

504: On site evaluation of U-value of opaque building elements: a new methodology

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Abstract

Concerning the evaluation of the energy performance of a building, in order to arrange an accurate energy analysis, it is necessary to collect the greatest number of information about the building and, most of all, its envelope, with particular attention to the accuracy of the technical parameters of the building materials and components used. Nevertheless, it should be important to refer to the as-built situation that is often different from the designed one, either because of changes occurred on site during the construction or because of the different behaviour of the building elements in real situation linked to a particular microclimate.

The paper deals with a research activity carried out at the Laboratory of Building Design of the University of Trento (Italy) concerning the critical analysis of two methods used for the acquisition of the thermal transmittance values of opaque building envelope elements: the heat flowmeter measurement method and the thermovision technique. While the first method is already quite consolidated and described by the International Standard ISO 9869:1994, the latter is still considered a qualitative method and its potential has not been adequately explored yet. The aim of the research is to propose a scientific protocol for the on site energy investigation through the thermovision techniques in order to acquire quantitative data of the real thermal transmittance of the building envelope in a quasi-steady state condition. An application on a case study will be presented and discussed.

Keywords: thermal transmittance, heat flowmeter, thermography, energy performance

1. Introduction

The European Directive 2002/91 on the energy performance of buildings, absorbed in Italy with the L.D. 192/05 later modified by the L.D. 311/06, requires the energy certification in order both to achieve an high energy saving and to guarantee adequate indoor comfort conditions for the users. One of the most important parameters for the calculation of the energy requirements of a building during the design phase is the value of heat losses through the envelope. In particular, for what concerns the opaque elements, it is important to calculate the thermal transmittance U-value [W/m^2K].

Very often, however, the difference between the theoretic thermal transmittance (calculated) and the real one (measured) may be very high. The result is an overestimation of the energy performance of a building. Thus, it is important to define some simple but effective methods in order to estimate the actual U-value under certain condition of use, by means of in-situ measurement in real situation.

The in-situ measurement of the thermal transmittance of a building element is governed by the ISO 9864:1994 that defines the heat flowmeter method (HFM). Even the prEN15203 refers to this standard where, in Annex A, states that "Thermal transmittances of building elements can also be measured according to ISO9869".

Anyway, the HFM method has some limits. In fact, in real situation heat flow is not constant and steady state conditions are not encountered. In order to compensate, some restrictions must be imposed: the minimum test duration is 72h, the users should collaborate during the test period (for example maintaining the inner temperature as uniform as possible), the minimum difference between inside and outside temperature must be at least 10-15°C (i.e. favourable weather conditions). It means that a good final result is not always possible and, most of all, reliable, in particular when the building element is light (low specific heat for units area) and, if multi layered, air spaces are present (even if slowly ventilated). In order to avoid the above mentioned problems, a new experimental methodology using the infrared thermovision technique (ITT) is proposed in this paper, so to acquire quantitative data of real thermal transmittances of the building envelope in a quasi-steady state condition.

Generally speaking, anyway, it must be considered that in-situ measurement of the U-value of a building element is strongly influenced by some factors briefly summarized as follows:

a. site conditions:

- weather conditions during the test or during the previous period of time (with particular reference to wind speed, solar radiation, rain)

- typical climate of the site, most of all humidity values that can significantly alter the thermal performance of the building materials
- b. building conditions:
 - aging of the building materials
 - proper laying of the elements during the construction
- c. running conditions:
 - managing of the building by the users (heating/cooling and windows opening/closing)
 - maintenance works (done or not)

Afterwards, the Italian standard UNI 9252:1998 states that the infrared thermovision technique is just a “qualitative” method that can be used only to assess and analyse the thermal irregularity of the building envelope but not to determine its thermal insulation level. The authors, however, think that, if the thermographic survey is carried out by a technician with specific knowledge of thermotechnics and building physics and in a proper manner following the procedure described in this paper, the result of the test can be meaningful and complementary to the one made with the heat flowmeter method.

2. The heat flowmeter method

The heat flowmeter method (HFM) is based on some simplifying hypothesis. In particular, it considers only plane and homogenous elements, uni-directional heat flow and heat transmission due only to conductive phenomena. Convection (due to air temperature and speed) and irradiation (due to the temperature of the surfaces positioned near and around the element) can be simply considered together by means of a so called “environment temperature” that must be properly measured.

The measuring equipment consists of: a heat flowmeter that is mounted directly on the face of the element adjacent to the more stable temperature (usually the inner side); at least two surface temperature sensors, one mounted on the inner surface of the element near the flowmeter, the other on the external surface opposite to the flowmeter; two air temperature sensors, one inside the other outside, at least 1.50 meters on the floor level.

Some practical rules to be followed during the test are:

1. the sensors must be mounted in such a way so as to ensure a result which is representative of the whole element (several flowmeters can be used in order to obtain a representative heat flow average);
2. thermal bridges, particular constructive joints and so on must be avoided;
3. the minimum test duration is 72h if the temperature is stable around the flowmeter, otherwise it can be more than 7 days; to be sure that a sufficient heat flow is present, the minimum difference between inner and outer temperature is 10-15°C;
4. the outer surface of the element should be protected from rain, snow and direct solar radiation; usually, the one with northern

exposure is preferred, otherwise artificial screening may be used as well.

Data should be recorded continuously or at fixed intervals over a period of a certain number of days. Test duration depends on:

1. nature of the element (heavy, light, multi-layers and so on);
2. inner and outer temperature variation (average and variation during and before the test);
3. methods used for data analysis.

Usually, the test duration is between 3 and 8 days while data acquisition interval must be at least 15 minutes. As written before, during the test the minimum difference between inner and outer temperature has to reach 10-15°C.

Data analysis can be made using two methods: average method and dynamic method. The main difference is that with the first one, greater is the number of data recorded higher is the possibility to get a correct final result. With the second method, the test duration can be shorter but higher indoor-outdoor temperature variation is needed. More information are provided in the ISO 9869 itself.

3. Infrared thermovision technique

As written above, in-situ measurement of an element U-value with heat flowmeter method is not always possible due to the great number of limitations.

An alternative method is the infrared thermovision technique (ITT).

Thermal transmittance of a wall is given by the ratio between the total heat Q passing through the element per unit time t (and then a heat power P) and the difference $T_{int}-T_{out}$ between inner and outer temperature:

$$P = Q / t \text{ [W/m}^2\text{]}$$

so :

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

Thermal power P, due to heat Q passing through the element, is dissipated from the outer element surface by means of conduction, convection, radiation. Contribution of conduction can be ignored. In this case, the following formula can be considered:

$$P = 5.7674 \varepsilon_{tot} ((T_i/100)^4 - (T_{out}/100)^4) + 3.8054 v (T_i - T_{out}) \text{ [W/m}^2\text{]}$$

so:

$$U = (5.7674 \varepsilon_{tot} ((T_i/100)^4 - (T_{out}/100)^4) + 3.8054 v (T_i - T_{out})) / (T_{int} - T_{out}) \text{ [W/m}^2\text{K]}$$

where:

P = thermal power dissipated through the element [W/m²]

ε_{tot} = emissivity on the entire spectrum (integral emissivity)

T_i = temperature of the element [K]

T_{out} = outer environment temperature [K]

v = wind speed [m/s]
 T_{int} = inner environment temperature [K]

All parameters except for v (that can be measured in the proximity of the wall using a hot-wire anemometer) can be measured using the same thermograph. In this way, systematic measurement errors can be minimized.

The greatest problem is the measurement of the emissivity ϵ_λ value of the outside surface of the element in the spectrum interval related to the thermograph used (and necessary to determine the element surface temperature T_i).

3.1 The measurement of emissivity ϵ_v

For what concerns the measurement of the emissivity ϵ_v value of the surface of the element in-situ (so in real condition of use), two methods can be used: the comparison with a reference material (for example special adhesive tapes with known emissivity) or the direct measurement of the radiance reflected by the material. In fact, if N_v is the source power as "seen" within the interval v in which the thermograph works, Kirchhoff's law states that

$$N_v = \epsilon_v N_v + \rho_v N_v + \tau_v N_v$$

It expresses the principle of energy conservation: a radiant power N_v is partly absorbed ($\epsilon_v N_v$), partly reflected ($\rho_v N_v$) and partly transmitted ($\tau_v N_v$). For opaque surfaces, it is

$$N_v = \epsilon_v N_v + \rho_v N_v$$

so

$$\rho_v N_v / N_v = 1 - \epsilon_v$$

that is

$$\epsilon_v = 1 - \rho_v$$

In order to proceed with the measurement, a soldering iron can be used as heat source (temperature around 400 K). It must be positioned near the surface under investigation at a distance of about 10 cm. A thermographical image is taken. The temperature of the real object and its reflected image visible on the element surface can be measured and compared.

Finally, the measurement of the surface temperature of the element is obtained by the thermographical images adjusted with the found emissivity value.

3.2 Other temperature reading

Both the outer temperature T_{out} and the temperature inside the building T_{int} are measured by means of the same thermograph so to minimize systematic measurement errors.

The method consist in considering some elements acting as black bodies, one for the outer temperature and the other for the inner one.

For the outer temperature, a good approximation of the theoretical black body can be a curved hosepipe, even partially coiled up, whose length is at least one order of magnitude more than its diameter.

For the inner temperature, a window can be partially and suddenly opened in order to let the thermograph record the inside environment. In this case, the black body is represented by the partial window opening, whose dimensions are limited in respect to the room whose temperature is detected.

It must be well stressed that with the thermovision technique, data concerning radiation temperature are recorded. Thus, once the emissivity ϵ_λ value is measured for every surface of the building elements, the data are corrected in such a way to acquire the actual value of the surface temperature T_i . About the recorded values of T_{out} and T_{int} , being the emissivity very close to the one of the black body, they are coincident with the real ones.

For what concerns the emissivity of the entire spectrum ϵ_{tot} (integral emissivity), values printed on specialized handbook can be used.

3.3 Pros and cons of the method

The measurement of the U-value by means of infrared thermovision technique has two main and meaningful advantages:

1. first of all, it is not a punctual measurement but it considers all the surfaces of the detected element whose global thermographic image is taken; in this way the areas with anomalous thermal behaviour can be rejected (local thermal bridges, areas with high moisture and so on);
2. the procedure is sufficiently fast: a medium size building (such as a two storey house) can be analyzed in-situ in about 2-3 hours (plus 15 hours of data handling in office).

The main limits are:

1. the measurement can be done only during evening so to avoid direct solar radiation; the best period of time is 3 or 4 a.m. when maximum is the difference between inner and outer temperature;
2. outside air speed must be lower than 1 m/s in order to avoid out of control convective phenomena;
3. the building elements must have stored a sufficient amount of heat during previous days in order to have a dispersed thermal power significantly measurable; that is, for at least 48h before the measurement the users should have taken inner rooms temperature at a uniform level of 20°C, while the meteorological situation must have been fair (clear sky, possibly sunny and non rainy or windy);
4. the difference between inner and outer temperature during the measurement must be at least 10-15 °C in order to allow a measurable heat exchange through the element.

The last condition is probably the most important. For this reason the ITT method described in this paper can be done only during some days of the

year and, anyway, only in winter time (even if some researches are going on in order to use the method in dynamic state conditions during spring and autumn).

4. A case study

Hereafter a case study is presented where the ITT method is discussed. In particular, a building with a timber post and beam structure and light external walls has been analyzed during winter 2007-'08. It is a single family house called "Villa dei Girasoli" placed in Gonars (Udine - Italy) near the Adriatic Sea, 24 m asl (Fig.1)



Fig 1. Case study: Villa dei Girasoli

In Table 1 the characteristics of the layer of the external wall are summed up.

Table 1: characteristics of the layer of the external wall.

Material	s (m)	c (kJ/kgK)	λ (W/mK)	ρ (kg/m ³)
plaster	0.02	0.84	0.9	1800
polystyr.	0.03	1.380	0.037	35
plywood	0.01	2.092	0.144	800
polystyr.	0.035	1.380	0.037	35
plywood	0.01	2.092	0.144	800
rockwool	0.04	0.836	0.04	40
air	0.06	1.004	0.333	1
plasterbrd	0.018	0.837	0.21	900

The total width of the wall is $d = 0.223$ m, the mass is $m = 64.135$ kg/m² (very light wall).

The calculated U-value is $U = 0.29$ W/m²K.

In order to measure the real thermal transmittance of the wall in-situ, the flowmeter method has been applied considering the North façade, while the infrared thermovision technique has been applied to all the four building sides.

4.1 Results with the HFM method

The heat flowmeter has been mounted on the North façade, the only one without direct solar radiation during the test period. Data has been acquired every 15 minutes. The test lasted three months, that is the winter period. Anyway, only some sub-periods suitable for the measurement (i.e. meeting the method conditions) has been considered.

Data have been analysed using both the average method and the dynamic one. Main results are summed up in Table 2.

It is immediately clear that data analysis gives results strongly dependent on the method used.

Moreover, even the same method do not converge, either considering different periods of time or considering different intervals in the same period.

Table 2: U-value of the North façade using the HFM method.

Period	U-value average meth.	U-value dynamic meth.
12-12 to 17-12	0.68	0.49
26-12 to 3-1	0.68	0.54
1-1 to 7-1	0.72	0.74
4-1 to 7-1	0.80	0.40
23-1 to 27-1	0.71	0.48

This result is probably due to the fact that the difference $T_{int}-T_{out}$ between indoor and outside temperature during the test period has been often very low, sometimes less than 10°C in the 24 hours (Fig.2 as an example).

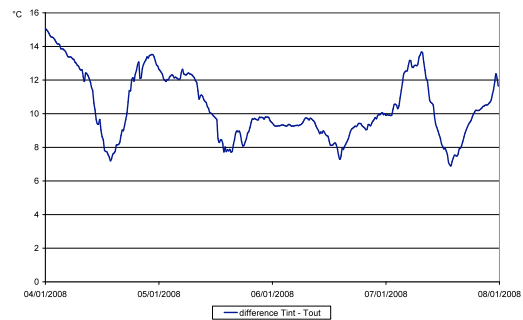


Fig 2. Difference $T_{int}-T_{out}$ in the period 4-8 January

In this particular case the average method is not the most suitable, but only the results obtained with the dynamic one should be considered. Rejecting the value 0.74 that is too far from the others, the average U-value of the external wall measured with the HFM method is $U = 0.46$ W/m²K. It is a value higher of 59% compared to the calculated one.

4.2 Results with the ITT method

The thermography has been done on the 23rd January 2008, considering all the four main façades of the building. Due to some difficulties encountered during the measurement and mostly due to space problems, thermographic images of the East façade have not been realized perpendicular to the element and the values measured have been discarded because not meaningful for the presented analysis.

The measurement of the emissivity value ϵ_v of the surface of the walls in-situ has been made following the procedure previously described (see chapter 3.1). In particular, in Fig.3 the thermal profile of the soldering iron is highlight.

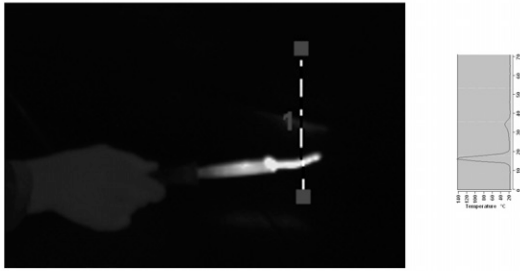


Fig 3. Analysis of the radiant temperature of the soldering iron and of its image reflected on the wall

Recorded data are:

1. source (soldering iron) temperature:
 $T_s = 140^\circ\text{C} \gg \gg 413.14 \text{ K}$
2. apparent source temperature reflected by the wall:
 $T_r = 30^\circ\text{C} \gg \gg 303.14 \text{ K}$
3. outdoor temperature:
 $T_{\text{out}} = 20^\circ\text{C} \gg \gg 293.14 \text{ K}$

It follows that:

$$N_v \equiv (413.14^4 - 293.14^4)$$

and

$$\rho_v N_v \equiv (303.14^4 - 293.14^4)$$

so

$$\varepsilon_v = 1 - (303.14^4 - 293.14^4) / (413.14^4 - 293.14^4) = 0.9512$$

U-values are summed up in table 3.

Table 3: U-value of the building façades using the ITT method.

façade	U (w/m ² K)
south	0.37
west	0.40
north	0.37

The average U-value of the external wall measured with the ITT method is $U = 0.38 \text{ W/m}^2\text{K}$. It is a value higher of 31% compared to the calculated one and lower of 21% compared to the one measured with HFM method.

5. Conclusions

Even if the procedures given in the standard ISO 9869 have been followed and the users have effectively cooperated, the heat flowmeter method has given non homogeneous results depending on the method used for data analysis. This is probably due both to unfair weather conditions during the test period (the difference $T_{\text{int}} - T_{\text{out}}$ between indoor and outside temperature was often lower than the limit of 10°C), to the low thermal inertia of the light wall and to the presence of an air space just before the last inner layer where the heat flowmeter was mounted. This could have caused a non-linear heat flow through the element itself.

The infrared thermovision technique method, on the contrary, has given good results: the U-value measured on the same wall typology but with different exposure are comparable. Moreover, it must be taken into account that data acquisition is not punctual (as with the HFM method) but related to a certain area chosen to be representative of wall behaviour and without thermal anomalies. So, results can be considered more reliable.

Finally, the quite strong difference between calculated and measured U-value is not a surprise. In fact, the thermal conductivity λ value of an element to be considered during the design phase should not be the one declared by the producer, but a correct value that takes into account the real condition of the elements and the way they have been laid down (that sometimes can be not the proper one). The Italian standard UNI 10351:1994 itself states that the deviation from the values measured in laboratory and the real ones found in usual production can be of 5% up to 50%. So, the standard gives a modified λ value considering the average humidity level in real condition of use, the ageing, the possible tamping of loosed materials, the handling, the installation made by the rule book, the thickness tolerance. The value is increased from 10 up to 50%, sometimes even 100% depending on the material.

It is obvious that the estimation of the U-value by means of in-situ measurement, strongly depending most of all on the λ value of the material composing the building element, can differ with the same percentage.

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7. References

1. ISO 9869:1994, Thermal insulation - Building elements - In-situ measurement of thermal resistance and thermal transmittance
2. prEN15203, Assessment of energy use and definition of ratings
3. UNI 9252:1998, Isolamento termico. Rilievo e analisi qualitativa delle irregolarità termiche negli involucri degli edifici. Metodo della termografia all' infrarosso
4. UNI 10351:1994, Materiali da costruzione. Conduktività termica e permeabilità al vapore