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Thermal performance of insulated glazing units established by infrared thermography

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Thermal performance of insulated glazing units established by infrared thermography

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Abstract. The targets for the building sector have been clearly defined starting with the Directive 2010/31/UE and ending with the long term strategy that implies the decarbonisation of the entire building sector. The aim consists in designing nearly Zero Energy Buildings (nZEB) starting from 2019 for public buildings and 2021 for all new buildings. For the energy retrofit of existing buildings, the last Directive 2018/844/UE on the energy performance of buildings sets a clear target for reaching nZEB also in the retrofit activity. Although that clear targets exists on a European level, some buildings are still poorly designed from the thermal point of view and are not able to meet these criteria. Thus, in many cases the thermal performance obtained in the design activity is not the one obtain in the operation phase of a building. That is why, not even buildings built after 2010, do not comply with the minimum recommended national thermal design criteria, and therefore need to be thermally retrofitted. Thus, the paper presents a thermography study done at a residential buildings, respectively the examination of the thermal performance of part of a façade. The focus is placed on a window-wall area that is examined by Infrared Thermography. The resulted thermograms are reconstructed by means of artificial intelligence in order to establish the thermal performance of the examined façade and building envelope components.

1. Introduction

In current practice, in the initial design stage of a building, the focus is placed more on structural aspects and less on the hygrothermal performance of a building, although that comfort is ensured based on an accurate hygrothermal design. A poor hygrothermal design, results in a poor energy performance of a building. As mentioned in literature, in some cases the final energy demand is in average about 20% higher compared to the designed value. [1] Thus, the Infrared Thermography (IRT) comes as a diagnosis solution for evaluating the thermal performance of the building envelope.

Infrared thermography is used as a non-invasive method at identifying thermal irregularities in the surface of the building envelope [2]. The irregularities are "shown" by the surface radiation temperature that varies on the thermographed surface. Thus, the heat flux directly associated with the infrared radiation emitted by the surface will offer an IR image called thermogram, which describes a thermal map of the investigated surface, indicating the weak parts of the building envelope, areas that need to be retrofitted. The thermal map can be expressed in vivid colours or using a black and white colour palette. In current practice IRT is mainly used in the thermos-energy retrofit activity with the aim of identifying: irregularities due to lack of thermal insulation, inhomogeneity and/or degradation of a material from the building envelope, weak thermal areas defined as thermal bridges, moisture issues in the mass of the envelope component, air leakages through the envelope and other issues regarding the envelope and the building systems. [3]

In the energy expertise and energy audit activity, specialist in the energy efficiency domain use IR cameras as an additional instrument in the auditing activity of a building. Nowadays the IR cameras available on the market are becoming popular considering that more producer exist on the market and thus a drop in prices took place. But the use of IR camera can also come in hand in other situations met in practice. In many cases of current practice, one of the next situations are found: the technical documentation of the building is not available, or if the technical documentation is available the information regarding the materials used for the building envelope are not accurate. The inaccuracy

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comes from the fact that in the execution phase of the building, the constructive details (i.e. the materials) are not followed 100%, and sometimes the same happens with the constructive details of the building envelope described by the designer in the project. Thus, the real thermal performance of the building envelope is not the one obtained in the design phase and the impact is seen and felt in the maintenance costs of the building. Higher costs are showing the inaccuracy between the designed thermal performance of the building envelope, and the real thermal performance from the operation phase. In this case IRT can be a significant tool in diagnosing the real thermal performance of the building envelope.

The paper presents the development of a calculation algorithm and methodology and the computer program THERMOG that can be used to establish the thermal performance of an existing building by using IRT tools. The methodology and computer program can be used in both case, if technical documentation of the project exists or not. With the help of the program, the non-destructive measurement tool of IRT can offer a quick and reliable image on the thermal performance of a building component.

2. IR examination procedure

The IRT needs to follow several steps given in [2]. In order to prepare the surfaces that need to be themographed, one needs to heat the interior spaces of the examined building (i.e. space of the building). The boundary conditions of the measurements (i.e. wind speed, solar radiation, exterior and interior temperature, exterior and interior humidity, interior and exterior relative humidity, cloud cover) need to be registered to have an accurate interpretation of the acquired data. The data acquisition is recommended to be performed at sunrise or at sunset, on days with no solar radiation. [3, 4] The standard also recommends a temperature difference between the heated and the exterior environment of at least 10^{o}C. That is why it is recommended that the measurement to be done during the cold period of the year, both in the exterior and in the interior environment of the building. Part of existing literature suggest measurement to be done in the early morning so that the effect of thermal inertia of a building can be avoided. [5]

In doing the thermography investigation, the emissivity of the materials defining the photographed surface (i.e. the finishing) must be defined or it can be taken as a standard value given by normed prescription or IR catalogues.

Although the thermographic non-invasive method is used lately as an adjacent resource for diagnose and testing of buildings [6], its accurate interpretation depends very much on the expertise of the specialist using it. Thus, by some practitioners the IR camera is presented as a tool that can calculate the thermo-energy performance of the building. Although that in some countries the IRT is an instrument in the energy auditing activity of buildings, the scientific literature mentions that errors in evaluating thermal performance by means of IRT are somewhere around 30%-100%. [5]

3. The calculation methodology and THERMOG program

In order to enable the use of the resulted thermograms as input data in establishing the thermo-energetic performance of buildings and also give an adjacent instrument that can be used with the IR camera for practitioners, a methodology and a computer program was developed in this purpose.

The developed algorithm is based on a mathematical model that reconstructs the thermographic image in order to identify the temperature value of each pixel (i.e. point) of the surface. The boundary conditions, the surface emissivity and the original IR thermogram, are used as inputs in the calculation algorithm. The thermogram reconstruction algorithm is based on an artificial intelligence (AI) approach. It is well known that AI implies different tools, starting from machine learning and data science, deep learning and other tools like unsupervised models, graphic models, reinforcement learning, and others. For developing the algorithm of reconstructing the thermogram, an AI feature is used that is trained for a process of retention and self-learning of the arrangements in the colour palette, so that the initial thermogram can be reconstructed in order to obtain all the temperature points identified on the surface of the examined building component.

The thermogram is a sequence of tens of thousands or hundreds of thousands of colour shades. To each colours shade corresponds a temperature contained between the minimum and maximum temperature values of the scale (i.e. legend). In the legend is usually presented an extract from the colour palette of the thermogram, somewhere between 100 and a maximum of 200 colours. The task of the algorithm, that includes the AI approach, is that to identify the correct order of the tens of thousands colour shades of the palette, having different nuances. Knowing the correct orderliness of the palette, through a ready at hand mathematical calculation, one can establish the temperature values belonging to the colour palette, values contained within the maximum and the minimum values from the colours legend. Therefore, the questions that are addressed are: how many different nuances exist and which is their correct order. The AI module is decomposing each colour in its RGB components allowing the AI algorithm to arrange the colour palette based on its increased or decreased intensity of various nuances, resulting in the end a colour palette as it can be seen in figure 3.a. For each domain of shades of colour, by nonlinear multi-criteria polynomial interpolation calculation formula are establish to determine the colour shades specific to each domain. A variant for the calculation formula can be as it follows:

$$CSh = a_o + a_1 \cdot R + a_2 \cdot G + a_3 \cdot B + a_4 \cdot R^2 + a_5 \cdot G^2 + a_6 \cdot B^2 + a_7 \cdot R \cdot G + a_8 \cdot R \cdot B + a_9 \cdot G \cdot B + a_{10} \cdot R \cdot G \cdot B + a_{11} \cdot \ln(R) + a_{12} \cdot \ln(G) + a_{13} \cdot \ln(B) \quad (1)$$

where CSh stands for color shade.

The validation of the algorithm is given by the new colour palette (i.e. colour legend/scale) described by the reconstructed themogram, colour palette that must be identical to the initial one. The reconstructed thermogram is than converted into heat fluxes values with the help of which the thermal performance of each building envelope component is established.

The problem of the mathematical formulation was also discussed by Vavilov [5] [7] who identify the necessity of reconstructing thermograms so that these can be used as a tool in expressing the thermal performance of the building envelope. The author offered a simple formula for estimating the heat losses based on the temperature differences between the exterior surface of a reference point of the building envelope component and the exterior air, the temperature difference between the average exterior temperature of the building component and the exterior air, the current heat flow density at a reference point from the interior surface of the building component, the duration of the heating season and the area for the obtained average results. Also the instrumental errors were discussed showing a possible error between 37%-110% in the measuring processes. [5]

Another approach in establishing the thermal performance of a building component was done by Danielski and Froling [8]. The study was divided in two parts, first to determine the heat transfer coefficient through convection by means of thermography and heat flux meters measurement. The second part includes the determination of the overall heat transfer coefficient of the building component by thermography. The results indicate that thermography is more efficient (i.e. about 11% higher) in giving accurate results compared to heat flux meters measurements.

In [9] the authors present an application of artificial neural networks analysis in the use themographic investigations. The developed program enables the analysis of a thermogram supplemented by a colour scheme. The analysis is done by a backward temperature field detection that is accompanied by several features, i.e. number of visual and statistic elements.

Thermography was also used in detecting thermal bridges by means of image processing approximation algorithms [10]. An enhancement of the thermographic images was done by optimizing the mathematical algorithm for digital image processing. The results obtained from the segmentation procedure give an improvement in the identification of the thermal bridges from the thermographic image and also provides the possibility of establishing heat losses using an incidence factor of thermal bridge denote by I_{tb}. The incidence factor is a parameter higher than one and its accuracy depends on the resolution of the thermal map.

4. The study case – application of the THERMOG program

In developing the assessment methodology and the calculation program for the thermal performance of a building envelope component, several cases from real practice were employed for its validation. The focus of this paper is on glazing units that are lately substituting the role of the opaque surface of the wall, due to the fact that beneficiaries want a greater connection with the exterior environment which is translated to larger glazing units at a building. It is well known that glazing units are weaker thermal areas compared to the opaque surface of the building envelope through which high heat losses occur [11]. Thus, a study case of a residential building located in Cluj-Napoca, Romania was chosen with the aim to demonstrate the usage of the developed methodology and computer program.

Figure 1. The thermographed area – west façade

The building is a block of flats with a height regime B+GF+2FL. Investigation were made at an apartment situated at the ground floor level of the building. The technical data provided by the project indicates that the building has a mixed structural system, reinforced concrete frame system. The exterior walls are made out of thermal efficient masonry of 30 cm on which is placed 15 cm of thermal insulation layers. For the glazing area, a double glazed PVC window was used. One of the thermographs taken for the building are evaluated and the thermal performance of the building envelope component is obtain.

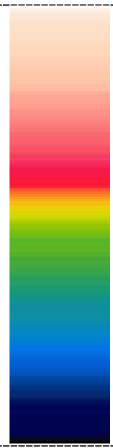
The thermograph (i.e. see figure 4) chosen to illustrate the usage of the methodology and computer program has a dimension of 315x253 pixels, which gives a total number of 79.695 pixels. To each pixel corresponds a colour from the colour palette. From the total number of pixels, 38.300 have distinct colours, the rest being colours that appear at least two times on the surface of the thermograph. To each distinct colour corresponds a temperature value between the minimum and maximum value from the colour pallet (i.e. legend of colours), respectively the maximum 11.3^{o}C and the minimum 4.4^{o}C (see figure 2).

The colours from figure 2 shows all different shades of colours existent on the surface of the thermograph. In figure 3 one can see all distinct colours arranged coherently based on their shades. In order to obtain an accurate colour palette presented in figure 3.a, the calculation module was used so that through the process of retention and self-learning of the arrangements in the colour palette, the colour scale presented at 3.b was obtained.

To each colour shade having the coordinates (x,y) corresponds a surface temperature $\theta_{si,(x,y)}$. Starting from the temperature in each point from the surface, the thermograph was established with the colours generated by the colour palette. It can be seen that figure 4 and figure 5 are identical, therefor demonstrating that the algorithm steps for the self-learning and restoration of all shades from the colour palette developed by the author, is validated.

Figure 2. The resulted colour pallette based on the first processing on the thermography

Figure 3.a The final colour pallete of the thermography



3.b

Based on the thermograph, the geometric characteristics for each type of surface were evaluated. The total surface, the opaque surface, the glazing surface divided by the frame are and the glass area. The next values were obtained: S_{total}=7.402 m^2, S_{opaque}=1.762 m^2, $S_{glazing}$=5.64 m^2 from which S_{frame}=1.462 m^2 and S_{glass}=4.178 m^2

Considering the formula given by nationals and internationals thermotechnical design norms [12] [13], the superficial thermal resistances in each point of the thermographed surface and the global average superficial thermal resistance on the surface of the thermograph was calculated $R_{se, av, T}$= 0.104 m^2·K/W. Also, the values for each component of the surface were calculated: opaque surface $R_{se,av,opaque}$= 0.105 m^2·K/W , $R_{se, av, glazing}$= 0.103 m^2·K/W global on the window surface, and on the frame $R_{se, av, frame}$= 0.104 m^2·K/W and on the surface of the glass $R_{se, av, glass}$= 0.103 m^2·K/W.

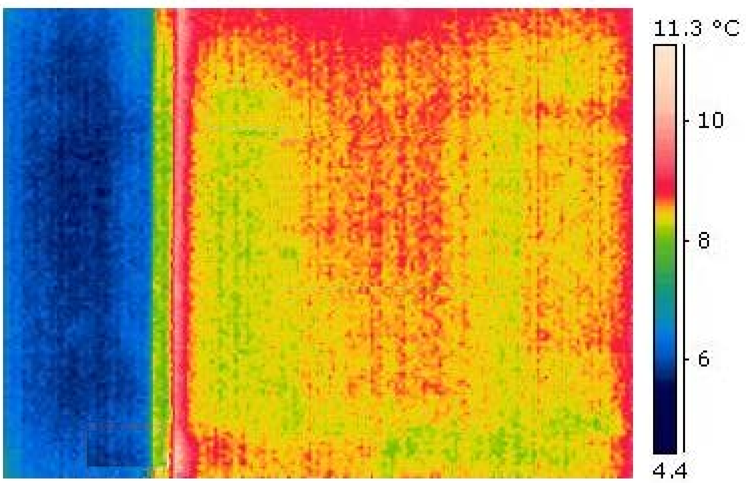


Figure 4. The initial thermogram corresponding to the window-wall area

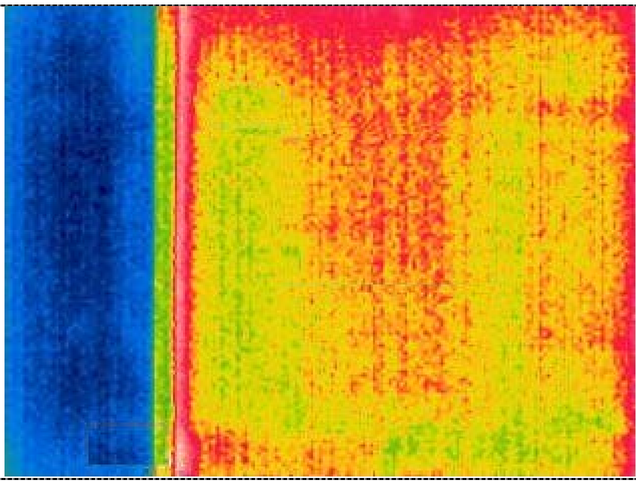


Figure 5. The processed thermogram corresponding to the window-wall area

Knowing the exterior temperature and the temperature in each point of the surface, the heat flows that dissipate from each point of the building element to the exterior environment, were calculated. The sum of the heat flows on the entire surface of the element, and separately on each type of surface, was obtain as it follows:

- globally on the thermographed surface Φ_{global}=234.719 W
- on the opaque surface Φ_{opaque}=6.250 W
- on the glazing surface $\Phi_{glazing}$=228.469 W
- on the frame surface Φ_{frame}=52.168 W
- on the glass surface Φ_{glass}=176.301 W

With the help of the heat fluxes, the exterior superficial thermal resistances (i.e. average values), the surfaces for each distinct area, the specific thermal resistance for the analysed surface, the thermal resistance in the current field of each specific zone R_o [$m^2 \cdot K/W$] is calculated:

- globally on the thermpographed surface R_{oe}=0.468 [$m^2 \cdot K/W$]
- on the opaque surface - $R_{oe,opaque}$=4.185 [$m^2 \cdot K/W$]
- on the glazing surface - $R_{oe,glazing}$=0.366 [$m^2 \cdot K/W$]
- on the frame surface - $R_{oe,frame}$=0.416 [$m^2 \cdot K/W$]
- on the glass surface - $R_{oe,glass}$=0.352 [$m^2 \cdot K/W$]

After calculating these values, knowing the exterior air temperature, interior air temperature, the average superficial thermal resistances and the average unidirectional thermal resistances for each specific zone previously mentioned, by doing an elementary iterative calculation the average interior superficial thermal resistance for each distinct zone is calculated. Finding this value can give us the thermal behaviour of each analysed zone.

Other calculations can be done to identify if the thermotechanical properties of the used materials correspond to the ones mentioned in the technical data of the project. Thus, for the opaque zone of the thermographed area: we know that the opaque area is given by the interior rendering having a thickness of 2 cm with thermal conductivity λ=0.87 W/(m.K), aerated cellular concrete (i.e. ACC) of 30 cm and thermal insulation of expanded polystyrene with a thickness of 15 cm. Based on the ACC available at the beneficiary, the thermal conductivity was established, resulting a value λ_{ACC}=0.243 W/(m·K). Knowing the geometric characteristics of each layer and the thermotechnical characteristics of the materials, and knowing the unidirectional thermal resistance for the opaque area $R_{oe,opaque}$ the thermal resistance of the insulation layer is established being equal to $R_{therm.ins.}$=2.467 [$m^2 \cdot K/W$], corresponding to a thermal insulation having a value $\lambda_{therm.ins}$=0.041 W/(m·K), greater than the one mentioned in the technical documentation of the building, as being $\lambda_{therm.ins}$=0.036 W/(m·K).

Analysing the thermal performance of the glazing area for the frame, an average thermal resistance was obtained R_{frame} =0.416 [$m^{2\cdot}K$/ W], which means a thermal transmittance U_{frame}=2.404 [W/$m^{2\cdot}K$]. Compared to U=1.2 [W/m^2K] that corresponds to a 6 chambers frame as mentioned in the technical documentation of the project, the value U_{frame}=2.404 [W/$m^{2\cdot}K$] corresponds to a PVC frame having three chambers [14], thus not meeting the data (i.e. the requirements) mentioned in the technical documentation of the project.
For the glass area of the window, an average value R_{glass}=0.352 [$m^{2\cdot}K$/ W] was calculated, that gives a thermal resistance U_{glass}=2.841 [W/$m^{2\cdot}K$] which correspond to a glass area without thermoreflective surfaces, a different solution compared to the one mentioned in the technical documentation of the project which is a glass surface filled with Argon gas and thermoreflective surfaces. As a global value for the glazing surface, the overall values is $R_{glazing}$=0.366 [$m^{2\cdot}K$/ W] which means half of the minimum recommended value $R_{min,glazing}$=0.77 [$m^{2\cdot}K$/ W] as imposed by national thermotechnical design norms [15]
Similar calculations can be done for other thermograms, for both vertical and horizontal building envelope components. Thus, the non-destructive measurement tool of IRT together with the program THERMOG can offer a quick and reliable information regarding the thermal performance of a building component and of the entire building envelope.

5. Conclusions
It is well known that in design phase, decisions that are not properly chosen for the building envelope will have a direct negative impact on the lifespan of the building, which translate to high energy consumptions and large greenhouse gas emissions. The Infrared Termography is a tool mainly used for quality control of buildings envelope, although that its usage can also be for quantitative evaluation of the thermal performance of it. The calculation methodology and the computer program THERMOG elaborated by the author can be used both in the energy expertise activity of existing buildings and in the reception phase of new buildings. Considering the long path strategy of the European Union of decarbonizing all building sector [16], the energy retrofit of existing buildings and the fulfilment of the nZEB criteria for new and existing buildings is pushing the market on a path that implies accurate solutions in designing and retrofitting buildings. IRT together with the computer program THERMOG is a tool that can answer this call by helping practitioners in choosing solutions based on an accurate assessment of the real thermal behaviour of a building.

6. References
[1] Danielski I 2012 Large variations in specific final energy use in Swedish apartment buildings: Causes and solutions *Energy and Buildings* **49** 276-85
[2] ISO 6781:1983 Thermal insulation – Qualitative detection of thermal irregularities in building envelopes – Infrared method I. O. f. Standardization
[3] Pleşu R, Teodosiu G and Ţăranu G 2012 Infrared Thermography Application for Building Investigation *Buletinul Institutului Politehnic din Iasi* **LVIII** 157-68
[4] Jaworski J 2008 The infrared thermography of buildings proceeding its surrounding and their thermal performance in *9th International Conference on Quantitative InfraRed Thermography* Krakow
[5] Vavilov VP 2010 A Pessimistic View of the Energy Auditing of Building Structures with the Use of Infrared Thermography *Russian Journal of Nondestructive Testing* **46** 49-54
[6] Asdrubali F, Baldinelli G, Bianchi F, Costarelli D, Rotili A, Seracini M and Vinti G Detection of thermal bridges from thermographic images for the analysis of buildings energy performance
[7] Vavilova VP, Marinetti S and Nesteruk DA 2009 Evaluating the Thermal Resistance of Building Structures," *Russian Journal of Nondestructive Testing* **45** 50-61
[8] Danielski I and Frolling M 2015 Diagnosis of buildings' thermal performance - a quantitative method using thermography under non-steady state heat flow *Energy Procedia* **83** 320-29

[9] Koštialová Jančíková Z, Kostial P, Zimny O, Heger M and Spicka I Artificial Neural Networks Application in Thermography," in *13th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics* 408-11

[10] Asdrubali F, Baldinelli G, Bianchi F, Costarelli D, Rotili A, Seracini M and Vinti G 2018 Detection of thermal bridges from thermographic images by means of image processing approximation algorithms *Applied Mathematics and Computation* **317** 160-171

[11] Babotă F and Iernuţan R 2019 Calculation and analysis of corrected thermal resistance in a common dwelling building in Romania, in various thermal insulation options – The exterior wall *Procedia Manufacturing* **32** 442-49

[12] SR EN ISO 6946 2017 Componente si elemente de clădire. rezistenţa termică şi transmitanţă termică. metode de calcul.(Building components and building elements - thermal resistance and thermal transmittance - Calculation methods) Asociatia de Standardizare din Romania

[13] SR EN ISO 10211 2017 Punti termice in alcatuirea cladirilor. Fluxuri termice si temperaturi superficiale. Calcule detaliate. (Thermal bridges in building construction - heat flows and surface temperatures - Detailed calculations.) Asociatia de Standardizare din Romania

[14] SR EN ISO 10077-2 2018 Performanţa termică a ferestrelor, uşilor şi obloanelor. Calculul transmitanţei termice. Partea 2: Metoda numerică pentru profilurile de tâmplărie.(Calculation of the thermal performance of windows, doors and shutters- Part 2) Asociaţia de Standardizare din România

[15] Order no. 2641/2017 to amend and supplement the Technical Regulation "Calculation methodology of the energy performance of buildings", Romania: Ministry of Regional Development and Public Administration

[16] Directive (EU) 2018/844 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency Official Journal of the European Union