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Title: A comprehensive experimental approach for the validation of quantitative infrared thermography in the evaluation of building thermal transmittance

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A comprehensive experimental approach for the validation of quantitative infrared thermography in the evaluation of building thermal transmittance

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Abstract

Quantitative thermography is now mostly accepted as a reliable method to measure energy performance of existing buildings, in particular the thermal transmittance U-values of opaque elements. Some researches have been conducted in this field, each presenting a different procedure verified by the application on simple case studies. Anyway, a comprehensive approach, based on a parametric analysis of walls with different typologies and exposure, but same boundary conditions, is still missing. This study proposes a systematic approach to the problem, based on a three years research activity carried on an experimental building where timber (light) and brick (heavy) structures were tested simultaneously with Infrared Thermovision Technique (ITT), also equipped with heat flow meter HFM sensors and a nearby meteo station. Standard deviation of U-values measured with ITT is given as well as absolute deviation against values calculated following international standards and measured with HFM method. Parameters having high significance for the achievement of good results compared to the expected U-values are assessed through a sensitivity analysis. Influence of weather conditions during the survey are also considered and a repeatable procedure is finally set up. The findings presented in the study show that the method gives good results for heavy constructions, while further studies are still needed for light and super-insulated walls.

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1. Introduction

This paper deals with a research project that follows the procedure for the on site determination of thermal transmittance U-value of opaque building elements based on Infrared Thermovision Technique ITT, previously proposed by the authors [1]. In order to deeply understand limits and strength of the method and to determine its accuracy for different walls typologies, the procedure has been validated on an experimental purpose-built construction. The importance of a proper evaluation of the building envelope real energy performance as well as the state of the art of the use of quantitative thermography has been already presented and discussed [1]. Anyway, from 2010 there have been important innovations and breakthroughs in this research area.

Considering international energy regulations, two European Directives came recently into force, the 2010/31/EU [2] so called NZEB (nearly zero energy buildings) and the 2012/27/EU [3]. They have forced public administrations, designers, private companies and building materials manufacturers to ensure the minimum deviation as possible between designed and real building energy performance, in order to achieve the Union's 2020 20% headline. Prada et al. [4] showed that, among the thermo physical properties of the building envelope, the uncertainty concerning thermal conductivity as input data for energy simulation is what mostly affects the final output accuracy during the design phase concerning heat losses, both outward during winter and inward during summer. Just to evaluate the as-built performance of buildings concerning the U-values of the envelope, in the last 5 years several researchers, other than the authors, used quantitative ITT leading to interesting results. Recently, in fact, the application of ITT has been enhanced as a result of the decrease of the cost of handheld thermal cameras due to the development in infrared detection technology [5] and to the significant improvement of the measurement accuracy. Sham et al [6] showed that ITT allows to make direct measurement of energy released by building fabrics with continuous surface temperature measurement with discrepancy of only 1.8-5.2% between estimated and calculated sensible heat loss. Fokaides and Kalogirou [7] proposed a method to determinate the overall heat transfer coefficient of building envelopes with the use of infrared thermography following a procedure defined in [8]. They found an acceptable absolute deviation percentage in the range of 10-20% between measured and theoretical expected values on typical heavy walls of Cyprus existing building typology. The performed sensitivity analysis proved the reflected apparent temperature, the wall temperature and the emissivity of the building surface to be the most sensitive variables. Asdrubali et al [9] proposed a methodology to perform a quantitative analysis of thermal bridges by means of thermographic survey and analytical post-processing, introducing the incident factor of the thermal bridge validated both in laboratory and on site. Ferreira et al. [10] followed the same procedure proposed by the authors for measuring the U-value of building envelopes, replacing the modified Jurges' equation with the convective coefficient obtained from the expression given by Y. Liu and D.J. Harris [11]. The difference between theoretical and real energy demand of existing buildings has been established. Dall'O et al [12] proposed an audit campaign on existing buildings in Italy measuring the difference between calculated and measured U-values following the procedure introduced by the authors, with slight changes concerning the measure of inner and outer air temperature particularly.

Nevertheless, at the state of the art a comprehensive study on the determination of U-values using ITT is missing. The study should be based on long-term monitoring, conveniently repeated also considering a parametric comparison between walls with different thermal properties and exposure but same boundary conditions; results should be compared with those obtained using accepted and standardized on site monitoring systems in order to evaluate both standard and absolute deviations.

The present study aims at filling this gap.

Nomenclature

c	*specific heat [J/kgK]*
C	*thermal capacity [kJ/m^{2}K]*
C_{10}	*effective thermal capacity [kJ/m^{2}K]*
E	*thermal power dissipated for radiation [W/m^2]*
f	*decrement factor*
H	*thermal power dissipated for convection [W/m^2]*
M	*mass per unit area [kg/m^2]*
P	*thermal power [W/m^2]*
Q	*heat [J]*
S	*total wall thickness [m]*
t	*single layer thickness [m]*
T	*temperature [K]*
U	*thermal transmittance [W/m^{2}K]*
v	*local wind speed [m/s]*

Greek symbols

ε	*thermal emissivity or hemispherical emittance of the surface (the two terms are considered synonymous in the manuscript)*
λ	*thermal conductivity [W/mK]*
ν	*wavelength range [µm]*
ρ	*density [kg/m^3]*
φ	*thermal delay (time lag) factor [h]*

Abbreviation

AD	*absolute deviation*
d	*design*
ITT	*Infrared Thermovision Technique*
HFM	*heat flow meter*
SD	*standard deviation*

W	*wall*

Index

h	*half wall thickness*
I	*surface*
int	*inner*
n	*north*
out	*environment*
s	*south*
w	*window*

2. Methodology

The methodology for the on site determination of thermal transmittance U-values of opaque building elements, described in [1] and briefly cited in the following chapter 2.1, has been applied on the walls of an experimental building (Fig. 1) in order to:

1. verify the discrepancy between the results of the ITT methodology, of the theoretical calculation following the standard UNI EN ISO 6946:2008 [13] and of the ones given by the thermal flux meter (HFM) method based on the ISO 9869:1994 [14];
2. verify the applicability of the method and the deviations on walls with different mass and heat capacity per unit area (light walls vs heavy walls);
3. investigate possible discrepancies in the outputs due to different exposure of the same element, so as to properly consider the influence of direct solar radiation;
4. analyze the influence of weather conditions prior to the monitoring, to set the most feasible boundary conditions leading to the minimization of measurement errors;
5. perform a sensitivity analysis to understand which parameters are significant for achieving good results compared to the expected U-values and then which are the most critical steps needing particular attention during the survey.

Fig. 1

At this point, a robust experimental campaign was set up on a building specially designed for the research (a complete description is proposed in chapter 3), with five test walls (two light and three heavy structures) facing north and five twin walls facing south. The thermo physical characteristics of each element were determined following the UNI EN ISO 6946:2008 [13] and five HFMs have been positioned on the walls facing north (one each) in order to determine the U-value as specified by the ISO 9869:1994 [14] with data acquisition every 10 minutes.

The experimental campaign was divided into three main periods:

1. First period: November 2010 – March 2011: setting of the survey methodology; monitoring under different weather conditions and multiple times per day; first comparison and analysis of results; proposal of modifications and refinements of the survey phases; setting up of a reliable procedure
2. Second period: November 2011 – March 2012: monitoring campaign following the procedure previously defined and verification of the assumptions; analysis of results and refinements
3. Third period: November 2012 – March 2013: final verification of the proposed procedure

A three-year research was considered necessary in order to collect a proper number of data and to perform a parametric analysis answering to the main questions stressed before. As Lehmann et al. [5] underline, in fact, “there are often pressure to present convincing results and do not have means of performing additional tests and calibrations, with the risk of misinterpreting the obtained thermal images”.

On site thermographic surveys were carried out alternatively by two teams, each composed by two trained technicians. During each survey, the thermal images of the ten walls from outside (five on the northern façade and five on the southern one) were collected. In total, during the three periods mentioned above, 56 measurement surveys were performed, which is equivalent to 560 single inspections of the walls under investigation.

2.1 Formulation of ITT equation

The formulation of the equation used to determine the thermal transmittance value of opaque building elements with ITT methodology is extensively reported in [1]. Here it is briefly cited with one modification and one clarification.

Thermal transmittance is the ratio between thermal power P and the difference between inner and outer temperature:

$$U = P/ (T_{int}–T_{out}) \text{ [W/m}^2\text{K]} \quad (1)$$

P is due to heat Q passing through the element, dissipated from its outer surface and finally transferred to the IR thermal camera sensor by means of convection and radiation. Therefore, P is the sum of E, thermal power dissipated for radiation, and H, thermal power dissipated for convection:

$$E = 5.67\ \varepsilon_v\ ((T_i/100)^4 - (T_{out}/100)^4 \text{ [W/m}^2] \quad (2)$$

considering the Stefan-Boltzman Law for grey body radiation, and

$$H = 3.8054\ v\ (T_i – T_{out})\ [W/m^2] \qquad (3)$$

considering Jürges’ equation when v<5m/s, slightly modified.

So

$$U = (5.67\ \varepsilon_v\ ((T_i/100)4 - (T_{out}/100)4) + 3.8054\ v\ (T_i – T_{out})) /(T_{int} – T_{out}) \qquad (4)$$

All parameters except for v (that can be measured in the proximity of the wall using a hot-wire anemometer positioned 0.1 m from the façade, being a so-called local wind speed) can be measured using the same thermograph to minimize systematic measurement errors.

Please note that unlike what reported in [1], the emissivity ε_v of the wall surface on the wavelength range of the thermal camera is now considered in place of the emissivity on the entire spectrum. So, also ε_v is measured with the same instrument used to detect all the others parameters of the equation and, most of all, the actual emissivity of the surface finishing material is considered in place of a value taken from literature surveys, considering in this way real material conditions, like environmental pollution, aging, laying mode for example. The method based on the ITT emissometer formerly presented and discussed by the authors in [15] is used.

2.2 Measurement procedure

A standardized procedure was established, strictly followed by the two teams of experts, consisting of four main steps, described hereafter.

1. For each one of the five north facing walls a thermographic survey of the outer façade is performed. The thermal camera is positioned perpendicularly to the element at a distance of 6.0 m, so to have a complete vision of the wall and no need to compensate for the fact that radiation is absorbed between the building fabrics and the camera. During the post-processing phase, the average temperature on a wide area characteristic of the thermal behavior of the façade is considered (Fig. 2) allowing the detection of a thermal field instead of a punctual measurement. During the survey, the local wind speed at a distance of 0.1 m from the façade under investigation is acquired using a hot wire anemometer.

Fig. 2

2. The temperature inside the building is acquired considering the inner environment acting as black body, through a thermographical image of a façade taken with a window partially and suddenly opened with limited dimensions with respect to the room whose temperature is detected. Inner temperature is considered equal to the one recorded focusing the opening with $\varepsilon_v = 1$. Thus, unlike

the technique proposed by Porras-Amores et al [16], all operations are performed outside, with no need to enter the room.

3. Outside air temperature is detected with a curved plastic hosepipe 2 m long and with a diameter of 0.08 m, closed at one end but with a hole 1 cm^2 wide (Fig. 3). The hosepipe is partially coiled up and positioned on a tripod 1.5 m above the ground level and near the building at least 15 minutes before the survey. The perforated edge is positioned parallel to the ground. This simple set up is a good approximation of the theoretical black body and the temperature recorded in the cavity, with $\varepsilon_v = 1$, is equal to air temperature. In fact, the system is similar to cylindrical blackbody described by De Vos [17] giving an emissivity $\varepsilon_v = 0.999$.

   Fig. 3

   The procedure consists in positioning the thermal camera in front of the hosepipe edge hole at a distance of about 25 cm. The temperature of the hole with $\varepsilon_v = 1$ is recorded very quickly to avoid possible undesirable interaction effects between the device and the operator. The temperature read is anyway compared with the one coming from the weather station positioned nearby (see chapter 3). The methodology described, already tested by the authors in previous researches [1], is important in order to acquire as many data as possible with the same instrument minimizing systematic measurement errors, as stated before.

4. Considering the same wavelength intervals, changing in emissivity of a material on site primarily depends on aging induced by the exposure to environmental and pollution conditions. In order to take into account possible variations during the research period, the emissivity ε_v values of the ten wall surfaces are detected with the ITT emissometer on a monthly basis, a period considered sufficient being emissivity quite stable in the short period.

The procedure referred to in points 1-3 is repeated for the south facing walls. The survey takes about 30 minutes, so weather conditions are quite stable and a steady state approach can be considered with a good approximation. Moreover, the measurement of the U-values of the walls are comparable having the same boundary conditions.

Inner and outer thermodynamic quantities are simultaneously recorded by probes described in the following chapter 3.

3. Experimental arrangements

The experimental building already mentioned has been specially designed for the research (Fig. 4) with plan dimension of 12.00 m x 4.70 m. It consists of two rooms:

1. a main room, 9.70 m x 4.00 m in plan and with a ceiling height of 2.60 m, thermostatically controlled at 21 °C;
2. an entrance-buffer zone to avoid a direct influence of outside weather conditions on the test room when entering the building.

Fig. 4

The walls under inspection are positioned on the north and south façades. Their main characteristics are defined in Tab. 1 and Fig. 5. Each wall is 1.50 m wide. As studies by Givoni [18] have demonstrated, as long as the envelope of thermal models have the same materials and thickness as real building, edge effect are negligible if the wall under test has a linear dimension of about 1.5-2 m, that is, the wall has the same thermal behavior of a wider one. The walls are separated one from another by a timber element (acting also as bearing pillar of the construction) with a basis area of 0.20 m x 0.40 m, in order to avoid possible heat transfer between adjacent elements. Besides, timber pillars are covered with a slab of insulating material (extruded polystyrene $\lambda = 0.031$ W/mK) 0.10 m thick so to further diminish possible heat bridges.

Table 1

Fig. 5

Walls W1-W2 are light elements, currently used by ITEA S.p.A. (the financing institution of the research) for the construction of timber buildings. Walls W3-W5 have a brick structure and they represent a typology used in new constructions (W3, insulation to the outside), one typical of existing buildings (W5, insulation to the inside) and a non-insulated reference wall W4.

The building envelope is made of XLam timber load bearing panels (walls, roof and slab) with a good external insulation in order to reach a maximum U-value of 0.23 W/m^{2}K.

A small window is located on the east wall (area 1.00 m x 1.00 m and $U_w = 1.1$ W/m^{2}K) necessary to measure the room temperature with the black body procedure as described in chapter 2.2.

The surrounding environmental conditions are known. In fact, both inside and outside environment is detected with a continuous monitoring:

1. on the outside, a weather-station by LSI-Lastem S.r.l. with thermo-hygrometer Pt100/capacitive sensor, wind speed and direction sensor and a pyranometer for global solar radiation. Data are acquired every 10 seconds and averaged on a period of 30 minutes.

2. on the inside, two mobile station LSI-Lastem S.r.l. with thermo-hygrometer Pt100/capacitive sensor and radiant asymmetry sensor between north and south façades. Data are acquired every 10 minutes.

On each one of the five walls facing north, a complete HFM system has been installed (Fig. 6) made by a thermal flux meter, a surface temperature probe on the inner side and two on the outer side as described in the standard recommendations [14]. Data are acquired every 10 minutes and results are obtained following the average method.

Fig. 6

Probes technical specification are given in Table 2.

Table 2

For the infrared investigation, a thermal camera Nec-Avio TVS-200EX has been employed, whose main technical specifications are given in Table 3.

Table 3

4. Results and discussion

The results for the estimated U-values are given in Table 4 and Table 5. They concern the second and third research period as defined in previous chapter 2 (see also chapter 4.2). U-values determined with ITT (U_{ITT}) refer only to north walls because, as specified hereafter, the element exposure has a great influence on the absolute deviation of the recorded data and north façades are found to provide the most accurate readings.

Table 4 and 5

It can be immediately noted that light walls (W1-W2) and heavy ones (W3-W5) behave differently.

W1-W2 are characterized by high standard deviation, showing that the results do not have a good repeatability index. Absolute deviations from expected results are quite high also. This is probably due to very low thermal flux values in super-insulated walls, that leads to a very low difference between outside surface temperature and air temperature (an important parameter to determine U-values on site). As the UNI EN ISO 13786:2008 [19], in fact, states, being the two walls insulated from outside, the first layer has a reduced thermal capacity per unit area and it can be assumed to be isothermal. So measurements errors are enhanced.

W3-W5 are characterized by results with a good repeatability index, as the dispersion from the average is acceptable (standard deviation between 10.8 and 17.8%). In addition, the absolute deviation is also acceptable but data reading depends on if we consider as the expected value of thermal transmittance U_d

(calculated following the standard in the design phase) or U_{HFM} (measured with the HFM method on site). In fact, difference between U_d and U_{HFM} goes from 30% in W3 to 43% in W5. As already remarked in [1], in scientific literature [20] it is stated that "results also suggested that as-build U-values of walls are typically around 20% higher than U-values predicted" using technical standards, and in a certain number of cases the difference is up to 100% especially if a layer of insulating material is present. Also national standards [21] take into account that the deviation from the values measured in laboratory and the real ones found in usual production can be of 5% up to 50% depending on the material, the average humidity level in real condition of use, the ageing, the possible tamping of loosed materials, the handling, the properly done installation, the thickness tolerance.

So, the main question is about which parameters, U_d or $U_{HFM,}$ we need to consider as expected value in order to evaluate U_{ITT} dispersion and therefore the accuracy of the proposed methodology. In the first case, absolute deviation goes from 17.5 to 22.8%, while in the second one values are lower, being in two cases out of three comparable with the error of the HFM methods that is usually between 8 and 15%.

It is also clear that the result accuracy depends on the mass per unit area of the wall: the greater the mass, the greater the accuracy. Anyway, considering both U_d and U_{HFM}, it's not possible to come to a direct correlation.

Some considerations can be made in relation to the thermal capacity per unit area, parameter that can be measured following the simplified method described in the standard UNI EN ISO 13786:2008 [19]. Considering walls W3-W5, the first layer of the component has a thickness *d* less than half its periodic penetration depth and the next layer is not an insulating material (as happens instead for W1-W2), so the effective thickness method can be used. In particular, the effective thickness is the minimum between: 1) half the total thickness of the component, 2) the thickness of materials between the surface of interest and the first thermal insulating layer, 3) a maximum effective thickness that, being 1 day the period of the variations, is 0.10 m. In our case, we should use this last value, that is the thermal capacity C_{10}. Anyway, C_{10} is the same for the three walls so it does not give any useful information (see Table 1). However, if we consider the thermal capacity C_h of half the total thickness of the component, finally a correlation with the absolute deviation can be found (Table 5): AD $U_{ITT\text{-}d}$ assumes lower values for higher C_h and vice versa, while it's the opposite considering AD $U_{ITT\text{-}HFM}$. C_h gives useful information even on standard deviation (Table 4): the higher C_h, the higher SD_{ITT}. Probably, this allows us to state that comparing the two methods developed for on site survey is the best way to proceed.

For what concerns the influence of the wall exposure on the results accuracy, in Table 6 the U_{ITT} values of façades facing north and facing south are compared, together with their standard deviation and the absolute deviation considering U_d and U_{HFM}. North façades have a lower dispersion around the average figure and so a greater expected accuracy, so as a lower absolute deviation in both cases (apart for W1, which has a very stable result and a lower absolute deviation for south exposure). It is found that exposure has a relevant influence on the measurement accuracy. If the wall under investigation is exposed for a long time to direct solar irradiation, in particular if its thermal lag (or time delay) factor φ is high, the amount of solar energy stored in the near-surface layers is relevant and the decay process is still ongoing even after 13/14 hours from sunset. The thermal behavior of the walls facing south (and west) is farther from a hypothetical steady state than north (and east) walls, whose decay process can be considered concluded at the time of the monitoring, if properly performed.

Table 6

4.1 Sensitivity analysis

A sensitivity analysis has been performed in order to understand which parameters influence the achievement of good results compared to the expected U-values. Sensitivity analysis attempt to assess the sensitivity of the model outputs to variation of the model inputs given by variables or parameters [22].

The analysis has been implemented considering the north walls. The variables considered are wind speed, outer environment temperature, inner room temperature and external surface temperature of the wall under investigation.

In Fig. 7-10 results of the analysis are presented. The graph indicates, on x-axis, the percentage variation imposed on each variable considered as model input and, on y-axis, the resulting percentage error on the expected U value (output) for the considered parameter.

Fig. 7 to Fig. 10

In all cases, the sensitivity of the variables depends on the mass of the wall, leading to the conclusion that the lighter the wall, the greater the sensitivity. A deviation of 50% in the determination of the wind speed can lead to a maximum error of 9% in the measurement of U_{ITT}, while it's negligible considering heavy walls. A deviation of 50% in the determination of the inner temperature can lead to a maximum error of 27% in the measurement of U_{ITT}, but we must take into account that, being inner temperature around 21°C, a perfect accordance between recorded values and the ones taken with ITT has been found, with maximum deviation of 0.8 °C (4%). Therefore, we can state that errors in U_{ITT} values are less than 5%. Things are quite different for outer and surface temperature. A deviation of 50% is converted into a deviation from 50% (heavy walls) up to 350% (light walls) in the determination of U_{ITT} values. This fact is of particular importance because very often air temperature is around 0°C during the monitoring, so the percentage deviation in the detection of environment temperature with ITT from the one given by thermo hygrometer can be very high. A confirmation of what has been already stated by Dactu et al [23] in a study on wall surface temperature measurement of buildings is found, stating that “the result confirms the importance of accurate knowledge of surrounding temperature in order to obtain good measurement, even when the studied surfaces have high emissivity”.

4.2 Influence of weather conditions before the monitoring

As already stated in chapter 2, the first year of the research was important to investigate the boundary weather conditions that allow a proper monitoring with necessary accuracy of the results. The environmental parameters considered were solar irradiation, cloudiness, windiness, humidity/rains, temperature. To this end, monitoring campaigns were performed under different conditions with attention to the values both during the monitoring and within 24 hours. Here follow some advices.

- The conditions that minimize the deviation of the results from the mean value is overcast sky within 12 hours of the monitoring (when sky temperature is near or equal to air temperature) so that radiative heat losses to the sky are significantly decreased. In fact, they are quite difficult to quantify even measuring reflected ambient temperature as already stated in other research works [7, 12].
- The most appropriate period of the day to perform the measurement is early in the morning, at least two hours before sunrise (usually between 4 and 6 a.m., depending on the season) in order to minimize possible solar influence of the day before. Measurements performed in late evening have given the worst results concerning surface temperature, due to the heat stored in the wall, especially for W3-W5.
- Local wind speed near the façade during the measurement must be lower than 0.5 m/s so that convective heat losses are lower than radiative ones.
- Free stream wind speed in the building boundaries 24 hours within the monitoring must be lower than 5 m/s (hourly average).
- The ITT methodology cannot be used during rainy days.

As usual while performing an infrared thermal survey, the minimum temperature difference between the inside and the surrounding area of the building must be 10°C so as to have a considerable thermal flux through the envelope [24]. Anyway, for a proper detection of U_{ITT} is preferable the difference to be at least 15°C and the outer temperature to have, in the 12 hours before the measurement, low swing (less that 6°C) to get conditions as near as possible to steady state.

Lehman et al [5] performing a complete study to quantify the influence of climatic conditions on the surface temperature distribution detected by infrared thermography on an existing building with insulated and non-insulated façades, have obtained similar results.

5. Conclusions

The present work consists in a deep investigation and validation of a method for the on site determination of U-values of opaque building elements by means of Infrared Thermovision Technique ITT, previously proposed by the authors [1]. This represents an important task in the present context, where efforts are primarily focused on energy-efficient rehabilitation processes for existing buildings and energy-efficient construction procedures for new ones. In the first case, the main goal is to verify the building energy performance and to plan optimal refurbishment interventions in term of time and costs. In the second one, it is important to verify the correctness of the construction process and the conformity of the final thermal performance of the building with the one quantified during commissioning. It is a kind of “quality control” to guarantee that the energy performance at commissioning stage meets the one expected at design stage. Therefore, recent standards on energy performance of buildings and new procedures for energy audit in real conditions of use have for some years given rise to an increase number of researches on the evaluation of thermal parameters of building elements on site, going beyond the values usually obtained in laboratory. As far as the authors know, in scientific literature it seems that only a few other methodologies have been proposed, verified on simple case studies and in short period of time. So, here a more comprehensive study is proposed, based on a three years intensive research activity in different weather conditions, on various walls typologies (light and heavy, timber and brick block differently insulated), with same boundary conditions both inside and outside but coupled with twin façades so to have also different exposure to solar radiation. Results have been compared with the ones expected by calculus using existing standards and the ones coming from on site continuous monitoring with HFM method, the only one explicitly recall in an international standard, namely UNI EN 15603:2008 [25].

The ITT method has the advantages to be rapid, non-invasive, non-destructive and, with the exception of wind speed measuring, to use the same instrument, the thermal camera, for the detection of all the parameters necessary to calculate the U-value, so as to minimize systematic measurement errors. Unlike other methods, it is important to notice that also the thermal emissivity of the surface finishing under investigation is measured on site following an innovative procedure defined in [15] giving high precision. Emissivity is a parameter that has a significant impact on the measured surface temperature [7], while it is usually defined by the operator out of literature surveys without taking properly into account surface roughness and surface microstructure, ageing of the materials, induced by the exposure to environmental, pollution conditions.

It has been demonstrated that the proposed methodology gives results with a good repeatability index for heavy walls (with a standard deviation between 10 and 18%), considering "heavy" a structure with a thermal capacity per unit area from the outside higher than 150 kJ/m^{2}K. On the other side, the repeatability index is quite low for light walls and outside super-insulated structures. Absolute deviation for heavy walls is acceptable between 8 and 20%, compared to the one given by HFM method. Anyway, it is important to notice that absolute deviation depends on the expected value considered: if U_d, the thermal transmittance calculated following the standard, or U_{HFM}, measured with the thermal flux meter method. The difference between them is in the range of 30 and 45%. U_d depends on the λ values of the materials as they are found in the manufacturer declaration or in reference standards, with possible uncertainties on real performance up to 50% and more. U_{HFM} depends on boundary conditions during the survey as well as on the methods used for data analysis (Average method, Black Box method, LORD) [26]. Even though it's quite hard to define which system is giving the most accurate result in certain environmental conditions and on a given building, results allow us to state that comparing the two methods developed for on site survey is the best way to proceed.

It has been found that walls exposure has a relevant influence on the measurement accuracy, and that more accurate results can be obtained by performing the survey considering walls facing north and east.

The requirements for the environmental conditions in order to have reliable results have been established. They are comparable to the ones investigated and proposed in similar studies: measurement performed early in the morning before the sunrise with overcast sky if possible; local wind speed near the building façade lower than 0.5 m/s during the survey; hourly average of free stream wind speed lower than 5m/s 24 hours prior the measure; difference between inside and outside air temperature of at least 15°C; outdoor temperature with low swing (less that 6°C) in the 12 hours prior to the measurement.

It has been stated that outer and surface temperature are the two parameters with greatest influence on the results accuracy. So, they must be detected with great attention and, if necessary, in comparison with the values coming from thermal probes.

A possible further development of the research is the definition of a different protocol to perform reliable measurement in case of light and super-insulated walls, still an unsolved problem. For example, the thermal flux through the envelope could be forcedly increased using heat transfer plates for radiant heating at high temperature, as performed in [27]. Operating in this way, the method would lose two main strength, namely the non-invasiveness and the speed in the measurement procedure, though.

Finally, it’s important to stress that ITT method can be used by public administrations in order to perform a fast survey of the thermal condition of existing buildings to plan investment policies for energy retrofit in the medium and long term. Moreover, working from the outside, the methodology described is not invasive and can be conveniently adopted independently of the users, without causing any disturbance to the inhabitants. A proposal for a national praxis using ITT by the Italian certification body is now under consideration so as to establish a national guide and to have the utmost feedback about the method.

Acknowledgment

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Captions

Fig. 1 The experimental building – north façade

Fig. 2 Thermal image of a wall under investigation with the area considered for surface temperature detection

Fig. 3 The black-body used for the detection of outer environmental temperature

Fig. 4 Plan of the experimental building

Fig. 5 Horizontal cross section of the wall under investigation

Fig. 6 View of the experimental arrangement from inside the building

Fig. 7 Percentage U-value calculation sensitivity to local wind speed

Fig. 8 Percentage U-value calculation sensitivity to inside temperature

Fig. 9 Percentage U-value calculation sensitivity to outside temperature

Fig. 10 Percentage U-value calculation sensitivity to wall external surface temperature

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Figure 1

Figure 2

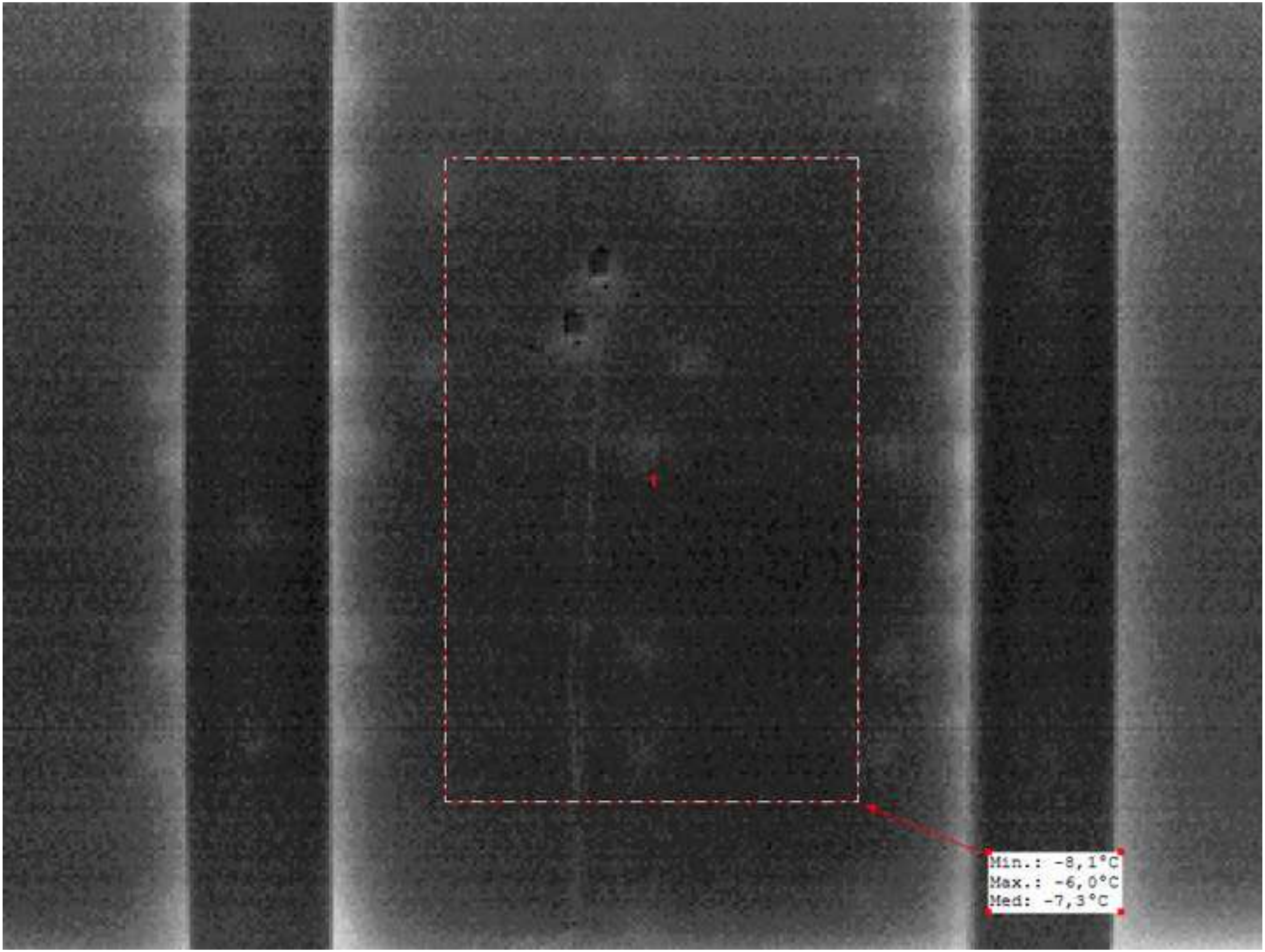

Figure 3

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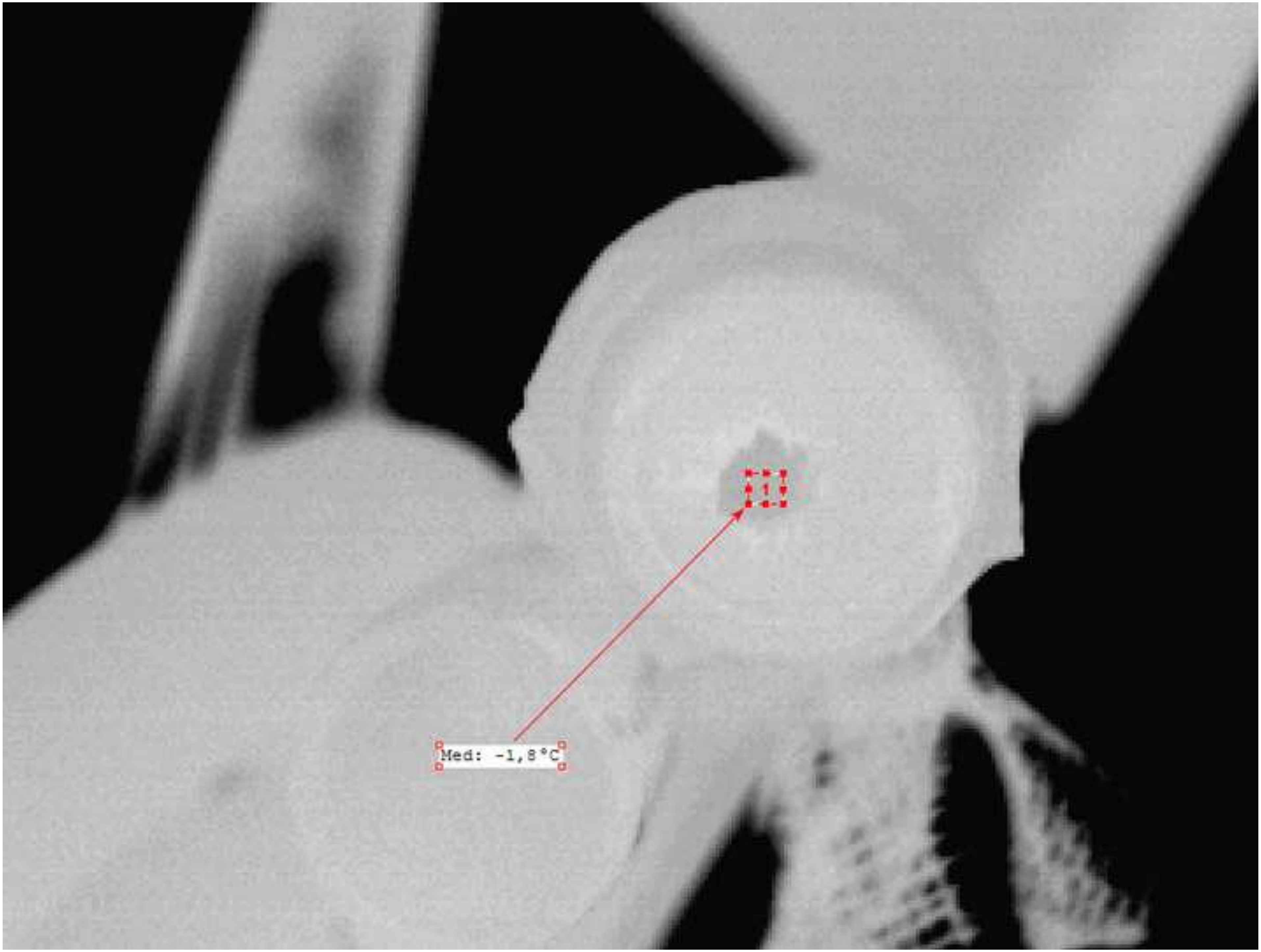

Figure 4

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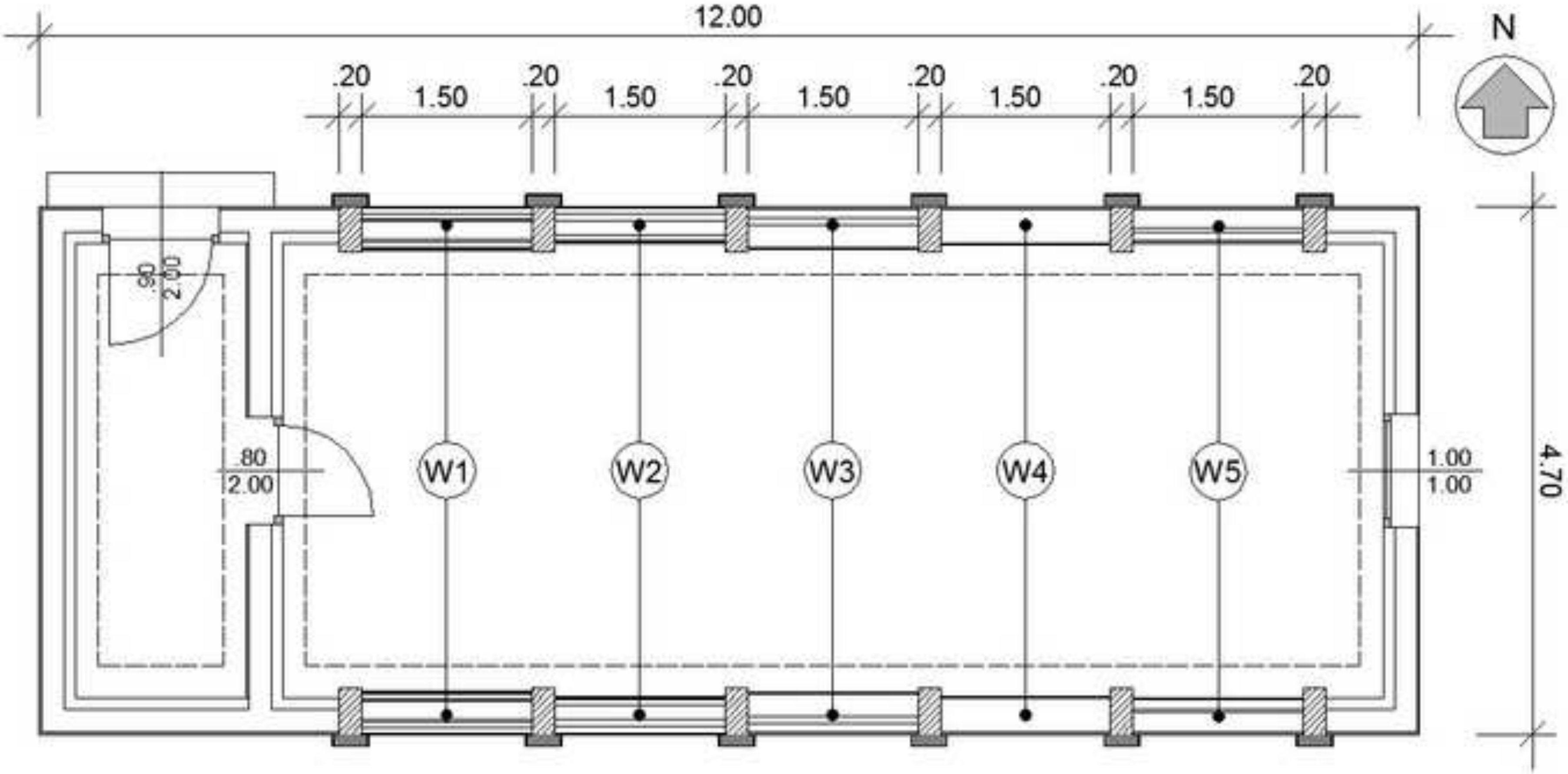
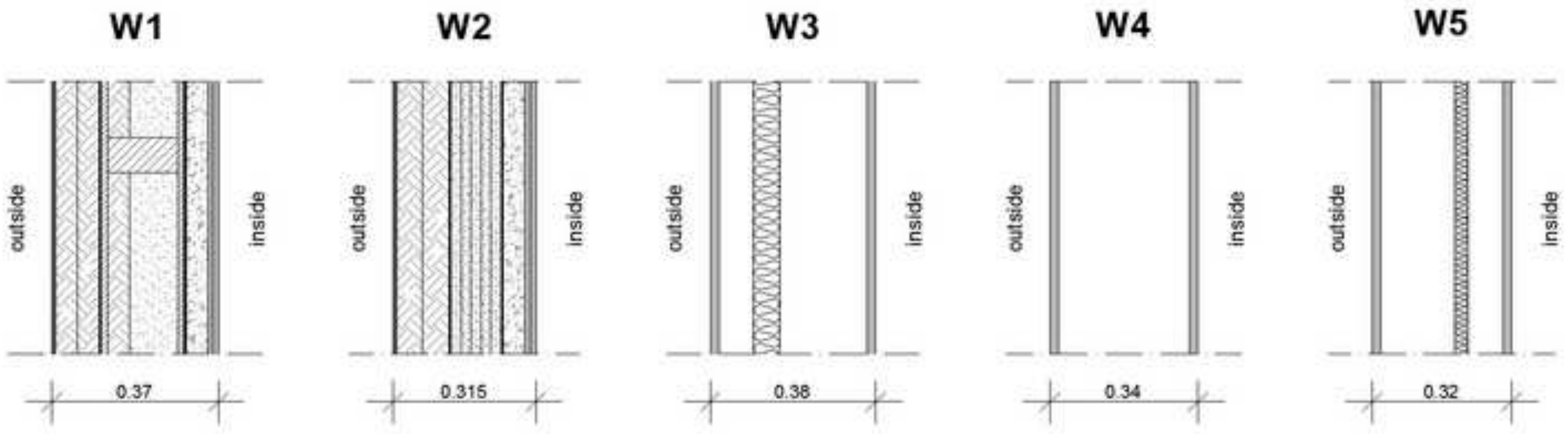


Figure 5


W1
outside
inside
0.37
W2
outside
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0.315
W3
outside
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W4
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W5
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Figure 6

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Figure 7

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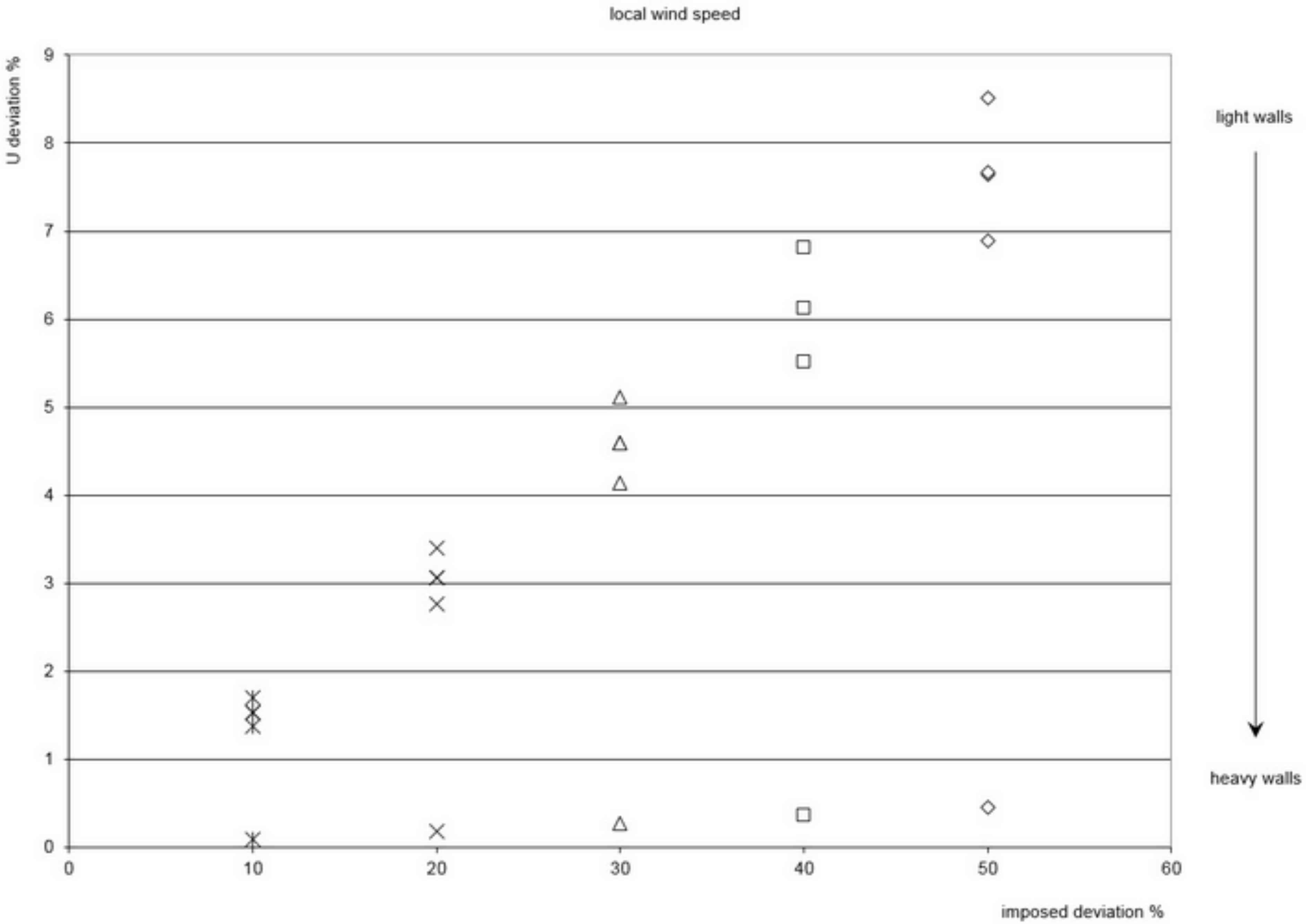

Figure 8

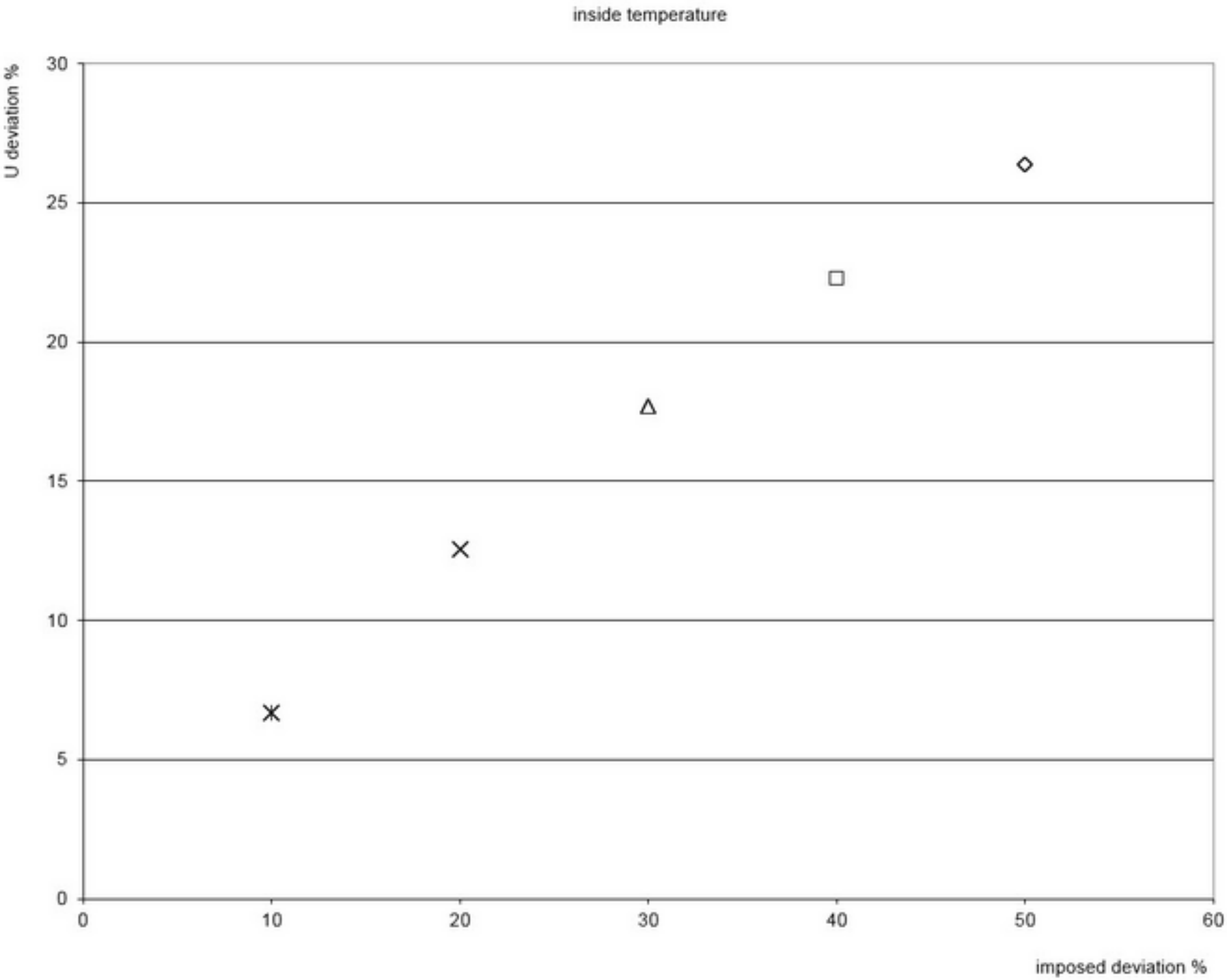
inside temperature
U deviation %
30
25
20
15
10
5
0
0
10
20
30
40
50
60
imposed deviation %

Figure 9

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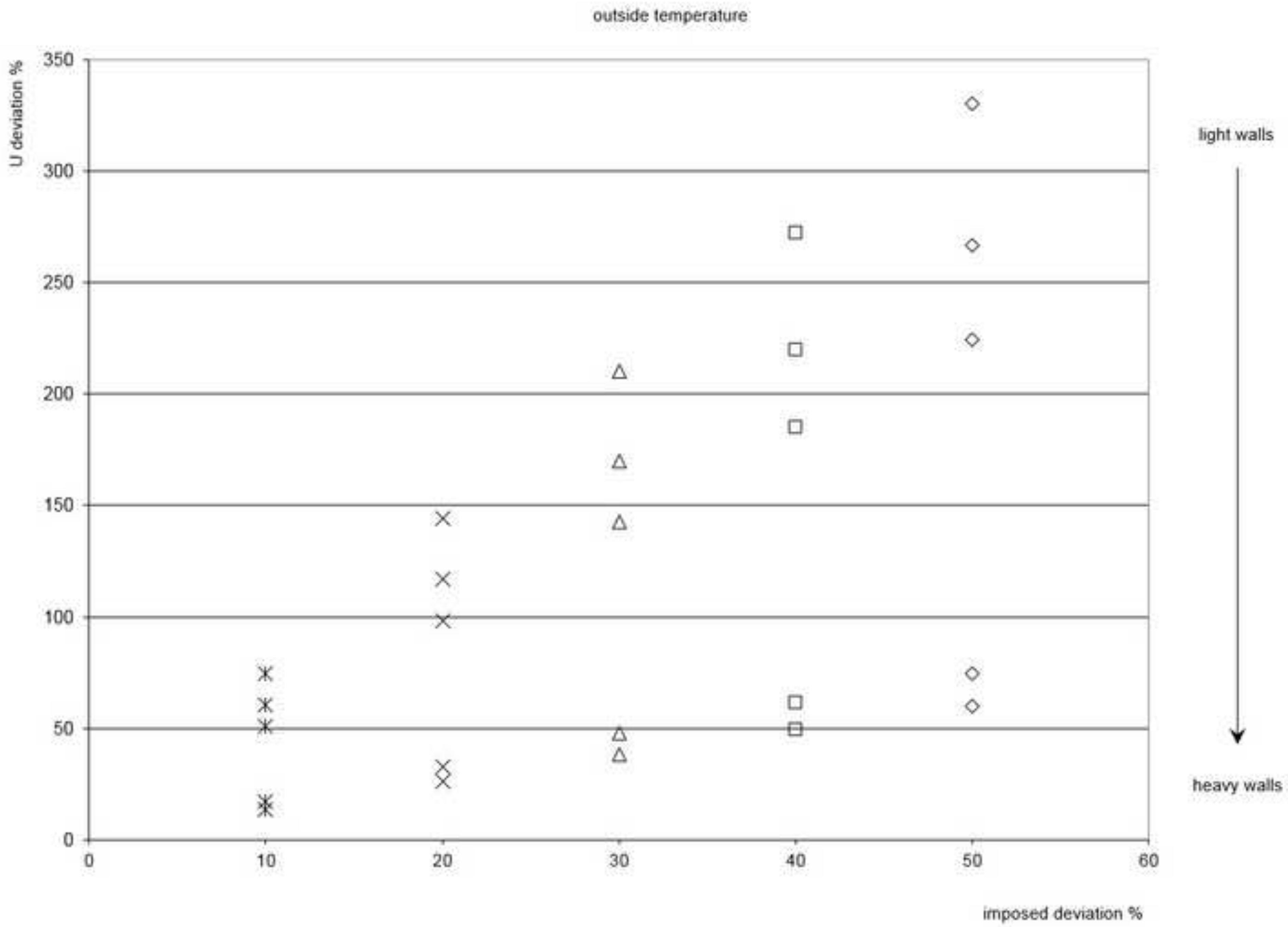

Figure 10

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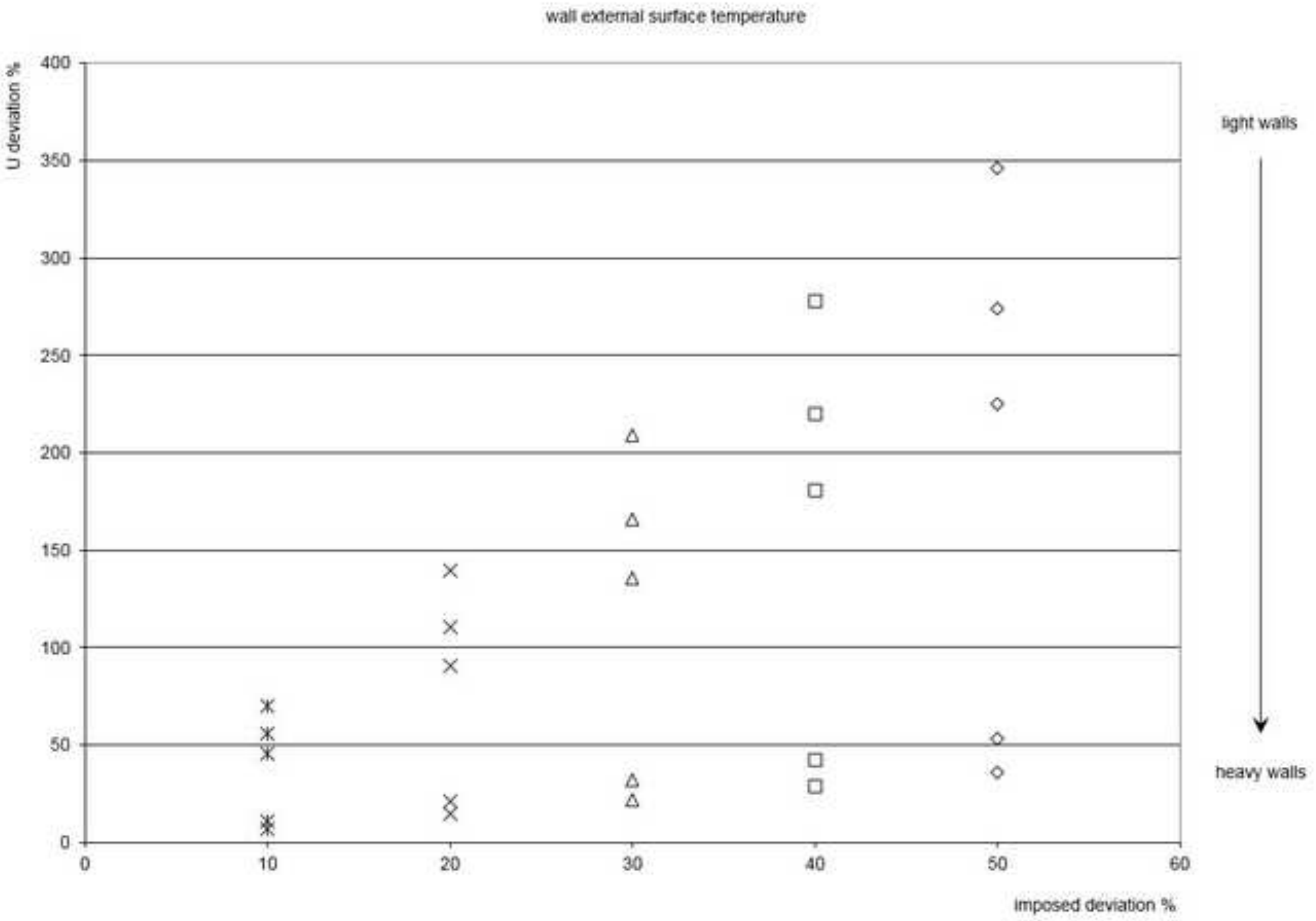

Table

Table 1:

Thermophysical properties of the walls under investigation.

Wall type	Material layer	t	S	λ	U	ρ	c	M	f_d	φ	C	C_{10}	C_h
	(Inside-Outside)	[m]	[m]	[W/mK]	[W/m^{2}K]	[kg/m^3]	[J/kgK]	[kg/m^2]		[h]	[kJ/m^{2}K]	[kJ/m^{2}K]	[kJ/m^{2}K]
W1	Plasterboard	0.025	0.37	0.36	0.17	1150	1100	83	0.268	10.65	95	25.37	46.07
	Fiberglass insulation	0.04		0.032		40	1030						
	DHF panel	0.02		0.12		600	1700						
	Air	0.1		0.67		1200	1005						
	Wooden fibre insulation	0.06		0.04		45	1000						
	DHF panel	0.02		0.12		600	1700						
	Wooden fibre insulation	0.04		0.04		160	1000						
	Wooden fibre insulation	0.06		0.04		160	1000						
	Plaster	0.005		0.9		1800	1130						
W2	Plasterboard	0.025	0.315	0.36	0.18	1150	1100	127	0.079	13.87	168	25.37	57.37
	Fiberglass insulation	0.04		0.032		40	1030						
	XLam panel	0.125		0.13		500	1600						
	Wooden fibre insulation	0.06		0.04		160	1000						
	Wooden fibre insulation	0.06		0.04		160	1000						
	Plaster	0.005		0.9		1800	1130						
W3	Gypsum plaster	0.02	0.38	0.21	0.30	1200	1000	454	0.054	17.91	377	125.60	162.24
	Brick wall	0.2		0.19		1400	800						
	Polystyrene	0.06		0.035		35	1450						
	Brick wall	0.08		0.19		1400	800						
	Lime plaster	0.02		1.00		1800	1000						
W4	Gypsum plaster	0.02	0.34	0.21	0.57	1200	1000	480	0.09	16.34	396	125.60	204.00
	Brick wall	0.3		0.20		1400	800						
	Lime plaster	0.02		1.00		1800	1000						
W5	Gypsum plaster	0.02	0.32	0.21	0.44	1200	1000	411	0.107	15.23	342	125.60	192.80
	Brick wall	0.08		0.20		1400	800						
	Polystyrene	0.03		0.035		35	1450						
	Brick wall “Trieste”	0.17		0.23		1400	800						
	Lime plaster	0.02		1.00		1800	1000						

Table 2:

Main technical specifications of probes.

Sensor	Measurement range	Uncertainty	Resolution	Threshold m/s	Spectral range nm
Outer thermo-hygrometer	-30÷+70 °C; 0÷100%	0,2°C (0°C); ±1.5%	0,04°C - 1%		
Wind speed	0-60 m/s	0÷3 m/s=1.5%; >3 m/s= 1%	0.07 m/s	0.26	
Wind direction	0÷360°	1%	0,3°		
Global solar radiation	0÷4000 W/m^2	<± 1% (-10÷40 °C)	< 2 W/ m^2 (unventilated)		285÷3000
Inner thermo-hygrometer	-20÷+60°C - 0÷100%	0.1°C (0°C); 2%	0,01°C; 1%		
Radiant asymmetry	-1500÷1500 W/m^2	3%	< 5 W/ m^2 (unventilated)		300÷50000
Heat flow meter	-2000÷2000 W/m^2	5% over 12 hrs measur.	50 μV/W/m^{-2}		
Surface temperature	-20÷+60°C	0,15°C (0°C)	0,01°C		
Hot wire anemometer	0÷5 m/s	0÷0.5 m/s: NA 0.5÷1 m/s: ±0.15 m/s 1÷20 m/s: 4% reading	0.01 m/s		

Table 3:

Technical specifications of thermal camera.

Wavelength range	8 – 14 µm
Field of view	30.1° (H) x 22.6° (V)
Instantaneous field of view	1.68 mrad
Minimum temperature resolution	0.1°C or below (30°C blackbody)
IR resolution	320 x 240 pixels
Observation display range	-20 to 500°C
Accuracy (at ambient temperature)	±2°C
Accuracy (at ambient temp. of -10 to 40°C)	±4°C

Table 4:

U values measured with ITT methodology and their standard deviation.

Wall	U_{ITT} [W/m^{2}K]	SD_{ITT} %	SD_{ITT} W/m^{2}K
W1	0.14	50.0	0.07
W2	0.16	37.5	0.06
W3	0.37	10.8	0.04
W4	0.62	17.8	0.11
W5	0.51	13.7	0.07

Table 5:

Comparison between U values by design (d), heat flow meter (HFM) and infrared technology (ITT) methods with absolute deviations between ITT and the others.

Wall	U_d [W/m^{2}K]	U_{HFM} [W/m^{2}K]	U_{ITT} [W/m^{2}K]	AD U_{ITT-d} %	AD U_{ITT-d} [W/m^{2}K]	AD $U_{ITT-HFM}$ %	AD $U_{ITT-HFM}$ [W/m^{2}K]
W1	0.17	0.18	0.14	39.6	0.07	39.8	0.07
W2	0.18	0.18	0.16	30.4	0.05	30.5	0.06
W3	0.30	0.39	0.37	22.8	0.07	8.9	0.03
W4	0.57	0.76	0.62	17.5	0.10	20.3	0.15
W5	0.44	0.63	0.51	18.6	0.08	13.8	0.08

Table 6:

Comparison between measured ITT values in north (n) and south (s) facade, their standard and their absolute deviation with expected design (d) and heat flow meters (HFM) values.

Wall	$U_{ITT,n}$ W/m^{2}K	$U_{ITT,s}$ W/m^{2}K	SD_n %	SD_s %	AD $U_{ITT-d,n}$ %	AD $U_{ITT-d,s}$ %	AD $U_{ITT-HFM,n}$ %	AD $U_{ITT-HFM,s}$ %
W1	0.14	0.12	50.0	10.8	39.6	28.5	39.8	30.1
W2	0.16	0.08	37.5	58.3	30.4	53.4	30.5	54.2
W3	0.37	0.31	10.8	24.2	22.8	25.5	8.9	20.6
W4	0.62	0.53	17.8	27.2	17.5	19.5	20.3	28.4
W5	0.51	0.54	13.7	31.4	18.6	38.2	13.8	23.5