A comparison between thermographic and flow-meter methods for the evaluation of thermal transmittance of different wall constructions

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Abstract. One of the key parameters that “meter” the energy performance of the whole structure of buildings is the thermal transmittance. This parameter can be evaluated with a theoretical approach, regulated by standard ISO 6946, once the stratigraphy of the envelope and the properties of the constituent materials are known, or by using a heat flow meter (HFM), following the recommendations provided in standard ISO 9869. Recently, the use of quantitative IR Thermography (IRT) has been proposed by several researchers; this method allows to determine the overall transmittance of an envelope in a short time (especially in comparison with HFM method). However, the theoretical or experimental transmittance, measured on real buildings having walls composed by different materials, can be rather distant from those calculated or measured with different procedures. For this reason, for a correct certification of the thermal performance of a building envelope, it is necessary the availability of experimental procedures for a direct and reliable evaluation of the thermal transmittance, suitable for different walls. Research has found that, especially in historical constructions, faults in the building envelope and the age of the materials can greatly affect the HFM measurements. The aim of this work is to analyze in situ the thermal performance of three different walls which have been selected according to: different materials, different age, and different construction. On each envelope, a comparison between U-values, measured by HFM and IRT, and computed according the standard procedure, has been effected.

1. Introduction
In the European context, the existing buildings are responsible for more 30% of the final energy consumption, 65% of which is due to residential buildings. To adopt proper energy policy actions, it is important to know the energy performance of this sector; clearly, it is not possible to base on a particular building but the attention must be addressed to a set of constructions belonging to a specific territorial context [1-2]. This need is particularly strong in Italy, where the building stock has a large range from historical to modern buildings, and almost 75% of the residential houses were built prior to 1991. Regarding the thermal performance of an envelope, the difficulties arise because of lack of information about important parameters that affect the thermal transmittance (U-value) of the components (age, materials, wall thickness, humidity and so on).
Unfortunately, the building energy data used for energy planning at national or local scale, or for requalification of ancient buildings, rarely are based on measured values; the laws propose standard data of U-value suitable for Italian context and particularly for new constructions. The thermal transmittance can be calculated with a theoretical approach, through specific software, regulated by standard ISO 6946 [3], once the stratigraphy of the envelope and the properties of the constituent materials are known or by using several non destructive and destructive methods; in particular currently the most used is a Heat Flow Meter (HFM) following the recommendations provided in standard ISO 9869 [4].

However, to evaluate the energy performance of a building stock, in situ measurements are needed, but they are often expensive, time consuming, or require expert knowledge. Recently, several researchers have proposed the use of quantitative thermography for a rapid in situ measurement of the overall transmittance of an envelope building in a short time [5-12].

Often some differences have been found between theoretical and/or experimental data obtained on real buildings [13-15], especially for ancient buildings, with these different procedures [16-18]; for this reason it is difficult to decide which technique to use.

The aim of this work is to present a series of experimental measurements of the thermal transmittance of different buildings belonging to different historical periods, comparing different non invasive techniques: infrared technology, heat flow meter method and calculated value following the standards mentioned above.

The experimental methods have been applied at the same time on an ancient masonry, a well insulated house, and a public building. The differences among the calculated and U value measured with both methods have been outlined. These data might constitute a base for a correct energy diagnosis of the opaque envelope, especially of ancient buildings with a rapid, economic and appropriate method.

2. Description of the test buildings

The test buildings used for in situ measurements of thermal transmittance are located in L’Aquila, a small city in the Abruzzo Region, in the centre of Italy. Detailed climatic data for this city are shown in table 1.

| Altitude (a.s.l) | Average annual temperature | 12.1°C |
|-----------------|----------------------------|--------|
| Geographical coordinates | Indoor Design temperature (heating season) | 20°C |
| 714 m | 2514* | 26°C |
| 42°21'14.43"N 13°23'31.17"E | Indoor Design temperature (cooling season) | |
| Degree Days | Outdoor Design temperature (heating season) | -5°C |
| Climatic zone | * according to Italian Law DPR 26/08/1993, n.412 |

The buildings selected as case studies are an historical building, a private house, realized with innovative and sustainable materials, and a public building characterized by large volumes and high ceilings. Figure 1 shows the main characteristics, the urban context, the construction materials and the IR images of the case studies together with the weather conditions during measurements, while the stratigraphy of the walls and their thermal transmittances are displayed in table 2.
2.1 Case study A: historical building
The selected case study is representative of the houses (second half of the 18th century) generally present in the historical centre of L’Aquila and surroundings, and linked to the local typology and technological traditions.
In fact, about 60% of buildings’ masonry in L’Aquila is realized with small stone elements (15-20 cm), of irregular shapes and setting, with possible lacks among the stones, sometimes filled by stone wedges. Typical masonry width is about 80 cm.
The earthquakes that hit the city during past centuries have determined the development of several construction techniques, and the reuse of recovered materials with different characteristics. The façade of the selected building is 80 cm width, and it is made of irregular ashlars of rough-squared, randomly arranged with other materials detected by preliminary thermographic inspections, and covered with plaster. Generally there is no information about materials’ characteristics, therefore it is important to use thermography for revealing decay and construction typologies.

2.2 Case study B: private house
This case study is a private house recently built in the suburb of the city with a cement-wood brick, internally insulated with 10 cm of high density EPS (expanded polystyrene).
This building material is widespread in the North of Europe, but still not diffused in Italy, especially in the Abruzzo Region. The building material used for this house is made up of wastes of wood processing techniques, in particular fir fibers, mixed with iron oxide, water and Portland cement. The production technologies, as well as the raw materials used for these bricks, are ever-evolving. Bricks are produced by extrusion, and a part of the inner cavity is filled with an insulating layer; in this case, an EPS layer has been used.

2.3 Case study C: public building
The facility was built in the early of ’90, and it hosts the Faculty of Engineering. The bearing structure is made with reinforced-concrete frames, while the masonry walls are made with clay bricks, an air layer, an insulating panel and a single or double curtain wall (depending on the facade). After the earthquake that hit L’Aquila in 2009, the building had undergone to structural damages, repaired in 2011. The interventions did not include the energetic refurbishment of the building.

Table 2. Thermophysical properties of the investigated walls, and their thermal transmittance obtained by theoretical calculus.

| Material                  | Thickness [m] | Superficial mass [kg/m²] | Conductivity [W/m·K] | Resistance [m²·K/W] | Thermal transmittance [W/m²·K] |
|---------------------------|--------------|--------------------------|----------------------|---------------------|-------------------------------|
| Case Study A              |              |                          |                      |                     |                               |
| Plaster                   | 0.020        | 28.0                     | 0.66                 | 0.03                | 1.25                          |
| Rough-cut stones          | 0.800        | 1520.0                   | -                    | 0.56                |                               |
| Mortar                    | 0.020        | 36.0                     | 1                    | 0.02                |                               |
| Case Study B              |              |                          |                      |                     |                               |
| Plaster                   | 0.015        | 27.00                    | 1.00                 | 0.015               | 0.23                          |
| Wood-cement (density 550 kg/m³) | 0.04        | 22.00                    | 0.13                 |                     | 0.308                         |
| Concrete                  | 0.18         | 432.00                   | 1.87                 | 0.096               |                               |
| Wood-cement (density 550 kg/m³) | 0.025       | 13.75                    | 0.13                 | 0.192               |                               |
| High density EPS          | 0.10         | 4.20                     | 0.031                | 3.387               |                               |
| Wood-cement (density 550 kg/m³) | 0.03        | 16.5                     | 0.13                 | 0.231               |                               |
| Plaster                   | 0.015        | 27.00                    | 1.00                 | 0.015               |                               |
| Case Study C              |              |                          |                      |                     |                               |
| Plaster                   | 0.02         | 28                       | 0.66                 | 0.66                | 0.51                          |
| Hollow brick              | 0.08         | 48                       | -                    | -                   |                               |
| Air layer                 | 0.10         | -                        | -                    | -                   |                               |
| Fiber glass panel         | 0.04         | 0.6                      | 0.04                 | 0.04                |                               |
| Concrete blocks           | 0.15         | 147.1                    | 0.48                 | 0.48                |                               |
| Plaster                   | 0.02         | 28                       | 0.66                 | 0.66                |                               |

a) The thermal transmittance has been calculated assuming as internal and external liminar resistances respectively 0.13 and 0.04 m²·K/W

3. U-value measurement: procedures and results
To evaluate the U-value of the envelopes, three different approaches have been used: a theoretical calculus, according to EN ISO 6946:2007 [3], the heat flow meter method following ISO 9869:1994 [4], and the IRT technique, a recently proposed technique already used by the Authors in a previous work [19].
For the theoretical calculus, the thickness and conductivity of each layer are needed, in order to calculate the thermal resistance of each component of the stratigraphy using the lumped-parameter electrical analogy. The sum of the resistances provides the wall thermal resistance, that, added to the internal and external liminar resistances, gives the total thermal resistance of the wall, whose reciprocal represents the overall wall transmittance.

The HFM provides the $U$-value by reciprocating the sum of the standard liminar resistances (both internal and external) and the wall thermal resistance, as in equation (1). The reciprocate of the wall thermal resistance is the thermal conductance $C$, that is calculated by the HFM by dividing the instantaneous measured flow rate through the wall by the superficial temperature difference measured on the inside and the outside of the wall, according to equation (1).

$$U = \frac{1}{h_i} + \sum R + \frac{1}{h_e}$$

$$C = \frac{1}{R} = \frac{\Phi}{\Delta T}$$

A heat flow meter (Hukseflux HFP01) and three thermal resistances (LSI Lastem Pt100) were used in our campaigns; data were acquired every 10 minutes with the help of a data-logger (LSI Lastem M-Log ELO008), and the series of the instantaneous thermal conductance values were processed by using the progressive average procedure, in order to obtain the asymptotic thermal conductance true value [20]. In addition, at the same time, outdoor and indoor air temperatures were recorded with two thermo-hygrometers (OnSet HOBO H8).

Anyway, a preliminary thermographic inspection of the outside walls has been performed for identifying the best position of the heat flow meter probes. As IR camera, a FLIR ThermaCAM® S65, operating in the range of 7.5 -13 $\mu$m and whose IFOV is 1.3 mrad, was employed, even to apply the IRT technique, following the procedure explained in [6].

According to this technique, by using an infrared camera it is possible to detect the heat flow through the envelope and its emissivity; the outdoor temperature is measured by using an approximating black body, namely using a black PVC pipe whose diameter is 6 times smaller than its length, while the indoor temperature is calculated approximating the black body with the opening of a window. The mean apparent reflected temperature is measured by means of a lambertian surface, like an aluminum foil crumpled and then stretched, taped on the surface and framed by the IR camera together with the wall itself.

The $U$-value is calculated by using the following Equation 2, proposed in [8]:

$$U = \frac{5.67 \varepsilon_v \left[ \frac{T_w}{100} \right]^4 \left( \frac{T_{out}}{100} \right)^4 + 3.8054 \nu \left( T_w - T_{out} \right)}{\left( T_{int} - T_{out} \right)}$$

where $T_{int}$ is the indoor environment temperature [K], $T_{out}$ is the outdoor environment temperature [K], $T_w$ is the surface temperature of the element [K], $\varepsilon_v$ is the emissivity of the material in the measurement range of the IR camera, and $\nu$ is the wind velocity, neglected in our application.

This technique has to be fully exploited, and the continuous updates of the procedure demonstrates that several researches on the matter are still ongoing; the variety of the building typologies proposed in this work can help to widen the knowledge of limits and strengths of this innovative application of the quantitative thermography.

Hereafter are shown, for each building analyzed, the main features of the façade, together with the elaborations of the data acquired by the HFM after a measurement campaign of 72 hours for case
study B and C, and 144 hours for the historical building, performed with the progressive average method using a simple tool provided by the HFM manufacturer (InfoFlux by LSI Lastem). Moreover, the U-value calculated with the IRT is proposed.

3.1 Case study A: historical building
The thermophysical properties of the materials that constitute the stratigraphy of this ancient building are not known; therefore, values foreseen by the UNI ISO 10351 [21] have been chosen, while the wall thickness has been deduced by similar buildings of the same historical period and then checked with an endoscope. The building has heavy walls, whose stratigraphy is shown in table 2, and the overall thermal transmittance equals 1.25 W/m²-K. Data acquired with the HFM for 144 hours have been processed using the progressive average procedure, gaining an asymptotic thermal conductance. The value of the thermal transmittance achieved by taking into account even the laminar coefficients is 1.17 W/m²-K. Finally, the thermal transmittance has been measured using IRT technique. In this case, the U-value recorded is 1.14 W/m²-K.

3.2 Case study B: private house
The stratigraphy of this house recalls the composition of the cement-wood bricks used and reported in table 2. Using the procedure explained before, it is possible to calculate the overall thermal transmittance, that equals 0.23 W/m²-K. The measurements with HFM were carried out on the north-west wall for three days. During the in-situ survey the internal surface temperature is almost constant although the building is lived, while the external temperature shows a periodic trend that recall the alternation of days and nights. The U-value obtained using the progressive average procedure is 0.42 W/m²-K. This value is much higher than the previous. The IRT technique provided U= 0.22 W/m²-K.

3.3 Case study C: public building
The stratigraphy of this building, listed in table 2 together with the conductivity, leads to an overall transmittance equal to 0.51 W/m²-K. Following the rules of ISO 9869:2014, in situ thermal transmittance measurements with HFM have been performed, obtaining once again an asymptotical trend of the conductance. The U value is 0.75 W/m²-K during the monitoring campaign (72 hours) the internal and external surface temperature have the trend shown in figure 2. Using the IRT, a similar value, 0.76 W/m²-K has been obtained.
Superficial temperatures (on the left) and progressive average of the thermal conductance (on the right) for case study A (a), (b), case study B (c), (d), and case study C (e), (f).

Results are summarized in table 3.

Table 3. U-values obtained with the different methods and their percentage differences.

|                  | U [Wm⁻²K⁻¹] | Percentage differences |
|------------------|-------------|------------------------|
|                  | Design     | HFM                    | IRT         | Design-HFM | HFM-IRT | Design-IRT |
| Case study A     | 1.26       | 1.17                   | 1.14        | 7.14%       | 2.56%    | 9.52%      |
| Case study B     | 0.23       | 0.42                   | 0.22        | 82.6%       | 47.62%   | 4.35%      |
| Case study C     | 0.52       | 0.75                   | 0.76        | 44.23%      | 1.33%    | 46.15%     |

For the case study A, the in situ measurements suggest that the thermal performance of the envelope is better than the one revealed by the calculation based on thermo-physical properties of the components of the wall. This might depend on the uncertainty related to the building construction and the ratio of mortar to stone in this particular wall construction. During the HFM acquisition the inside surface temperature is almost constant (being the house unoccupied) but the difference between internal and external conditions does not seem to strongly affect the results.

The HFM and IRT values are near, and their percentage difference is 2.56%, confirming the validity of the IRT technique even for heavy walls, if the measurement campaign follows the procedure mentioned and IR images are acquired during a proper heat release phase, that is after important heat storage during the day.

For case study B, the thermal transmittances obtained by theoretical approach and IRT are similar (difference of 4.35%), but results don’t merge with the value obtained with the HFM. This mismatch can be due to several reasons; first of all, the flux meter might have been exposed to direct solar...
radiation since it has not been possible to install it to a completely north-exposed wall. This condition, although inadvisable, is unfortunately common in the practice, unless the probe is sheltered. Moreover, as seen in figure 2, the wall temperature difference that occurred during the measuring campaign has not been greater than 10°C, but it swung through the days and this can significantly influence the final results [22-23].

In this case, the envelope can be considered as made of light wall, and it has been assessed that there is a great sensitivity to small variations of the wall temperature measured along the investigated wall. For case study C, the design U-value is smaller than the ones obtained experimentally. Considering that the wall has a complex stratigraphy, the calculated value can be considered as less reliable, whilst the U-value measured with HFM can be considered trustworthy since the surface temperatures of figure 2e) had quite the same trends, maintaining a constant gradient along the measurement campaign. The results provided after the post process with the average method is near the one obtained with the IRT (difference of 1.33%), demonstrating the validity of the new technique.

4. Conclusion

Based on the results mentioned above, the following conclusions can be outlined.

Three envelopes of buildings built in L’Aquila with different techniques were investigated. The U-values obtained in situ by using HFM and IRT have been compared with the one obtained knowing the thermal properties of the materials of each stratigraphy.

Firstly climatic conditions suggest when thermographic measurements should or should not be undertaken [24-25]; the recommendation is a cloud covered sky, low wind speed and a temperature gradient of at least 10°C between internal and external rooms. However, as demonstrated by a study of Fox [26] climatic changes can also have an impact on the thermal properties of the materials on a transient basis. Consequently, thermographic measurements should be performed for multiple days in different environmental conditions for having more accurate results, since

Furthermore, it has been noticed that temperature changes in the investigated areas cause an uncertainty in the U-value measurement: an IR image shows a temperature distribution by a pixel pattern, and by selecting different pixel of the wall IR image it is possible to gather different temperatures and, therefore, different U-value. A confirmation of these results, obtained from experimental data, can be found in the study of Albatici et al [8], that shows a sensitivity analysis of the expected U-value by simulating percentage differences on the input parameters. As recommendation for future works, the investigations on the same wall but on different positions could be furthered and the average U value could be evaluated. Also for data calculated following ISO 6946 important differences between the results can be noticed, due to the uncertainty on the conductivity and thickness values of materials.

HFM measurements were performed in compliance with standard ISO 9869 and results seem to be in accordance to the data obtained with IRT method. In two case studies similar values of thermal transmittance are obtained from calculations and in situ measurements, with the exception of case study B.

Anyway it is important to notice that the errors and uncertainties are present in all methods; the influence factors of the in situ measurement are very complex: the U-value obtained with HFM depends on the variability of the climatic conditions during the monitoring, as well as on the method used for the data process (progressive average method, black-box method) [27-28].

Measurement uncertainty is reduced if the temperature of the internal surface is kept constant as much as possible, and the difference between indoor and outdoor temperature is higher than 10°C. As a general remark, according to norm ISO 9869 the uncertainty of in situ measurement performed by HFM ranges from 14% to 28%.

The U-value obtained by IRT depends on local conditions, on the wall emissivity, the air temperature gradient between indoor and outdoor (which has to be at least 15 °C), while in our campaigns it didn’t seem to depend on the thermal capacity of the walls (light or heavy ones).
IRT provides better results if the measurement is performed on the North wall, since there isn’t direct solar irradiation.

Finally, it is important to note that IRT method is non-invasive and allows the knowledge of the thermal transmittance of a large area, while the HFM provides only a punctual measurement.

In conclusion, basing on the case studies proposed, it is difficult to establish which method gives the best result, the one that is more representative of the real thermal transmittance of the envelope, but it is not possible to establish a common method, that has to be chosen case by case. In scientific literature, however, it is stated that U-value of walls measured in situ with different methods can vary up from 20% to 50% [29-30].

However the results proposed in this paper seem to show that IRT method might be used in alternative to HFM especially for historical buildings, where faults in the building and the ageing of the materials can greatly affect HFM measurements, although the errors sources are not still identified and quantified, as explained in a previous work.
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