildings. The average heat flux density sensor covers a diameter range of several dozen to two hundred millimetres and as a result of the measurement, this sensor generates an electrical signal corresponding to the average heat flux density of the area covered by the sensor. When the heat losses of building fragments that are many times larger than the sensor size are determined, and additionally the sensor is mounted on a surface with a homogeneous temperature field during measurement, the averaging does not negatively affect the measurement accuracy.

Sensors allow you to measure heat fluxes penetrating through walls, roofs and other building partitions and thus verify that the measured values on the object are not greater than those assumed in the project or standards, or identify the condition of the object before the modernization project. Measurements of homogeneous heat streams make no problems.

The situation of measuring heat losses within heterogeneous heat streams is different, and these occur around heat bridges. Depending on the type of heat bridge (structural, technological or operational), the heat flux and the shape of the heat bridge change. The measurement of heat loss within the heat bridge requires the attachment of a sensor for measuring the heat flux density within the heat flux gradient. Such placement leads to large measurement errors due to averaging and thus ultimately disqualifies heat flux density meters in the field of heat loss measurements within heat bridges.

With the spread of thermographic technique, thermographic cameras are used to locate places with a surface temperature different than the main part of the partition. A different temperature is a signal of occurring places with locally inferior insulation properties, i.e. heat bridges. The advantage of a thermographic camera is the registration of the surface temperature distribution of the area observed by the camera lens at several dozen or several hundred thousand points simultaneously. Such a large number of measuring points is processed by the camera's microprocessor, saved on a memory card. The user usually gets a colourful map of the surface temperature distribution displayed on the lens or on the camera screen. However, recording the surface temperature image and searching for temperature anomalies (temperature increases or decreases in relation to the remaining part of the partition) is only a symptom that at the observation site the insulation continuity has been violated, and thus the heat flux is greater than in other parts of the observed image. Unfortunately, a thermographic camera is not a tool for measuring the amount of heat related to a unit of surface. A thermographic camera based on electromagnetic radiation of various spectral wavelengths (SW, MW, LW) and many internal data programmed in the camera microprocessor and provided by the user calculates the surface temperature. The correct interpretation of the observed and recorded temperature fields on the observed surface is the task of the camera operator or the person developing the thermographic images.

I. LITERATURE REVIEW

The use of thermography to determine the local heat factor U for various building partitions is described in the literature [1]. The paper presents the results of laboratory and field tests on real objects of insulation parameters of typical building partitions. Heat flux density sensors - recognized by many authors [2] as the only reliable method of measuring the heat transfer coefficient U - and a thermal imaging camera were used as measuring instruments. Based on the analysis of the comparison of the results of both methods (measurements using heat flux density sensors and thermographic), the author showed that "... the U value can be determined on the basis of measurements made both by thermography and a heat meter, it does not depend on the adopted measurement method ... "," ... but whether the measurements were carried out in a steady state heat flow through the partition. "

The author pointed out in her work the limitations of measurements with a heat flux density sensor "... using heat meter measurements it is difficult (or even practically impossible) to determine the surface distribution of thermal insulation of a partition (thermal bridges, insulation defects) and to choose a representative place of measurement." The work of the author and her research team indicated that the current tool - heat flux density sensor colloquially called a heat meter does not properly deal with a heat flux located in a non-homogeneous heat flow and the problem is the resolution of the measuring method understood as the sensor size related to the size of the heat flux heterogeneity, so that within the 50-80mm diameter sensor, the heat flux was uniform.

Since refrigerated bodies have operational heat bridges [3] with sizes definitely smaller than in construction, there is a need for measurements of these heat bridges but with measuring instruments operating on a smaller area and thus capable of measuring within gradients. The method that allows measuring the surface temperature and determining the map of surface temperatures (also variable as in the field of operational thermal bridges) is the thermographic technique. Unfortunately, a thermographic camera based on electromagnetic radiation and many characteristics of camera elements (detector, optics) and variables entered by the user regarding the conditions of measurement calculates the surface temperature and not the heat flux penetrating the partition observed by the camera.

Hence the need to link surface temperature measurements (using thermographic cameras) within a gradient caused by a variable heat flux penetrating through damage to the body with the heat flux density.

II. METHOD DESCRIPTION

Determining the surface temperature based on electromagnetic radiation is complicated, so the results obtained are subject to a measurement error of 1-2°C, i.e. a lot. To improve accuracy, use the differential method of determining the temperature difference within one thermographic image.

To calibrate the thermographic method, a set of layered partitions with different insulation properties with different thicknesses of Styrofoam insulation core (10, 20 and 40 mm), thermally loaded with a known heat flux, was used. Fig. 1. shows the model stand with replaceable plates and Fig. 2. shows a photo of the heating box mounted inside the body model for setting the heat load of the tested plate with a known heat flux.

Fig. 1. Photo of a body model with exchangeable plates

Thanks to the use of sandwich panels with an insulation core of various thicknesses and various settings of temperature controllers for heating and cooling devices, which were installed inside and outside the body model, different heat flux values were obtained. The variability of heat flux used for calibration was in the range of 20-60 W / m^2.

Fig. 2. Photo of the heating box inside the body model

The partition for tests under heat load with known heat flux (Fig. 3. Plate on the left) after assembly on a model stand equipped with an additional plate not thermally loaded for reference measurements (Fig. 3. Plate on the right) was subjected to warmer stabilization. After achieving thermal stabilization, the model stand was observed with a thermographic camera.

Fig. 3. Photo of the test stand

During the tests, the thermographic camera lens was directed at the tested plate, loaded with a known heat flux, and a control plate placed next to the tested plate, made of the same materials (surface emissivity coefficient ε) as the tested plate, which was not heat loaded. Figure 4 presents a thermographic image of the tested panels.

After taking a series of thermographic images and registering the operating parameters of regulators and environmental conditions in the body model and its surroundings, the analysis of the measurement results began. After a series of tests (for heat fluxes in the range of 20-60 W/m^2), the obtained thermographic images were analysed.

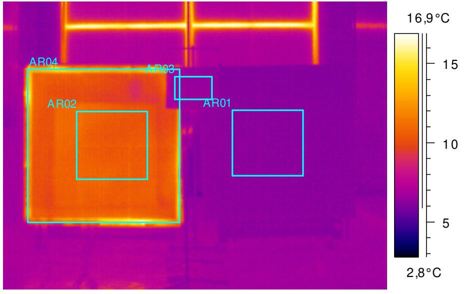

Fig. 4. Photo of a heat-charged plate (on the left) and a control plate (on the right)

The dedicated software provided with the thermographic camera ThermaCAM Reporter 2000 was used for the analysis. The analysis consisted in selecting the area on the heat-loaded plate (area AR02 in Fig. 4), i.e. within the operation of the heating box and the reference area (AR01 in Fig. 4) on the heat-unloaded plate and calculating the temperature difference between average area temperatures. To eliminate the effect of thermal drift of the microbolometer detector the final value of the temperature difference was calculated as the average temperature for 6 thermographic images recorded every 10 minutes. Based on the time stamps of the analysed thermographic images, the recorded parameters of the heating box were read from the file, which were used to calculate the heat flux penetrating the sandwich wall subjected to observation by a thermographic camera and the average value of the heat flux was calculated in the same way as for thermographic images.

The results of the analysis of the test series allowed to obtain the dependence of the temperature difference and heat flux in the range of the most common temperature differences on the heat bridges in refrigerated bodies.

III. TESTS RESULTS

The graph (Fig. 5) shows the relationship between the average temperature differences of heat loaded and reference areas and the heat flux obtained during a series of tests.

Noteworthy is the almost linear relationship between the heat flux and the temperature difference. The high value of the correlation coefficient R^2 confirms the good fit of the linear regression to the experimental data measured in the test series.

$$Q_{sg} = 14.49\ \delta t + 0.27\ W \qquad (1)$$

To assess whether the developed thermographic image analysis tool allows determination of the heat flux value passing through the plate with a heat bridge with satisfactory accuracy, i.e. comparable with the accuracy achieved by means of the heat flux density meter, the method was validated.

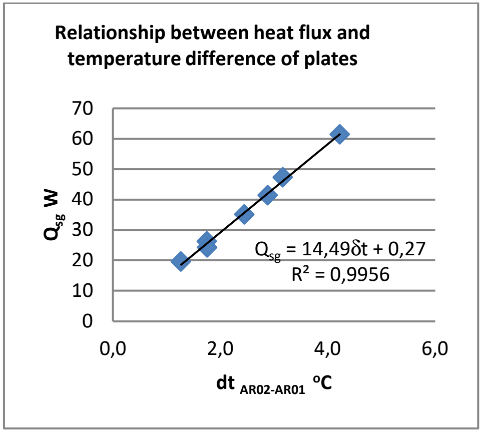

Fig. 5. A graph showing the relationship between the heat flux Qsg and the temperature difference of heat-loaded and control panels δt

IV. METHOD VALIDATION

For method validation, a model station was used, in which, instead of panels with different thicknesses of insulation material, panels with models of heat bridges appearing in refrigerated bodies were mounted. The following were selected as models of heat bridges: floor reinforcement model, strengthening model for mounting the aggregate and a model of bolts fixing body elements.

After thermal stabilization of the station (24h), measurements were taken with a thermographic camera of the plate system (plates with bridges and control plate).

During the analysis of thermographic images, an area was determined on the plate of an area equal to the area covered by the heating box, i.e. 1m2. After reading the temperature on individual pixels of the area covered by the heating box, the difference (increase) in temperature in relation to the reference temperature on the heat-unloaded plate was calculated. The temperature difference was substituted for equation (1) and the heat flux density was calculated for individual pixels of the image. To calculate the amount of heat permeating through a plate with a heat bridge it was necessary to multiply the heat flux density by the surface of the area observed with a single sensor of a microbolometric detector of a thermographic camera. The plate surface observed with a single camera detector sensor was determined from the geometrical relationships and parameters of the thermographic camera lens. After adding up the heat for individual pixels of the area covered by the heating box ($1m^2$), this calculated value was compared with the value measured with the heating box.

Table 1 presents a comparison of the results of calculations of heat bridge models on the basis of thermographic image analysis with the results of heat flux measurements made with the help of a heating box.

Table 1. Comparison of calculation results of heat bridge models with the results of heat flux measurements measured with a heating box

Model of heat bridge	Q_{IR} W	Q_{SG} W	Error %
Floor strengthening	24.9	22.6	9.9
Reinforcing aggregate suspension	25.2	22.9	10.0
Screw model	31.3	29.1	7.3

V. MEASUREMENT UNCERTAINTY

Thermographic camera measurements are not the most accurate measurements. A number of factors negatively affect the accuracy of the electromagnetic radiation measurement (reflected temperature, air temperature and humidity, optics temperature, camera detector calibration tables, surface emissivity ε). Based on the electromagnetic radiation, internal parameters and external parameters settings, the camera microcomputer calculates the temperature for individual pixels of the image.

Manufacturers of thermographic cameras guarantee the accuracy of surface temperature measurements with thermal imaging cameras of the range ±1-2°C or ±1-2%.

In the literature [4, 5] methods for determining the uncertainty of temperature measurement with a thermographic camera are described. The following partial uncertainties of the temperature measurement model implemented for the thermographic camera were adopted for analysis: plate surface emissivity ε=0.97(+0.03/-0.10); apparent reflected temperature reaching the lens from other objects T_{amb} = 280 ± 3K, air temperature between the plate and the lens T_{atm} = 280 ± 3K, relative humidity of the air between the plate and the lens ω=50 ± 10% RH, distance between plate and camera lens d=9.0±0.1m.

Total uncertainty was determined on the basis of the formula given in [4]:

$$\delta_{T_{ob\%}} = \sqrt{\left(\frac{\partial T_{ob}}{\partial \varepsilon_{ob}}\delta\varepsilon_{ob}\right)^2 + \left(\frac{\partial T_{ob}}{\partial T_{amb}}\delta T_{amb}\right)^2 + \left(\frac{\partial T_{ob}}{\partial T_{atm}}\delta T_{atm}\right)^2 + \left(\frac{\partial T_{ob}}{\partial \omega}\delta\omega\right)^2 + \left(\frac{\partial T_{ob}}{\partial d}\delta d\right)^2} \qquad (2)$$

After substituting the data read from the graphs of the impact of errors on individual components of the model on the uncertainty of temperature measurement [5] is:

$$\delta_{T_{ob\%}} = \sqrt{(-0.75)^2 + (-0.15)^2 + (-0.02)^2 + (0.0002)^2 + (-0.02)^2} = 0.8\% \quad (3)$$

Measurements of heat flux density using a heating box were made by measuring the DC voltage and current consumed by a set of radiators mounted in the heating box with equipment calibrated every 2 years as part of the PCA accredited activity. The accuracy of the heat flux measurement is within 2%.

VI. CONCLUSIONS

As a result of the analysis of thermographic images of heat bridge models, it follows that the described method of determining heat loss based on a thermogram allows the heat flux to be determined with an accuracy comparable to the accuracy of the heat flux density sensor but in an area much smaller than the area covered by the heat flux density sensor and thus allowing work in areas containing structural and operational heat bridges of irregular shapes. Since the thermographic technique belongs to non-contact measurements, it does not interfere with the heat exchange system, it allows you to visualize the temperature distribution from a short or long distance with variable optics, thus determining the heat flux can be subject to a small or large area depending on your needs.

The author who professionally researches refrigerated transport means has developed and validated a comparative method that he uses to test heat bridges in refrigerated bodies, but the presented method of thermogram analysis can be a helpful tool in other areas of heat loss research, e.g. in construction.

POMIARY NIEJEDNORODNYCH STRUMIENI CIEPŁA PRZENIKAJĄCYCH PRZEZ USZKODZENIA NADWOZI CHŁODNICZYCH

W artykule przedstawiono autorską metodę oceny strumienia ciepła na podstawie zdjęcia termowizyjnego. Metoda bazuje na porównaniu temperatur powierzchni dwóch obszarów z których jeden jest obszarem obciążonym cieplnie znanym strumieniem ciepła (zmierzonym w omawianym przypadku skrzynką grzewczą) a drugim obszarem kontrolnym, który nie jest obciążony cieplnie. Na podstawie badań wstępnych dokonano „skalowania" techniki termowizyjnej różnymi strumieniami ciepła i obserwowano wzrost temperatury za pomocą kamery termowizyjnej w stosunku do temperatury powierzchni płyty wykonanej z tych samych materiałów ale nieobciążonej cieplnie. W wyniku „skalowania" powstała zależność wiążąca różnicę temperatur obserwowaną kamerą termowizyjną ze strumieniem ciepła, mierzonym skrzynką grzewczą. Dla zwalidowania opracowanej metody wyznaczania gęstości strumienia ciepła na podstawie zdjęcia termowizyjnego przeprowadzono kolejne serie badań z modelami mostków ciepła. Po dokonaniu obróbki uzyskanego materiału, porównano uzyskane wyniki z wynikami pomiarów strumienia ciepła za pomocą skrzynki grzewczej. Uzyskane rozbieżności między wynikami analizy a danymi doświadczalnymi są porównywalne z dokładnością pomiaru strumienia ciepła za pomocą mierników gęstości strumienia ciepła. Opracowana metoda pozwala analizować strumienie ciepła w miejscach o dużych gradientach strumienia ciepła, jakie występują w obrębie mostków ciepła szczególnie eksploatacyjnych związanych z zawilgoceniem materiału, a w których czujniki gęstości strumienia ciepła, uśredniające strumień na powierzchni czujnika, mogą wprowadzić znaczące błędy.

Słowa kluczowe: gęstość strumienia ciepła, mostek ciepła, nadwozie chłodnicze, termowizja

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