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Comparative Analysis of Some Thermal Technical Indexes of Building Envelopes, Obtained through Quantitative Infrared Thermography (IRT)

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Abstract: - Almost 50% of the final energy consumption in the Union is used for heating and cooling, and 80% of the latter is used in dwellings. The thermal technical indexes of buildings and facilities, built in the last century, don't correspond to thermal technical regulatory framework, actual now. The normative requirements have changed, as well as the thermal technical characteristics of the buildings due to the aging, the aggressiveness of the environment in livestock farm buildings for raising pigs - high temperature and humidity, an evaporation of aggressive gases. There we have a controlled microclimate, a stationary mode of operation of a system (building envelope) could be accepted. The analytical value of the heat transfer coefficient (U) is determined. Then we determine the instantaneous values of the heat transfer coefficient (U) of the building envelope with IRT only, but using different standards. The principal contribution of this research is the attempt to examine, analyse, compare the results, obtained to determine the U-values only using quantitative external infrared thermography with different methods and calculation formulas. We try to go one step ahead - to answer how to choose the most suitable method for such an investigation and what are the criteria for exactly to asses the uncertainties for each method.

Keywords: Energy Consumption, Energy Efficiency, Stationary Mode of Working Systems, "In-Situ" Methods, Quantitative IRT, Uncertainties

I. Introduction

In recent decades, attention has been directed on the implementation of the Paris Agreement [1] about the climate change, following the 21st session of the Conference of the Parties to the United Nations Framework Convention on the Climate Change [SOR 21]. According to the tasks of other European Union Directives [1,2,3,4,5,6,7], a sustainable, competitive, secure and decarbonized energy systems have to be developed by 2050.

Almost 50% of the final energy consumption in the Union is used for heating and cooling, and 80% of the latter is used in buildings. The last ones, especially built in the last century, don't correspond to thermal-technical regulatory framework, actual now. In the last decades, both normative requirements have changed, as well as the thermal-technical characteristics of the buildings due to the aging of working systems. [8,9]

Our interest and principal contribution is the determination the actual instantaneous values of the heat transfer coefficient [U] and a comparison with the analytically calculated values. The livestock buildings for raising pigs have a controlled microclimate, so a ***stationary mode of operation of a system (building envelope) could be accepted.*** The environment is characterized with high temperature and humidity, an evaporation of aggressive gases due to the production processes.

II. Objective

Determination of the instantaneous values of the heat transfer coefficient (U) of the building envelope in dwellings with a controlled microclimate with an assumption of a stationary mode of operation of a system with IRT using different standards.

The research is carried out on the territory of the south – eastern Bulgaria during the winter heating period according to requirements of the standard that this survey has been based. The used devices are calibrated and we are responsible that they meet the requirements of the standard as well.

To achieve the stated goal, we solve the following tasks:

1. The analytical value of the heat transfer coefficient (U) is determined with a classical formula, according to the current regulatory framework, which includes the thermal conductivity coefficient (λ), the thickness of the corresponding layer (d), and the heat transfer coefficient (h). [8,9]

2. Determination of the instantaneous values of the heat transfer coefficient (U) using an "in-situ" method - infrared thermography (IRT). [14,15]

3. Determination of the heat transfer coefficient (U) with different methods (different calculation formulas in standards, with the same data of the surface temperature, obtained by IRT).[14,15]

4. Analysis, comparison and assessment of the instantaneous values of the heat transfer coefficient (U), obtained with different formulas and methods, and the analytical ones.

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5. Assessment the credibility of the results using different methods, valuation of the environmental condition in application of different methods in practice, conclusions and recommendations in order to choose the most suitable methods.

III. Methodology

The building envelope is a barrier that separates the exterior from the interior space, and aims to protect people and animals. In production buildings is maintained a controlled microclimate for the implementation of a given production process and technology. We determine the real values of a heat transfer coefficient - U values, in a stationary mode of working systems - building envelopes with an “in-situ” method.

IV. Goals

We investigate a production complex – an agricultural center for raising pork in the south – eastern Bulgaria. The area of the complex is 8 250 m^2. The built up area is 3 880 m^2. The size of the production areas depends on the possibilities of applying industrial cultivation technologies and a maximum of their advantages. The buildings are placed in such an order to respect the sequence of the production process.

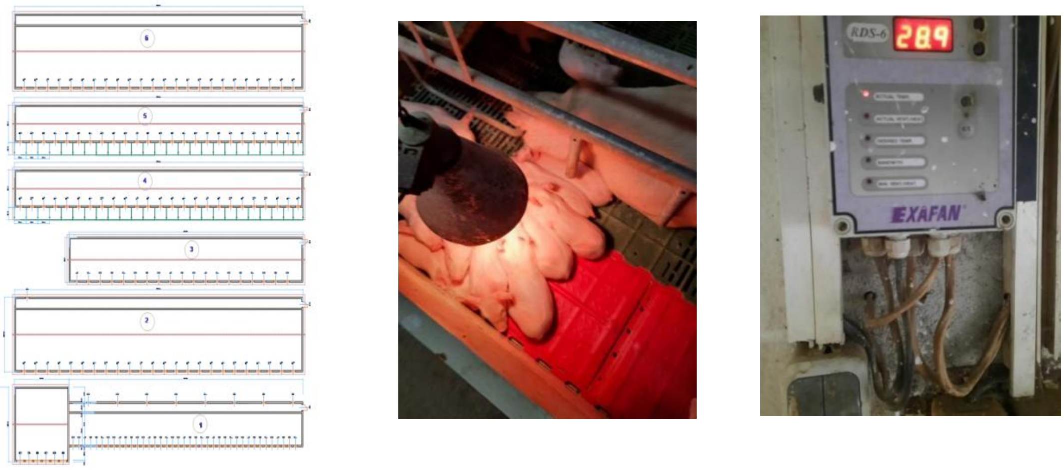

Fig. 1. A livestock farm buildings for raising pigs –architectural plan and technological requirements

A. *Analytical calculation to determine the heat transfer coefficient (U)*

The classical formula is used to determine the heat transfer coefficient (U) for a multi-layer opaque wall during the design process and after accomplishing the construction and whole building with the normative values of the the thermal conductivity coefficients of insulation materials. [8,9]

$$U = R^{-1} = \left[\frac{1}{h_i} + \sum_{j=1}^{n} \frac{d_j}{\lambda_j} + \frac{1}{h_e} \right]^{-1}, \left[W / m^2.K \right] \tag{1}$$

Here we don’t take into account the changes in the structure of the used materials cause the long-term work of a production buildings and their aging, also the influence of external aggressive factors in atmosphere, in our case – the aggressiveness of the environment due to the technological conditions of production activity. We pointed out at a difference comparing the values of the laboratory determined and real ones. The actual values of a thermal indexes in existing production buildings may be considered with “in-situ” methods. Thus we could get the idea of a real thermal condition of a building envelope in order to overcome the so-called “performance gap”. [10,11,12]

B. *The determination of the heat transfer coefficient with “in-situ” method – infrared thermography [IRT].*

A difference in the values of the heat transfer coefficient (U) is noted cause of the snapshot of the building, that shows the actual temperatures in the thermal images of the walls of the investigated area of the building envelope.

Fig. 2 Thermal camera E54 for thermal inspection of livestock farm buildings with a controlled microclimate

1.) A formula is proposed by Fokaides et al. for a calculation of the heat transfer coefficient (U) [18-19] according ***ISO 9869 – 2 "Thermal insulation – Building elements – on-site measurement of thermal resistance and thermal transmittance – Part 2:Infrared thermography for surveying the device of a dwelling or building.***

$$U = \frac{\varepsilon_v \sigma . \left(T_{s,out}{}^4 - T_{out}{}^4\right) + 3.805 v (T_{s,out} - T_{out})}{T_{int} - T_{out}}, \; [\mathrm{W/m^2.K}] \quad (2)$$

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Where: ε_v is the wall spectral emissivity; σ is the Stefan–Bolzmann constant [$W/m^2.K^4$]; $T_{s,out}$ is the outer surface temperature [K]; T_{out} is the outdoor ambient temperature [K]; ν is the wind speed [m/s]; and T_{int} is the indoor ambient temperature [K].Under similar conditions, internal thermographic inspection is preferable to external thermographic imaging.

Results of thermal imaging can be evaluated both qualitatively and quantitatively [16,17]. In qualitative analysis the thermograms are examined for temperature anomalies based on the temperature difference at the location of the presumed defect and the reference zone [18, 19, 20–25]. The reference zone should be selected similarly to the controlled zone and to be in the same heat exchange conditions (located near the inspected area).

Qualitative analysis of thermal images allows determining the location of a construction defect. This type of assessment of the control objects about technical conditions is based solely on the temperature field generated by the thermal images, specifically on the temperature difference reading on a structurally homogeneous element of the enclosure. The presence of sharp temperature gradients and minimum (or maximum, depending on the location of the thermographic imaging) temperatures concentrated in a specific area of the thermogram provides grounds to believe in the existence of a temperature anomaly and, consequently, a construction defect.

Quantitative assessment of temperature anomalies is carried out to determine their degree of danger for the normal functioning of the building. Usually, the results of quantitative analysis are compared with benchmark values, typically regulated by various normative documents (state standards, sets of rules, etc.).

Some variants of quantitative analysis of thermal images proposed by different normative acts and advisory documents (methodological recommendations) are examined.

2). The calculations according to the Russian standard regulatory requirements - State Standard R 54852-2021. Buildings and constructions. Quality control of enclosing structures insulation thermovision method. [15].

A quantitative analysis of thermal images is based on calculating local relative (compared to the baseline section) thermal resistance. The value of the ***relative thermal resistance at a selected point*** on the surface of the enclosing structure is determined as follows:

$$R_{(x;y)} = 1 + \frac{\theta_{(x,y)}}{T_{out} - \tau_{out}^{b} - \theta_{(x,y)}} \quad (3)$$

The θ *(x;y)* is the difference between the temperature τ *(x;y)* of the isotherm passing through the point with coordinates x and y on the corresponding surface of the enclosing structure and the temperature of the surface of the baseline section τ_{out}^{b}, °C; T_{out} is the temperature of the external air in the zone of the examined fragment, °C; τ^{b} is the temperature of the surface of the baseline section for internal and external inspections, °C.

The value of the random relative error in determining the relative thermal resistance is calculated according to the equation:

$$\delta\bar{R}_{\text{н}} = \left|\frac{1}{t_{\text{н}}-\tau_{\text{н}}^{\text{б}}}\right| \sqrt{\left[\frac{\theta(x,y)}{t_{\text{н}}-\tau_{\text{н}}^{\text{б}}}\Delta t_{\text{н}}\right]^2 + \left[\frac{\theta(x,y)}{t_{\text{н}}-\tau_{\text{н}}^{\text{б}}}\Delta \tau_{\text{н}}^{\text{б}}\right]^2 + \Delta\theta^2},$$

*3). **A common method of quantitative analysis of thermal images is the identification of areas of enclosing structures with increased heat losses.***

The thermal resistance, R [m²*.K/W], is calculated on the basis of a*** Newton's equation for quasi-stationary conditions and the formula of ISO 9869-1:2014 [13] are used. The areas of enclosing structures with increased heat losses are identified by comparing the thermal resistance of enclosing structures obtained as a result of field measurements with the required value, determined according to the formula:

$$R_o^{theor} = \frac{T_{in} - T_{out}}{{}_{\Delta}T \cdot \alpha_{in}}, \; [m^2.K/W] \qquad (4)$$

There T_{in} is the calculated temperature of the indoor air, T_{out} is the calculated temperature of the outdoor air in the cold period of year, °C. For the region of Stara Zagora, the T_{out} is 7 °C, T_{in} for this production technology is 28°C. ${}_{\Delta}T$ is the normalized temperature difference, °C, between the temperature of indoor air T_{in} and the temperature of the inner surface of the enclosing structure $\tau_{in,}$ °C. According to current regulatory requirements in the territory of Bulgaria - ${}_{\Delta}T$ = 4,0 °C; α_{in} is the coefficient of heat transfer of the inner surface of the structure, usually assumed to be equal to 7,69 $[W/m^2.\,K]$.

4.) To determine the thermal resistance based on field measurements in external inspection, the following equation can be used:

$$R_o^{fact} = \frac{1}{\alpha_{out}} \cdot \frac{T_{in} - T_{out}}{\tau_{out} - T_{out}}, \quad [m^2.K/W] \qquad (5)$$

Where - α_{out} is the coefficient of heat transfer of the external surface of the structure, $[W/m^2.\,K]$ at a wind speed of v =1 м/s the heat transfer coefficient α =**25** $[W/m^2.\,K]$, τ_{out} is the temperature of the external surface of the enclosing structure determined from thermography.

V. Results

TABLE I. ANALYTICAL CALCULATION TO DETERMINE THE HEAT TRANSFER COEFFICIENT(U)

№	**Name**	**Components**	**d**	**λ**	**R**
			[m]	**[W/m.K]**	**[m².K/W]**
Heat transfer resistance and heat transfer coefficient for building envelope –walls at the south facade at windows N2, N6, N10 and N 11					
1	Internal heat transfer	R_{si} - heat transfer			0.1300
2	Internal lime-cement plaster	R_1 - thermal conductivity	0.015	0,7	0.0214
3	Bricks (ordinary)	R_2 - thermal conductivity	0.25	0.52	0,48
4	External lime-cement plaster	R_3 - thermal conductivity	0.015	0,7	0.0214
5	External heat transfer	R_{se} - heat transfer			0.0400
6	Total heat transfer resisitance	R_T			0,6928
		dimension			[W/m².K]
7	Heat transfer coefficient	U			1.443

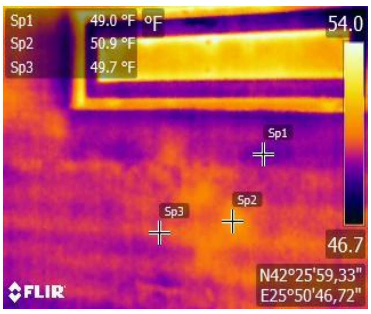

Fig. 3 Thermal and visible image at window 2 of the building wall – envelope

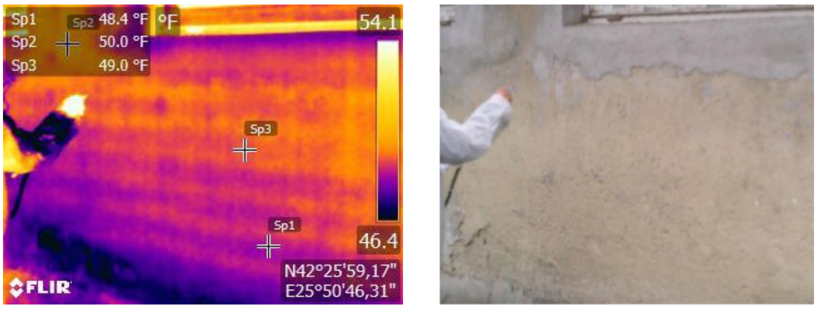

Fig. 4 Thermal and visible image at window 6 of the building wall – envelope

TABLE II. EXPERIMENTALLY OBTAINED VALUES WHEN USING "IN-SITU' METHOD TO DETERMINE

THE CURRENT VALUES OF A HEAT TRANSFER COEFFICIENT (U) - INTRARED THERMOGRAPHY (IRT)	*Wall (envelope)*					*Temperature in the working area raising pigs*
A stationary mode of working envelope systems – building with controlled microclimate	*T_{out} (C°)*	*Marker*			*$T_{s,int}$ (C°)*	*T_{int} (C°)*
		p1	*Sp2*	*Sp3*		
		Point				
		Cold	*Hot*	*Average*		
South facade – Window 2	*9,00*	*9,44*	*10,50*	*9.83*	*20,3*	*28,9*
South facade – Window 6	*9,00*	*9,11*	*10,00*	*9,44*	*20,8*	*23,9*

TABLE III. CALCULATED VALUES TO DETERMINE THE HEAT TRANSFER COEFFICIENT (U) ANALYTICALLY AND USING INTRARED THERMOGRAPHY (IRT)

South facade – Window 2	$T_{s,out}$ (C°) obtained from IRT images		
	Marker		
	Sp1	Sp2	Sp3
	Point		
	Cold	Hot	Average
	9,44	10,50	9,83
Wall (envelope) – the obtained values of the heat transfer coefficient (U[W/m^2.K])			
Analytical calculation to determine the heat transfer coefficient (U)	1,443	1,443	1,443
Calculation of the heat transfer coefficient (U) according ISO 9869 – 2	0,98	3,06	1,69
Calculation of the heat transfer coefficient (U) from relative thermal resistance according Russian standard regulatory requirements - State Standard R 54852-2021.		1,82	
A common method of quantitative analysis of thermal images - theoretically.	1,47	1,47	1,47
A common method of quantitative analysis of thermal images – factually	0.88	2.04	1.14
South facade – Window 6	$T_{s,out}$ (C°) obtained from IRT images		
	Marker		
	Sp1	Sp2	Sp3
	Points		
	Cold	Hot	Average
	9,11	10,00	9,44
Wall (envelope) – the obtained values of the heat transfer coefficient (U[W/m^2.K])			
Analytical calculation to determine the heat transfer coefficient (U)	1.443	1.443	1.443
Calculation of the heat transfer coefficient (U) according ISO 9869 – 2	0.67	2.56	1.58
Calculation of the heat transfer coefficient (U) according Russian standard regulatory requirements - State Standard R 54852-2021.		2.27	

A common method of quantitative analysis of thermal images-theoretically.	1.47	1.47	1.47
A common method of quantitative analysis of thermal images – factually	0.26	1.82	0.88

VI. CONCLUSIONS

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

The principal contribution of this research is the attempt to examine, analyse, compare the results, obtained to determine the U-values ***only using quantitative external infrared thermography with different methods and calculation formulas.***

The formula, proposed by Fokaides et al., for a calculation the value of the heat transfer coefficient (U) [18-19], is according to ***ISO 9869 – 2.*** [14]

The results ***for relative values of a thermal resistance*** are from the Russian standard regulatory requirements - ***State Standard R 54852-2021. Buildings and constructions. Quality control of enclosing structures insulation thermovision method.*** [15]

Also we calculate the values of the thermal resistance with normative values of the specific area of investigation, and with these, set up at the moment, with Newton's equation for quasi-stationary conditions and the formula.Our purpose is the comparison of all results, obtained with only one "in-situ" method, with the same temperatures, but with different calculation formulas.

Thus we expand the scope of examined data of U-values with practical "in-situ" methods, the development in the expanding knowledge, therefore the possibility to receive the most reliable and real information about the thermal technical condition and working mode of building envelope.

In the used formula according ***ISO 9869 – 2 "Thermal insulation – Building elements – on-site measurement of thermal resistance and thermal transmittance – Part 2:Infrared thermography for surveying the device of a dwelling or building*** [14], the heat transfer by radiation and convection are calculated. In the ***State Standard R 54852-2021. Buildings and constructions. Quality control of enclosing structures insulation thermovision method*** [15] the values of a relative thermal resistance are obtained Also the empirical formula, based on therrmographic analysis is used.

The quantitative analysis of thermal images allows determining the location of a construction defect. The presence of sharp temperature gradients and minimum and/or maximum temperatures concentrated in a specific area of thermogram provides data for an identification of a temperature anomaly and, consequently, a construction defect. Quantitative assessment of temperature anomalies is carried out to determine their degree of danger for the normal functioning of the building. According to regulatory requirements [15], quantitative analysis of thermal images is based on calculating local relative (compared to the baseline section) thermal resistance. The value of the relative thermal resistance $\bar{R}(x, y)$ at a selected point on the surface of the enclosing structure is determined.

A common method of quantitative analysis of thermal images is the identification of areas of enclosing structures with increased heat losses. In this case, thermal resistances, are calculated for the base and other characteristic sections and compared with the required value. There the Newton's equation for quasi-stationary conditions and the formula of ISO 9869-1:2014 [13] are used.

$$U = \frac{h_i (T_{\text{int}} - T_{s,\text{int}})}{T_{\text{int}} - T_{out}}, [W / m^2.K] \tag{6}$$

The presented results firstly confirm that thermal imaging diagnostics requires both a qualitative and quantitative assessment of the building envelope. It is necessary for a plain comprehensive research and for a comparison of the calculated parameters using "in-situ" methods with the analytically obtained values with normative indexes. We found out that there is a sharp difference - 15 - 20% (40%) between the analytical calculated values and the set up "in-situ" ones.

We repeat and confirm this difference between the thermal technical indicators when using analytical calculation and "in-situ" methods, in other scientific researches. We go one step further, exactly - we ask how and when this difference changes, what is decisive when choosing one or another method, what method is more suitable in some practical cases, for a purpose to obtain the optimum real data of the U-value.

In our case we have an old livestock farm building, the principal leading factor is a controlled microclimate and therefore an ***assumption of a stationary mode of operation of the system. The production technology and processes are suitable for our investigation.***

We emphasize that the use of IRT in building survey is very wide-ranging principally, mean qualitative and quantitative survey. When doing the quantitative investigation we choose the right and suitable methodology and calculations. We make an attempt to obtain the exact methodology with minimum system errors, and suitable calculations.

There are some requirements to implement the methodology: the surface of the walls must be dry, it's necessary to avoid the presence of dust particles, the roughness etc., it shouldn't rain, wind speed no higher than 8m/s, recommended inspected wall not exposed to direct sunlight. Should be considered, that the quality of the thermogram worsens with distance from the control object, the water vapor in the air absorbs long-wave infrared radiation, thermal imaging should be conducted at the minimum possible distance from the control object. Under similar conditions, internal thermographic inspection is preferable to external thermographic imaging.

All these problems and questions require a serious and thorough professional attention, deep analysis of the external factors, the capabilities of the used devices, the kind of buildings surveyed, the period of inspection and investigation, in order to obtain right results and to minimize the error.

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