TITLE

Quantification of heat energy losses through the building envelope: a state-of-the-art analysis with critical and comprehensive review on infrared thermography

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ABSTRACT

The large majority of the building heat losses occur through the building. Hence, the accurate evaluation of energy leakages, quantified by the thermal transmittance (U-value), is necessary, especially for energy labelling or city energy planning purposes, to foresee proper retrofit intervention and energy strategies. Among the techniques for the U-value assessment, the one that employs the quantitative infrared thermography (IRT) has spread in the last years, thanks to the possibility of easing the abovementioned processes due to reliable results, fast inspection, measurement carried out on large areas. However, a work that collects all the available techniques, explaining their weak and strength points, together with analogies and differences among the literature experiences, and which focuses on IRT, has not been carried out until now.

This study starts from the common approaches for the U-value evaluation (analogies with coeval buildings, the calculation method, the *in-situ* measurements and the laboratory tests), with the underlying standard procedures and the most important advantages, problems, and potential sources of errors defined by the literature. Then, the IRT technique, and its development through the years, is detailed and discussed, focusing on analogies and differences among the available literature sources. Also, several recurring energy related problems, such as the detection and estimation of thermal bridging as well as the assessment of the ε-value of building materials, are shown. Finally, the qualification of IRT personnel and the perspectives in the building sector are briefly explained, to remark the need for specialized thermographers who deal with an ever evolving methodology.

Keywords: infrared thermography; IRT; thermal transmittance; U-value; HFM; design value.

Index

Nomenclature	
Symbols	
s	Thickness [m]
d	Distance [m]
T	Temperature [K]
T_a	Air temperature [K]
T_s	Surface temperature [K]
ΔT	Temperature difference [K]
T_{sa}	Apparent surface temperature [K]
T_{refl}	Reflected apparent temperature [K]
C	Thermal conductance [W/(m^{2}K)]
U-value (or U)	Thermal transmittance [W/(m^{2}K)]
R	Thermal resistance [(m^{2}K)/W]
c_p	Specific heat [J/(kg K)]
h	Convective/radiative heat transfer coefficient [W/(m^{2}K)]
h_i	Internal convective/radiative heat transfer coefficient [W/(m^{2}K)]
h_e	External convective/radiative heat transfer coefficient [W/(m^{2}K)]
A	Area [m^2]
Greek symbols	
λ	Thermal conductivity [W/(mK)]
ε	Thermal emissivity [-]
ρ	Density [kg/m^3]
μ	Vapor pressure resistance [-]
υ	Wind speed [m/s]
Φ	Heat flow rate [W/m^2]
Subscripts	
a	Air
s	Surface
e	External
i	Internal
tot	Total
Acronyms and abbreviations	
HFM	Heat flow meter
LDT	Low-destructive technique
NDT	Non-destructive technique
IRT	Infrared thermography
IR	Infrared
GHP	Guarded hot plate
CHB	Calibrated hot box
GHB	Guarded hot box
RH	Relative humidity [%]
HVAC	Heating, ventilation, and air-condition system

FOV	Field of view
NETD	Noise equivalent temperature difference
MDTD	Minimum detectable temperature difference

1. INTRODUCTION

The worldwide growing awareness of buildings' energy consumption and their environmental impact, mainly due to space heating and cooling, is pushing the sensibility of policymakers to energy conservation, which starts from the evaluation of the thermal performance of building elements.

Indeed, the proper evaluation of energy leakages, quantified by the thermal transmittance (U-value), is necessary, also to foresee accurate retrofit interventions, that pass through the proper design and the selection of thermal insulation materials needed to reduce space conditioning loads [1; 2; 3].

Several techniques for the U-value evaluation are available: analogies with coeval buildings, calculation method, in-situ measurements and laboratory tests; they are differently employed according to the specific requirements and needs (in terms of accuracy, time, and economic effort).

However, practitioners, technicians, research groups and policymakers agree with the need for a quick, cheap, and reliable method to easily determine the thermal transmittance of buildings, in order to speed up the decision processes and energy policies involving the building sector, that in turn affect the macro-policies that Countries adopt to countermeasure climate changes.

For this reason, over the last decade another technique, that employs the quantitative infrared thermography (IRT), is taking shape and spreading for the U-value determination, thanks to its advantages, such as reliable results, fast inspection, measurement carried out on large areas. However, literature experiences propose different (if not conflicting) outcomes, depending on factors like procedures, features of the investigated building element, environmental parameters considered and so on. This work is proposed to compare these techniques and studies, starting from their similarities and differences, focusing specifically on the quantitative IRT, as a result of the growing attention that the scientific community has given to this technique. Given the research gap represented by the lack of an overall view on the U-value assessment via common procedures and IRT, this comprehensive study on the state of the art of the U-value determination is presented.

1.1. Aims and methodology

The paper aims at proposing a critical review on the employment of the quantitative IRT survey for the assessment of the U-value of the building envelope. Also, several recurring energy related problems, such as the detection of thermal bridging as well as the assessment of the emissivity (ε) [-] of building materials, are presented and discussed. After a brief background on infrared thermography, the approaches for the U-value evaluation of building elements are described, based on the analogies with coeval buildings, the calculation method, the *in-situ* measurements, and the laboratory tests. The standard procedure at the basis of each approach is showed, arguing also the most important advantages, problems, and potential sources of errors defined by the literature. In this context, the IRT test is an emerging approach thanks to the advantage of air's transparency to the infrared (IR) radiation emitted by the surfaces over short distances, reduced costs, and measurement times. Finally, the qualification procedure for the thermographers as well as the future perspectives of quantitative IRT have been described. A concluding paragraph summarizes the main outcomes and findings from the methodological approach and the critical review.

The research methodology is based on two research steps: (i) literature review based on key-words to determine the most important issues on the use of the quantitative IRT test for the assessment of the U-value of the building envelope; and (ii) deeper investigation of specific topics on bibliographies suggested by the literature. Key words concern procedures (e.g. laboratory test, in situ measurements, and so on), IRT approaches and methodologies (e. g. qualitative IRT, quantitative IRT, IRT survey, tests, U-value measurement), important topics (e. g. thermal performance assessment, thermal bridging detection, and so on), and energy performances measurements of different building technologies (façade, roofs, glazing systems, windows, and so on).

The literature background of this paper includes academic studies (i.e. scientific papers, relevant conference proceedings, published books), and "grey literature" (i.e. standards, professional guides, technical reports, and governmental guidance notes), to consider scientific interest and theoretical approaches as well as technical advice and practical methodologies. Professional works (including web pages of IRT associations and thermal camera producers) are also analyzed, but they don't give a specific contribute for discovering the new products or innovative approaches. In total 225 literature sources, spanning from the last 64 years (1954-2018), have been analyzed and compared to have a global outlook on the topic.

2. BACKGROUND ON INFRARED THERMOGRAPHY

The infrared thermography technique (IRT) employs an infrared (IR) detector and an imaging system that allow to convert the surfaces emissive power in temperature pattern [4; 5]. Surface temperature distributions can be used to identify thermal irregularities due to, for example, structural features, building materials, thermal insulation defects, moisture contents, energy problems, and air leakages within the building components [6; 7; 8; 9]. The employment of IRT rapidly increased over the last 50 years thanks to commercial and industrial applications [5; 7; 10; 11; 12]. The simplified timeline proposed can help to define the evolution of this technique (Figure 1).

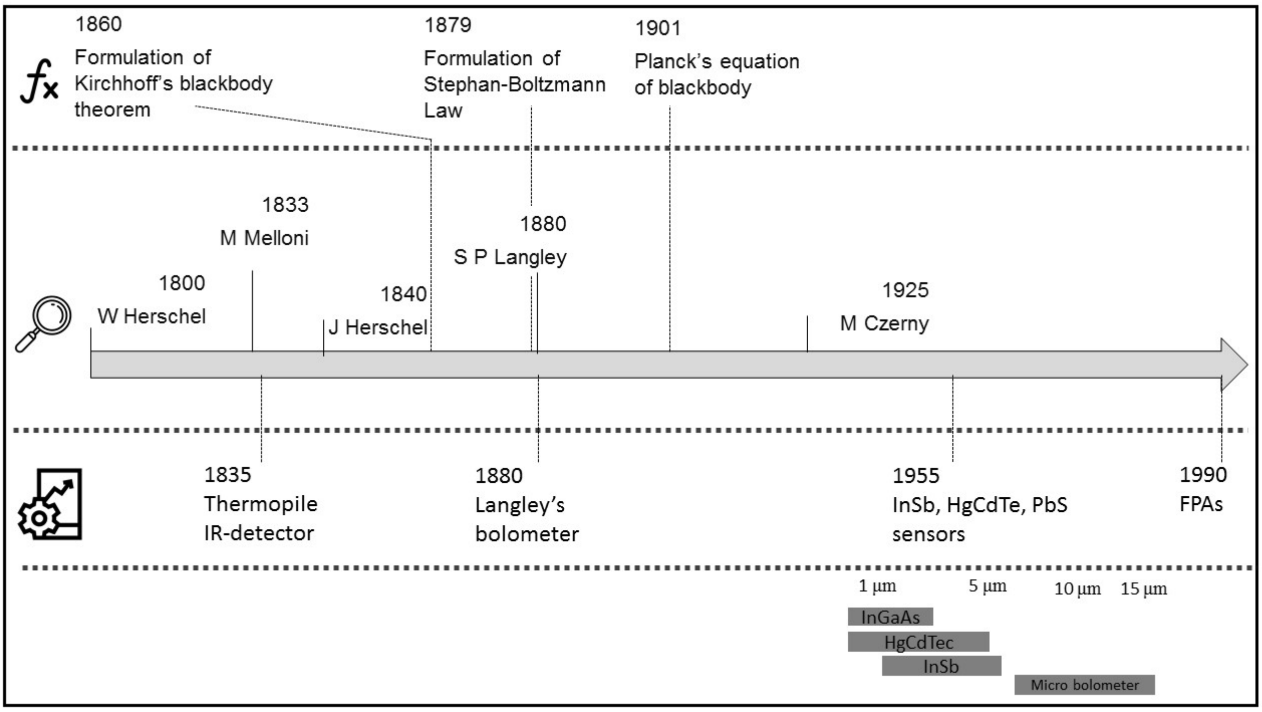

Figure 1. Milestones in the history of IR detection.

The discovery of the electromagnetic spectrum, the theory of radiation, and the first detectors based on the IR-radiation are dated back to the XIX Century [7; 10; 12; 13; 14, 15]. On the basis of these detectors, the thermal imaging cameras (IR-camera) were realized over the two World Wars for military purposes [7; 14; 16]. These big IR-cameras needed cooling devices and were used for the identification of military requirements during night [16; 17]. A few years later, a single detector was settled out for medical applications [18]. In 1966, real-time IR-cameras were commercialized, kickstarting their employment for the diagnosis of power lines, electric installations, heating, ventilation, and air-condition (HVAC) systems [12; 17; 19]. In the 1980s, the addition of new functions for improving the usability and the interpretation of results (i.e. chromatic palettes, simplified software, single cooled sensors) pushed the use of IRT in several fields, spanning from medicine to the preservation of cultural heritage, from civil engineering to transportation [5; 7; 12; 20] . In 1990s, the size of the IR-camera began to get smaller thanks to the introduction of uncooled micro-bolometers [7; 20]. In the last fifteen years, IRT was considered as a powerful tool for fast and accurate building diagnostics [5]. It is becoming progressively utilized especially for the restoration of cultural heritage, civil engineering, preventive maintenance, and energy audit [5; 7; 12; 21, 22], thanks to the progresses in technology, and costs reduction [20].

The IR-camera working principle (Figure 2) is based on the evaluation of the radiant flux that comes from the investigated object and reaches the IR detector. Under the hypothesis of a mean air transmission (that varies along with wavelength), and of a grey body for the investigated surface, in the case the ε-value of object is less than 1 (most likely to occur), the radiative heat flux is given by two contributions: (i) the flux emitted (radiated) by the object due to its temperature; (ii) the flux incoming from the surrounding elements that is reflected by the object itself. The total radiant flux is converted by the IR-camera in the apparent surface temperature (T_{sa}) [K], that considers all radiation incident on the sensor, and it should be compensated according to some operating parameters: ε-value of the object, reflected temperature (T_{refl}) [K] (to account the radiant flux reflected), IR-camera-to-object distance (d) [m], air temperature (T_a) [K], air relative humidity (RH) [%]. Once all these parameters are accurately defined and used in the IR-camera setup, the real surface temperature (T_s) [K] can be retrieved and shown in the thermogram.

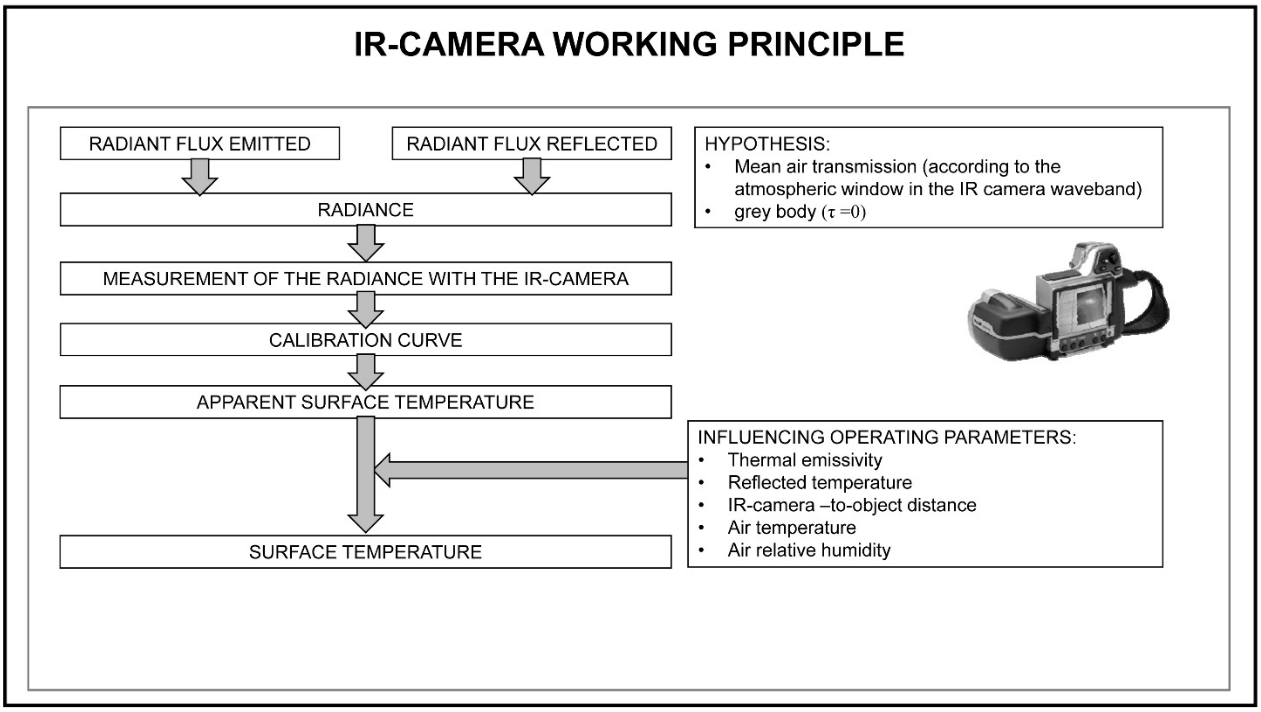

Figure 2. IR-camera working principle.

Qualitative IRT surveys have been extensively used to gather thermal and energy information using simplified procedures, low costs, and reduced times [23; 24]. This growing interest in the building diagnosis is demonstrated by the increase of review papers on qualitative IRT survey [5; 7; 20; 25; 26; 12]. On the contrary, quantitative studies have been employed for quantifying the thermal performances of the building envelope [4; 12, 27], focusing particularly on the thermal transmittance (commonly indicated as U-value or U) measurements of the building envelope. The interest in this topic is witnessed by the spread of research articles dealing with it, although none of them aims at resuming the main outcomes, which can be divergent according to the procedures, approaches, and experiences. Methodologies proposed in literature have been compared in the following study, in order to define limitations, problems, and potentials of each technique.

3. COMMON APPROACHES TO THE U-VALUE ASSESSMENT

The thermal transmittance can be defined as the heat flow rate (Φ) [W/m^2] that, in steady state regimen, crosses a surface (A) [m^2] under a ΔT [K] between the surroundings on both sides of the given system, supposed flat [28]. In other words, the U-value (U) [W/(m^2·K)] defines the rate of the heat that flows through one square meter of the analyzed component when the temperature on its two sides differ by one Kelvin. The definition fits both opaque (walls, roofs, ceilings) and transparent (glazed) building elements, and derives from the Fourier' s law, expressed for a plane geometry (wall) in steady state condition free of heat sinks or sources. The U-value allows the estimation of energy losses through the characterized element. It is clear, therefore, that, in the perspective of buildings' energy simulation, certification and audit, the knowledge of the U-value is mandatory [29]. Moreover, the accurate identification of the appropriate thermal performance is a key requirement to ensure effective energy efficiency improvements, and successful decision making when building renovation projects are planned [30].

The thermal performance of a building component depends on the following elements [28]: (i) global layout or stratigraphy; (ii) thermal characteristics of each material; (iii) water content or presence of moisture on materials; and (iv) presence of decay or damage. [31]. Nevertheless, the provided definition of the U-value implies some simplifying hypotheses [28], which allow the employment of an eased conduction-and-convective heat transfer model, necessary in the approaches for U-value assessment.

According to project and/or equipment availability, the estimation of the U-value can be carried out with different techniques (Figure 3) as detailed in the following sections. Two approaches are possible: (i) without measuring campaign, using the analogies with other coeval buildings or the standard calculation method; and (ii) with measuring campaign, using heat flux meter (HFM) measurements, laboratory tests, or infrared thermography (IRT) surveys. The accuracy of these approaches is related on one hand on reliable data availability, on the other hand on measurement procedure and instrumentation. Literature experiences often propose different (and sometimes conflicting) remarks on the approaches, depending on the investigated building and its features, on the set up, or on the procedure. It's worth noting that some of these approaches are already regulated by technical standards, worldwide adopted, while others do not have specific regulations yet.

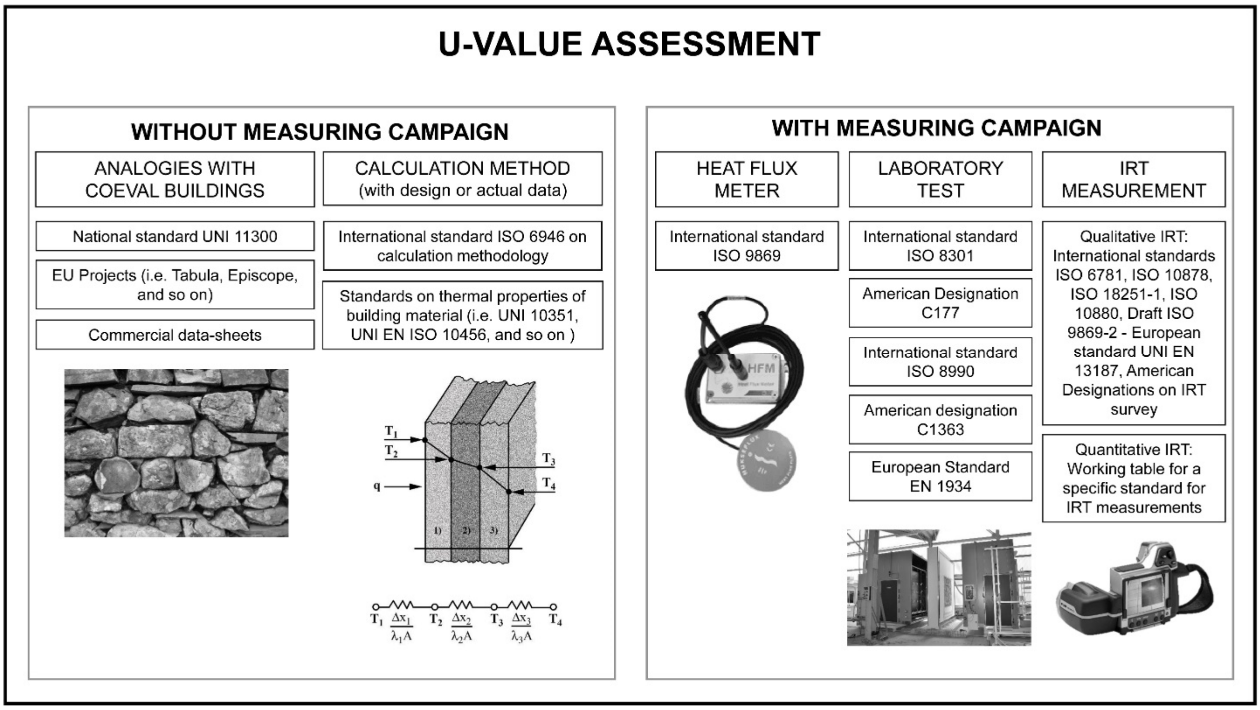

Figure 3. U-value assessment approaches and related technical standards.

3.1. Analogies with coeval buildings

This approach is commonly employed when detailed information on the building structure or materials are missing. This occurs especially with historical and existing buildings [32; 33]. In this case, the knowledge of the construction period and the urban context in which the building is located, permitted to infer the U-value by referring to other buildings similarly aged, whose thermal characteristics and masonry texture are known [34; 35]. As foreseeable, this approach is characterized by factors that may affect its reliability. Possible causes of uncertainty can be due to: (i) wrong information concerning the construction period [36; 37; 38]; (ii) particular construction features of the investigated building that are neglected by a simple analogy with coeval building [38; 39]; (iii) different wall textures employed on the building [39; 40; 41; 42; 43]; (iv) different walls' thicknesses (s) [m] of the same texture (i.e. thicker wall for lower level floors, and thinner for the ones of higher floors) [36; 37; 38; 39; 40; 42; 43]; (v) pronounced material ageing, that affects the thermal performance [42; 43]; (vi) possible ignorance of refurbishment/renovation intervention occurred in the past and not pointed out in report or documents concerning the building [37; 39; 40]; and (vii) moisture contents that has an impact on the final energy performance [36]. The evaluation of total heat transfer through a building element was affected by the difficulties related to the accurate identification of thermal properties of existing masonries [36; 37; 38; 39; 40; 42; 43; 44], with significant overestimations of the energy consumption of the whole building [41; 42; 43]. The use of inadequate parameters causes disadvantages for the calculation of the global energy balance of buildings, favoring substitutions or energy improvements without any advantage for these buildings [38; 40]. On the contrary, the application of accurate data inputs improves the agreement with the on-site results [38; 41].

The disadvantages of this approach are balanced by the pros, mainly related to the applicability for energy policy evaluation [41]. In fact, when a large amount of buildings needs to be thermally characterized (for instance, for energy planning measures or policies, both at local, regional and national scale), this approach is the fastest one [37]. The collection of data is essential for drafting databases of the building stock [45, 46]. Moreover, collected data can be compared to those from other countries having similar building stock [47; 48; 49; 50; 52; 53]. Thanks to these databases, the consequences (in terms of cost and energy demand) of energy efficiency measures or possible refurbishment strategies can be also evaluated.

3.2. Calculation method

This approach allows the assessment of the U-value referred to as "*design*" or "*theoretical*" or "*calculated*" or "*analytical*" or "*notional*" or "*estimated*" *value*. The method can be applied to components or elements having thermally homogeneous layers (including air) known in terms of thickness and design thermal conductivity (λ-value or λ). This method consists in calculating the thermal resistance (usually indicated as R-value) of each layer of the assembly (given by the ratio of its thickness *s* by its λ-value), and then in combining the individual R-values (R) [$(m^2 \cdot K)/W$] to obtain the thermal resistance of the component. Then, by including the effect of surface resistance (h) [$W/(m^2K)$] (also referred as to convective or radiative heat transfer coefficient) on both sides of the component, the R_{tot} is evaluated, whose reciprocate provides the U-value. A complete description of the method is provided by the International Standard ISO 6946 [54] that also claims the cases of non-applicability (e.g. doors, windows and glazed units, curtain wall, slab that transfer heat toward the ground, and elements air permeable). The standard, however, is applicable to elements having thermally inhomogeneous layers, using a simplified method. This procedure requires detailed and accurate input data on stratigraphy, position and thermal properties of each building material, in terms of λ-value, density (ρ) [kg/m^3], specific heat (c_p) [J/kg K], vapor pressure resistance (μ) [-], and ε-value. Non-contact methods for the assessment of thermal properties are also available [51]. In all cases, the estimation of the λ-value for the calculation method refers to standard values or databases. For instance, in code UNI 10351 [55] in force in Italy, λ-value, μ and c_p of construction materials are provided. The same role has code UNI EN ISO 10456 [56], in which it is stated that materials' properties can be assumed by declared values assessed after measurements. If the design conditions are different from those of the declared value, data concerning hygrothermal properties need to be modified to respect the applicable conditions. This standard, moreover, explains the methods and data for carrying out this conversion. In case measured values are not available, design values can be picked from tables, also provided by the code. The standard [56], however, does not take into account λ-value dependence on temperature [57], therefore it may vary along the season.

3.3. Heat flow meter measurements

The HFM measurements is a non-destructive test (NDT) for determining building envelope heat transfer capability directly *in situ*. The overall measuring device consists of a data-logger that collects data from thermistors (at least one on each side of the investigated element) and from a heat flux plate. Such system allows to measure and register the internal and external temperatures and the heat flows through the walls. This technique is useful especially for the U-value measurements of existing masonries, in order to avoid the inaccuracies related to the evaluation of wall morphology, material properties, damage, and application techniques [58; 59; 60; 61; 62].

The International standard ISO 9869 [63] explains the procedure for measuring the thermal transmission properties of a plane building component. It outlines the following elements: (i) apparatus to be used; (ii) calibration and installation procedures; (iii) data processing techniques; (iv) correction of systematic errors; and (v) reporting format. Significant errors and large uncertainties are related to: (i) measurement location [36; 64]; (ii) influence of boundary conditions [36; 64; 65, 66]; (iii) non-homogeneity of the materials [36; 65]; (iv) heat flux variation due to the presence of the HFM itself; (v) thermal inertia of the walls [36]; (vi) water content of walls [64; 65]; and (vii) data processing techniques [64, 67; 68; 69]. Proper conditions for employing HFM (specifically for low U-value façades) have been recently discussed [70].

The standard [63] defines the installation procedures and the data processing techniques for reducing the influence of measurement location, boundary conditions, non-homogeneities, thermal inertia, and moisture content of the wall. The main problem is related to the variability of operating parameters (i.e. sun radiation, υ, and outdoor temperature) that affect the heat flow and the temperature gradients through the component during measurements [64; 65; 71]. For avoiding solar radiation, the apparatus must be located in the north-facing walls [63]. Moreover, the outer surfaces of the equipment must be protected from the climatic parameters by a proper screen. Finally, to minimize the potential influence of heat sources and users on the inner surface, it [63] suggests sitting the apparatus away from sources of heat, such as radiators, fan coils and lamps. Furthermore, the use of IRT survey helps in the proper installation of sensors, avoiding the influence of thermal singularities, moisture content, and damage that could bring to incorrect results [59; 60; 61; 63 71; 72]. Several studies employed IRT survey for the evaluation of existing walls for the qualitative point of view [42; 43; 73; 74; 75; 76] in order to discover the presence of: (i) non-homogeneities in the wall stratigraphy or surface finishing; (ii) internal moisture and water absorption; (iii) presence of decay and damage (e.g. cracks, moisture, water seepage) and (iv) energy inefficiencies (e.g. like thermal by-passes). In this sense, the use of IRT for identifying the most suitable HFM probe location suggests the high cost of the HFM technique. For this reason, it has been important, for the scientific community, to develop a technique for the U-value assessment that involves the less equipment as possible, and attention has been paid to the IRT survey.

Similarly, the thermal storage effects related to the thermal inertia of the wall can be reduced by long continuous monitoring periods [63]. The standard monitoring period must be an integer multiple of 24 h and at least consecutive 72 h, according to the component features and the T_a variations [63]. New devices have been developed to overcome this issue [77; 78]. Air temperature differences (ΔT_a) [K] lower than 10 K and low heat flow (or heat flow inversion) lead to unacceptable uncertainties [60; 61]. Additionally, the filtering of the data during the periods with larger ΔT_a (up to 20%) improves the measurement accuracy [36; 42; 43; 64; 79].

3.4. Laboratory testing

Laboratory testing permits to measure the heat transfer capability in steady-state conditions of the building components exposed to conventional controlled environmental conditions. The thermal properties of homogeneous specimens can be tested with the guarded hot plate (GHP) [80; 81] or the HFM [82] apparatuses. The GHP apparatus allows the determination of the λ-value and the R-value of homogeneous and flat specimens. The International standard 8302 [80] and the American Designation C177 [81] lay down the minimum requirements for designing the GHP apparatus and the testing procedure. This apparatus is mainly used for measuring the λ and R values on homogeneous materials, only in a few cases for plane laminar elements. Also, several studies proposed different analytical models to reduce the errors connected to gaps and edge losses [83; 84; 86].

The International standard ISO 8301 [82] explains the HFM method for measuring the steady-state heat transfer phenomenon occurring through flat slab specimens. Basically, the sample is placed between two heated plates with ΔT_a and ΔT_s. To measure the flux through the sample, heat flux transducers which largely cover both sides of the sample are employed. The h-value is retrieved by dividing the Φ measured through the sample by the cross-section area and the applied ΔT_a.

GHP test and HFM method are not appropriated for heterogeneous specimens, because the metering area might not cover a representative portion of the sample, leading significant and unpredictable errors due to a non-uniform T_s distribution within the test facilities. The thermal properties of heterogeneous specimens can be measured with a hot box apparatus. In this framework, two alternative methods are available: (i) the guarded hot box (GHB); and (ii) the calibrated hot box (CHB). GHB is composed of three independent chambers: (i) the climate chamber for simulating the cold outdoor temperatures; (ii) the metering box heated to simulate the indoor conditions, and (iii) the guard box heated exactly at the same T_a of the metering box for minimizing the lateral Φ at the edges of the metering chamber [87; 88]. CHB is composed only by the hot and the cold chambers that are surrounded by a "temperature-controlled space" [87; 88]. To precisely account for the heat transmitted through the sample, a full characterization (calibration) of the apparatus is needed, in order to know the amount of heat that is lost by the equipment itself (metering chamber, surround of specimen, sealant, etc). In this case the robustness of the results can be obtained by a strong thermal characterization of the apparatus and the boundary conditions [87; 88; 85].

The American designation C1363 [87] and the International standard ISO 8990 [88] explain the design criteria and the procedure for measuring in steady-state condition the R-value of heterogeneous specimens. In both cases, the specimen is positioned between the two chambers maintained at different T_a in steady-state conditions. The R-value is obtained by measuring the power required to keep the hot chamber at constant T_a [87; 88]. The comparison between different standards outlines few divergences in the results [89; 90]. The European Standard EN 1934 [91] has been proposed to minimize these problems for the steady-state R-values measurement of homogeneous and "moderate inhomogeneous" (i.e. brick masonries) specimens into a GHB, in accordance to [88]. The specimen is interposed between the two chambers and the R-value is measured using a HFM plate mounted in the center of its surface. The studies focused on the definition of specific laboratory procedures for solving specific problems related to heterogeneous specimens [79; 89; 92; 93; 94; 95] (i.e. hollow blocks, sandwich, porous clay bricks, and historic walls). These studies concluded that the result accuracy is related to the use of the HFM plates instead of single point of measurement [79; 96], the enlargement of the metering section [79; 89; 92; 95], and the increasing of the measurement points [79; 93; 94].

Furthermore, the hot box measurements are employed to validate the numerical models carried out by various computer simulation programs. Some experiences agree in concluding that the numerical estimations are most likely to overestimate the U-value compared to the experimental approach [92; 93; 97; 98; 99]. In general, the numerical calculation resulted more disadvantageous than the measured U-value [93], R-value and response time calculation [92]. In all cases, the literature recognized the importance of the numerical models for supporting the design of laboratory tests and defining correct boundary conditions, reducing costs, times and measurement inaccuracies.

3.5. IRT survey

The employment of IRT survey for the energy assessment can be ranked in qualitative and quantitative studies [4; 100]. International and national standards establish specific procedures for the building sector inspection, like International standard ISO 6781 [6], that outlines a procedure for sketching thermal anomalies and air inlets in the building envelope, also involved in standards EN 13187 [101], that defines a simplified test for revealing the thermal performance of several construction materials, and ISO 18434 [102], that focuses on mechanical engineering systems. The ASTM has introduced practical advices for the IRT survey [103; 104; 105; 106; 107] and general ways for detecting [108; 109]. Furthermore, the Residential Energy Services Network (RESNET) [4] and the Building Services Research & Information Association (BISRA) [110] suggested also specific guidance for the use of IRT in the energy audit of buildings.

Qantitative survey helps to infer the thermal anomalies/differences on the investigated object, the quantitative approach aims at estimating the magnitude of such difference. A precise evaluation of the involved parameters (ε-value, T_{refl}, environmental condition and object-to-camera distance) plays a key role. Post-processing techniques and algorithms may also be applied to evaluate specific issues. Quantitative IRT is taking shape, as long as the experiences of different working groups give contributions. The topic has become so relevant, that in Italy a committee instituted by the CTI (Comitato Termotecnico Italiano) (Italian Heat Engineering Committee) is working on the possibility of drafting a national technical report concerning the use of IR-cameras for a quick U-value assessment for opaque vertical building elements [111]. The applications of quantitative IRT has detailed in section 4.

4. APPLICATION OF QUANTITATIVE IRT TO BUILDINGS

The quantitative IRT measurement for the overall U-value assessment of building envelopes has been evaluated in several studies, both for in situ and laboratory measurements. The IRT test, compared to the analogies with coeval buildings, is faster, if we consider that the draft of building databases requires the inspection and identification of several buildings. Besides, compared to the HFM measurements, the IRT measurement has large T_s measurements [113] and shorter test duration [57]. Additionally, it considers the radiation effects such as the radiative temperature and the emittance of the surfaces, ensuring accurate results [57]. However, its deviance to the HFM measurements increases until 80% with wind speed greater than 1 m/s, because the higher h_e enlarged the dispersion of the data [112]. The main fields of the study on the quantitative IRT tests on the building shell regard: (i) the U-value measurements of building façade; (ii) the U-value measurements of roofs; (iii) the U-value measurements of windows and glazing systems; (iv) the thermal bridging detection; and (v) assessment of the surface ε-value of building materials.

The great importance that the U-value assessment via IRT gained over the last 11 years is proved by the overview on the most important studies detailed below (Table 1). The spread of research activities, plotted in bar chart, is shown in Figure 4. A world map of publishing Countries is showed in Figure 5.

Table 1. Overview of the most important studies on the U-value assessment using the quantitative IRT survey.

Authors	Year	Country	Building element analyzed	IR camera positioning	Test duration	Test equipment for IRT measurements	Validation tests	Max percentage absolute deviation [a] [%]	Main issue(s)	Most important parameter	T_{refl} compensation	ε-value measurements	Sensitivity analysis	Procedural suggestion	Notes
Kato et al. [114]	2007	Japan	S, F	Hot side of controlled environment + indoor	5 days	IR-camera	MEAS	6%	-	-	-	-	-	-	-
Albatici et al. [73]	2008	Italy	F	Outdoor	Defined by IR images	IR-camera, anemometer, heater	CAL	32%	-	-	-	✓	-	-	-
Madding [115]	2008	Wisconsin (USA)	S, F	Cold side of controlled environment + indoor	Defined by IR images	IR-camera	MEAS	*12%	-	T_{refl}	✓		✓	-	-
Vavilov et al. [116]	2009	Russia	F	Outdoor	60 h	IR-camera 	CAL MEAS	*3-193% *10%	Solar radiation	-	-	-	-	Survey late at night	-
Kisilewicz et al. [117]	2010	Poland	S	Hot side of controlled environment	48 h	IR-camera, thermocouples, reflector	MEAS	*43%	-	h	✓	-	-	Survey lasting integer multiple of 24 h	-
Albatici et al. [112]	2010	Italy	F	Outdoor	Defined by IR images	IR-camera, black-body simulators, soldering iron, anemometer	CAL MEAS	30-161% 53%	υ, solar radiation	-	-	✓		Early in the morning; low υ; ΔT_a above 10 K	-
Grinzato et al. [118]	2010	Italy	F	Hot side of controlled environment	-	IR-camera, anemometer	CAL MEAS	8-114% 8-95%	Analysis of environmental boundary conditions during survey	-	-	-	-	-	Φ is measured, h mapped
Fokaides & Kalogirou [57]	2011	Cyprus	F, R, G,	Indoor	3 h	IR-camera, thermohygrometer	CAL MEAS	59 21	Roof and glazing	T_{refl}; ε	✓	✓	✓	-	-
Asdrubali et al. [*71*]	2012	Italy	S	Hot side of controlled environment	Defined by IR images	IR camera, thermometer	MEAS MOD	***5% <***1%	-	-	✓	✓	-	-	-

Thouvenel [119]	2012	France	S	Cold side of controlled environment	10 h	IR-camera, thermocouples	CAL	5%	-	h	□	✓	-	-	-
Dall'O et al. [120]	2013	Italy	F	Outdoor	Defined by IR images	IR-camera	CAL	2-154%	High insulated walls	υ	✓	-	✓	Choose appropriate days for survey on high thermal mass walls; consider average υ of previous hours	Percentage difference strongly depend on υ (ranging 1.5-154%)
Ham et al. [121]	2013	Illinois (USA)	F	Indoor	Defined by IR images	IR-camera	-	-	-	-	✓	-	-	-	-
Ohlsson et al. [122]	2014	Sweden	S	Cold side of controlled environment	Defined by IR images	IR-camera, hosepipe, anemometer	MEAS	-	h	υ	✓	-	-	-	Comparison with Φ measured by IRT and HFM
Simões et al. [123]	2014	Portugal	S	Cold side of controlled environment	1 h	IR-camera, thermocouples, anemometer	MEAS	36%	-	-	✓	✓	✓	-	Test on small samples of homogeneous materials
Tzifa et al. [124]	2014	Greece	F	Indoor	less than a day	IR-camera, thermometer	CAL	2-204%	Seasonal dependent results	-	✓	✓	✓	Best period is winter especially early in the morning	Comparison of summer and winter measurements
Nardi et al. [148]	2014	Italy	F	Outdoor	Defined by IR images	IR-camera, hosepipe	CAL MEAS	29% 38%	Outdoor enviromntal conditions	ΔT	-	✓	✓	Sufficient ΔT; stable weather conditions	
Ham et al. [126]	2014	Illinois (USA)	F	Outdoor	Defined by IR images	IR camera, thermometer	-	-	Unsteady boundary conditions		✓	✓	-	-	3D visualization of the R-value and visualization of possible condensation points were applied
Nardi et al [210]	2014	Italy	F	Indoor	Defined by IR images		MOD	**73%	Seasonal dependent results	-	-	-	-	-	-
Aversa et al. [127]	2015	Italy	F	Indoor	82 h	IR-camera, thermohygrometer	CAL MEAS	5% 7%	-	-	-	-	-	-	
Kim et al. [128]	2015	South Korea	F	Outdoor	Defined by IR images	IR-camera	-	-	Seasonal dependent results	ΔT; υ; location	-	✓	✓	Survey between November and March, between 01:00 and 09:00 h; high daily mean ΔT; outdoor υ < 3 m/s	The approach is based on ΔT ratio

Nardi et al. [129]	2015	Italy	F	Outdoor	Defined by IR images	IR-camera, hosepipe	CAL MEAS	46% 47%	Unsteady boundary conditions	ΔT; wall thermal mass	✓	✓	-	Overcast sky, υ; ΔT of at least 10 K	Walls having different thermal mass were analyzed
Albatici, Tonelli, Chiogna [130]	2015	Italy	F	Outdoor	Less than 1 h	IR-camera, hosepipe, weather-station, anemometer	CAL MEAS	23% 22%	Light walls	υ; ε	-	✓	✓	Overcast sky, early in the morning, with low υ; avoid rainy days	Different walls were compared even under different orientation
Nardi et al. [131]	2015	Italy	S	Cold side of controlled environment	Defined by IR images	IR-camera, hosepipe, thermohygromet er	CAL MEAS	7% 13%	Boundary conditions	-	✓	✓	✓	-	-
Ibos et al. [132]	2015	France	F	Indoor + outdoor	3-7 days	IR-camera, thermocouples, weather station, emissometer	CAL MEAS	*57% *60%			-	✓	-	-	Different IRT techniques were compared
Danielski et al. [113]	2015	Sweden	F	Indoor	less than 3 weeks	IR-camera, thermometer,	MEAS	11%		h	-	✓	-	Steady state heat flow is not mandatory if IR measurements number is large enough	Large and small portions of the wall were assessed for comparison
Nardi et al. [125]	2016	Italy	S	Cold side of controlled environment	less than one hour	IR-camera, thermohygromet er, hosepipe	CAL MEAS	39% 20%			✓	✓	✓	Sufficient ΔT_a; stable weather conditions	4 mathematical approaches proposed in literature were compared, according to different parameters
Donatelli [133]	2016	Italy	S	Indoor	10 h	IR-camera, thermohygromet er, halogen lamps, anenometer	CAL	4%	-	-	✓	✓	-	-	Pulsed heating was employed (via halogen lamps) on two walls
Marino et al. [27]	2017	Argentina	F, G, D	Outdoor	1 (3 series x day)	IR-camera, laser distance meter, thermometer, thermoresistance s, weather station,	-	-	Glazing	T_{refl}; Dynamic response of the building	✓	✓	-	Dynamic response should be considered to obtain more reliable results	-
Tejedor et al. [134]	2017	Spain	F	Indoor	2-3 h	IR-camera, reflector, blackbody, thermohygromet	TAB	4%	-	h; ΔT_a	✓	✓	✓	Reliable results are achievable also with ΔT of 7 K	Different h-values were employed for comparison

						er or thermocouple	CAL	2-20%							
							MEAS	12-27%							
Choi et al. [135]	2017	South Korea	F	Outdoor	Defined by IR images	IR-camera, anemometer	CAL	1-44%	Boundary conditions	-	✓	✓	✓	-	Deviations change according to building typology and mathematical approaches; evaluations considering the thermal storage effects were also carried out
							MEAS	5-42%							
O'Grady 2017 [211]	2017	Ireland	S	cold side of controlled environment	Defined by IR images	IR camera, anemometer,	MEAS	**12%	Boundary conditions	υ	-	-	✓		
O'Grady 2017 [213]	2017	Ireland	S	hot side of controlled environment	Defined by IR images	IR camera, anemometer,	MEAS	**36%	Boundary conditions	-	✓	✓	✓	-	
Baldinelli at al. [215]	2018	Italy	S	Hot side of controlled environment	Defined by IR images	Ir camera, temperature probes	MEAS	**52%			✓	✓	-		
Marshall et al. [136]	2018	UK	F	Indoor	Defined by IR images	IR camera,	TAB	2-27%	Boundary conditions	-	✓	✓	-	Different IR-images resolutions differently fit to the analyzed structures	Comparison between low and high resolution IR-images and different design U-values
							MEAS	9%							

Legend: -: not available; S: sample; F:facade; R: roof; G: glazing ; D:door
TAB: tabulated value; CAL: calculated value, MEAS: measured value; MOD: modeled value; * R-value; **ψ-value; ***I_{tb}

[a]evaluated as: |(Uirt-U)/U|

(white)	**façade**
(grey)	**thermal bridge**

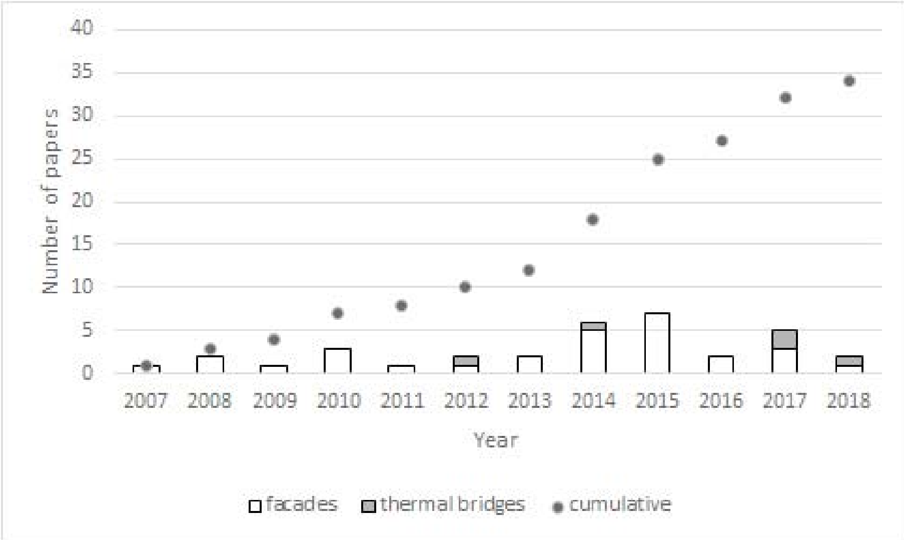

Figure 4. Number of papers (per year) and cumulative number published on the U-value and thermal bridge assessment using IRT methodology.

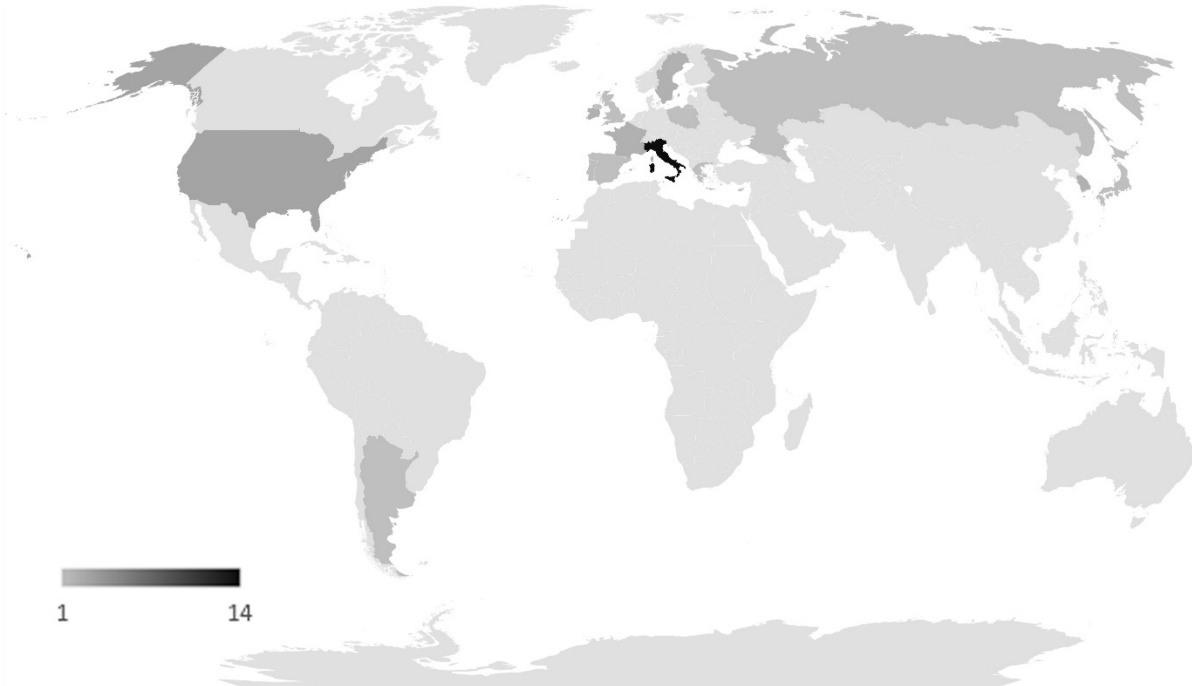

Figure 5. World map of publishing Countries (data from Table 1).

4.1. U-value measurements of building façade

The assessment of the thermal performance of walls and façades using the IRT measurement is a promising field of the research in the building diagnostic. Systematic attempts of employing infrared thermography for accurate temperature evaluation of building elements are dated back to 1980s', when Flanders and Marshall proposed [137; 138] a method for coupling thermographic inspection results with HFM data acquired on single points.

Later on (1990s'), the Lawrence Berkeley Laboratory (LBL) started a series of campaigns aiming at validating heat transfer models of a sample wall [137; 140; 141]. In 1998, a work by Grinzato [142] employed the "quantitative" IR thermography for building diagnosis purposes, i.e. to identify and locate thermal bridges and defects. In the same year, the results proposed in [143] aimed at integrating the information provided by IRT with those obtained with HFM, in order to plan proper refurbishment interventions on the vertical elements of a building. In 2002, Grinzato et al. [144] successfully employed thermography for evaluating the thermal diffusivity of brick samples. A work by Datcu et al. [145] proposed a technique to improve the building wall temperature reading via IRT. Investigations were carried out both in controlled environment and in situ. The procedure included the evaluation of reflected flux by using a foil of rough aluminum. In laboratory, a sample multi-layered vertical wall was investigated with IRT and HFM, whilst an outdoor campaign was carried out on a building during nighttime. Results showed that T_s measurements can be improved with some easy and simultaneous additional measurements. A work by Kato et al. [114] performed laboratory tests and in situ measurements to validate a method for measuring the thermal insulation performance of building elements via IRT. This can be considered the kick start of the research activities focused on IRT for U-value assessment of building façades: the literature, from then on, spread on contributions that are giving an ever-defined shape to the technique.

Both long and short term tests were performed, although the literature underlined the difficulties related to the use of short-term IRT inspections for quantitative measurements [57; 114; 115; 120; 124; 146]. Despite this, mainly short-term IRT campaigns are considered (from 0.30 to 3 h). To overcome the problems, the IRT tests are repeated several times in order to collect a proper number of data and to perform a parametric analysis (i.e. [130] did a 3 years' campaign with 560 IRT inspections).

Both, inside and outside IRT tests are performed. Inside measurements benefit of the controllable boundary conditions [147]. External measurements are more susceptible to the environmental conditions and the thermal reflections on the specimen [134]. To overcome these problems, this test is conducted in specific climate conditions. To avoid solar radiation and to have overcast sky, the test is realized preferably in the early morning before sunrise and/or in the late evening after sunset [57; 120; 125; 148]. Similarly, to avoid the influence of the local wind, its υ near the building façade is lower than 0.5 m/s during the survey and the stream υ is lower than 5 m/s 24 h prior the measure [130; 148]. The target distance (d) [m] between the IR camera and the building has a broad range from 3 m to 20 m. The IRT tests should consider: (i) ΔT_a [27; 57; 112; 120; 146]; (ii) the heat power flow through the element [112]; (iii) the ε-value of walls [57; 112; 120; 130]; (iv) the T_{sa} [6; 27; 57; 112; 114; 115]; (v) the T_{refl} [120; 130]; (vi) the υ [147]; and the h_e. Following, the procedure for the U-value assessment (Figure 6) is presented.

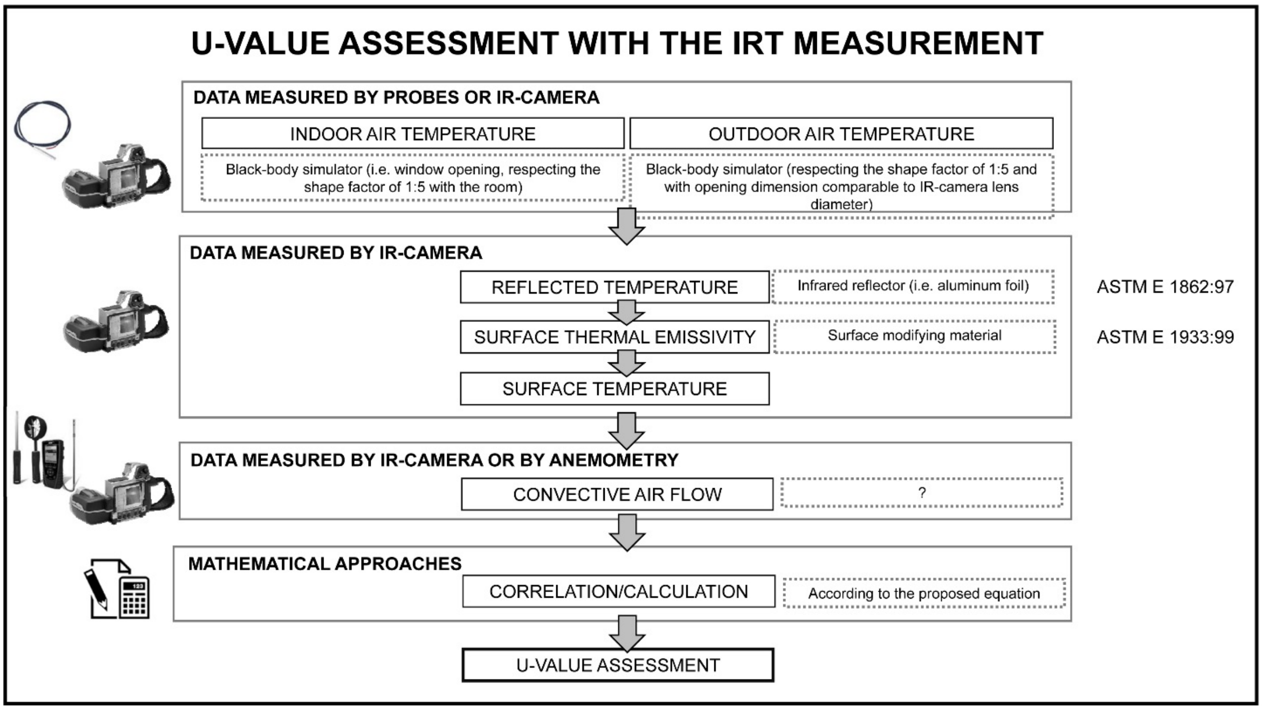

Figure 6. U-value assessment with the IRT measurement.

In general, the tests are carried out with a ΔT_a across the wall of at least 10-15 K, to allow measurable heat exchanges through the element [148]. Tejedor et al. [148] proposed a method for reducing this ΔT_a to the lowest level (7 K $<\Delta T_a<$ 16 K), achieving a high level of accuracy. This situation is particularly useful also for unoccupied or unheated buildings. Since the IRT methodology for U-value assessment starts from the energy balance of the wall, it is necessary to evaluate the amount of heat power flown through the envelope. Such evaluation considers the radiative and convective contributions. The radiative term is evaluated by applying the Stephan-Boltzmann law, that has been employed involving T_s and Te (as in [112]) or, by its linearization involving T_{sa}, T_{refl} [57] or their mean value [115]. The convective term is expressed, in literature, in different ways according to the simplifying model adopted, as it will be better explained in the following. Concerning the ε-value of the wall, it can be derived, according to materials, from tables and datasheet, or from comparison with a target whose ε-value is known. The first method is fast and inexpensive; the second one requires a surface modifying material (for instance, a sticky target [125] or a black tape [57, 120; 123]) to be applied on the investigated object and in thermal equilibrium with it. The proper temperature reading on the target allows to infer the object emissivity by setting the ε-value of the image until the object temperature shown equals the one previously measured on the target. This method is mid-expensive (in terms of money and time) but provides accurate results. T_{sa} can be measured after compensating for the T_{ref} and the surface ε-value, and it should be acquired under a proper viewing angle (not exceeding 45° from the perpendicular to the object). In case of acquisitions carried out close to the surface, to avoid the interplay between personnel or IR-camera and the surface itself, a remote controllable IR camera should be preferred when possible.

T_{refl}, which can be defined as the mean apparent temperature of other items and objects that the target reflects into the IR-camera, is one of the most important definitions in thermography: an erroneous assumption of this parameter can lead to remarkable errors in the target temperature estimation [223]. The large majority of the works that consider this parameter employ an aluminum foil crumpled and stretched to assess the T_{ref} [57; 112; 120; 123; 125; 148]; other [149] employ a mirror.

As explicated before, υ is reduced or additionally measured by an anemometer [130], although techniques based on IRT are also available [149; 150, 151; 152]. In many cases, the external IRT measurements require the calculation of the h_e on the basis of the weather conditions to achieve reliable results [12; 120; 134]. Several times [112; 120; 130; 148], h_e is determined by the Jürge's equation that establishes a linear relationship between h_e and υ. As said, attention should be paid to the convective term of the wall energy balance, and many research activities focus on this crucial point [154; 155, 156; 157; 158; 159; 160;161]. Such studies aim at determining the best correlation to be employed when studying building walls, by comparing existing correlations that depend on υ, experimental data and recommendation provided by codes. The correct evaluation of such contribution plays a key role even in HFM measurements, where for sake of simplicity the Standard suggests easy correlations that involve, as usually, υ.

As foreseeable, portions of building walls might be differently exposed to air movements, and the phenomenon is more relevant in high-rise buildings. For instance, the presence of objects (like trees or overhangs) or facing structures (buildings in the nearby) can deviate, slow or accelerate υ, depending on the relative positioning, height, and exposure [134; 163; 164].

The approaches to the evaluation of the convective and radiative contributions give rise to different equations for the evaluation of the U-value. For instance, Madding [115] used the linearization of the Stephan-Boltzmann law by employing the third power of the mean temperature between T_s and T_{refl}; Fokaides et al. [57] also employed the linearization, but they used the third power of the wall T_s; Dall'O' et al. [120] used the energy conservation, therefore the U-value is evaluated as the ratio between the external convective contribution and the air temperature gradient between inside and outside. Albatici et al. [130] expressed the U-value in terms of T_s, T_{ae}, T_{ai}, and with a modified Jürge's equation. Concerning T_{ai} and T_{ae}, many approaches can be used [162; 165; 166], but they can result in complex procedures or set ups, whose effort (in terms of time and money) might not be justified for the U-value assessment. In fact, the employment of the IR-camera for the U-value evaluation aims at speeding up the evaluation timing. For this reason, in current practice, different alternative ways are proposed to determine T_a: (i) use some simple black body simulators, given by a hosepipe with specific dimensions (for T_{ae} measurement) and the window opening (for T_{ai} measurement) [73; 122; 130; 147; 148] this approach is based on the black body theories and common practices [167; 168; 169]; (ii) using thermos-hygrometers or temperature probes [125; 134]; (iii) by assuming some hypothesis on temperature, for instance in [120] T_i has been estimated as indoor design temperature (according to national laws) with a tolerance of 2 K. Finally, the value of h_e varies widely at different positions on the surface of a building [134], depending on surface-to-wind angle and wind intensity, which are strongly affected by the building's surroundings [120]. The impact of υ will be greater in elements with low thermal mass, since they cool down faster [134].

In general, the in situ IRT measurements are validated by tabulated (that derives by analogies with coeval buildings) [148], calculated (that refers to the use of standard procedures) [120; 148] and measured (that means HFM measurements) [112; 113; 148] data. The deviation between calculated and IRT measured U-values might be greater for light walls compared to heavy ones [112; 120; 130]. Similarly, the absolute percentage deviation between HFM and IRT measured data is higher for well-insulated walls (where it could be more than 50%) [120]. Generally, a sensitivity analysis has been performed to understand which parameters influence the final result compared to tabulated, calculated, or measured U-values [57; 130; 134].

The quantification of systematic and random errors improves the method in terms of bias correction and reduction of measurement uncertainty [112; 113; 122; 145; 147; 179]. For this reason, few studies have been done in the laboratory under controlled climatic conditions to reduce the impact of weather [117; 122; 170]. For instance, in [122] the Φ measured by IRT is compared to the one provided by heat flux plate under controlled υ moved by a fan close to the wall surface. In [117] the controlled conditions were set in a hot box, where the two boundaries of the wall were settable, The R-value was assessed via instantaneous and accumulated (for 24 h and 48 h) data, proving that the longer is the survey, the more reliable are results. In [125], boundary conditions were imposed on one side of a specimen wall, whilst the other was facing a controlled environment with still air.

The reliability and accuracy of these different IRT tests [57; 112; 120] has been proved by employing climatic chamber on typical walls [125]. Approaches provide reliable results under specific sets of parameters (e.g. ε, T_{refl}, ΔT) [130]. Experiences showed that IRT results are close to design values, but lower than results from HFM. Thus, each method should be used on specific wall compositions. On the contrary, long-lasting survey and averaged data give more reliable results. A work [117] outlined that quick IRT surveys are not able to represent the thermal performance with unsteady boundary conditions, therefore other techniques (passive time-lapse or transient thermography) should be employed to measure the T_{sa} over a longer period [114; 115; 170; 171]. These methods allow a correct estimation of specific heat losses within a precision range below ±10 % compared to the HFM measurements [114; 115; 171].

4.2. U-value measurements of roofs

The possibility of inspection of roof has gained more attention from the '1970. First approaches were, as foreseeable, for qualitative assessment of heat loss or leakages, with aerial thermography carried out with light aircrafts or helicopters. In the 1980s', research activities were shifted to the quantitative approach. Particularly, in 1979 a work carried by NASA Laboratories [173], proved the possibility of employing aerial thermography for the quantification of roof losses: three roofs were investigated for the purpose, with good agreement between results gathered also from in-situ measurements. The same year, a technical report [174] was published concerning the possibility of ranking roofs according to their thermal resistance, proposing a sensitivity analysis on operative parameters; however, the work focuses on the investigation of the differences in apparent radiance temperature between roofs having different thermal resistances. In 1983, another work [175] deals with the topic, but once again the efforts are devoted to the roof temperature measurements refinement. According to [176], the main relevant advances in the topic and the first successful studies were carried out by Schott [177; 178].

Up to now, given also the brief literature review discussed in [176], the employment of IRT for U-value assessment of roof is still an open field of work, since several difficulties have to be faced (atmospheric transmittance, focus, spatial resolution due to the distance). The recent advances in the use of drones [179], however, are promising for this research topic, even for the drafting of cities energetic models [180].

4.3. U-value measurements of windows and glazing systems

The peculiarity of glass is that it is opaque in the waveband 3-14 μm, gives rise to specular reflections and it has a ε-value of about 0.837 [181]. For this reason, radiation sources can deeply affect IRT tests on glass [116; 182]. The most important errors are associated to: (i) specular reflections of surrounding objects [183]; (ii) inadequate estimations of the sky temperature [183]; and (iii) presence of glass treatment (i.e. low-e glass, selective glass) [184]. Advices have been suggested by literature to overcome the problem of specular reflections due to clear sky or nearby buildings, for instance by using adjunctive devices as a reference point (i.e. reflection errors are corrected by accounting the radiance of an object reflected on the glass in a specular way [183]) or specific equations for multiple incidence angles [185]. Moreover, easy expedients can be followed to avoid these reflections, including: (i) inside IRT surveys [186]); (ii) use of materials having high emissivity to get reference ε-values [184] (e.g. black emissivity tape, electric tape, black rubber coating or spray); (iii) uniform environment, especially for υ and T_a [184]; and (iv) ΔT_a over 15 K across the glazing [181]. The thermal characterization of glass, glazing systems, and insulating glass units is possible only under these strict boundary conditions [181; 183; 184; 172].

4.4. Thermal bridging detection

Thermal bridging is defined as the increased heat loss through the building façade due to higher thermal transmission than the current fabric [4; 182; 187; 188; 189], causing significantly higher energy consumption for heating and cooling [190; 191; 192]. Attention has been paid, in the last years, to the evaluation of thermal bridges caused for instance by studs, fastening elements, brackets employed for securing insulating elements on the building shell [193; 194; 195; 196; 197] since they might cause local relevant heat loss increase. One of possible ways of evaluating the impact of thermal bridges requires the knowledge of the thermal model (whether 1- ,2- or 3-dimensional), that can be retrieved by numerical simulations and calculation codes [198; 199; 200; 201; 202; 203; 204; 205]. However, IRT survey can sketch thermal bridges by using mature procedures [4; 6; 101; 110; 188; 189; 206], and research efforts are devoted to find a way for the automatic detection of thermal bridging via IRT [207]. As well, the presence of post-processing techniques in the professional software permits to verify the risk of condensation and mold growth linked with the thermal bridging [23, 208]. In the last years, IRT has been employed for the assessment of thermal bridging effects both in situ [71; 209; 210; 211] and through laboratory tests [71, 212; 211; 213; 214; 215; 216].

Particularly, it is possible to reveal the effect of thermal bridges by assessing the temperature pattern variation with respect to the undisturbed area, that is, the one that is not affected by the thermal bridge itself. The procedure is eased by the employment of an IR camera, since it can sketch wide portion of the structural element under investigation. This can lead to the evaluation of the "incidence factor of the thermal bridge", as defined in [71]. On the basis of this approach, the research activities of working groups are still ongoing, aiming at refining the methodology, based on infrared thermography, for the evaluation of linear thermal transmittance and thermal bridge incident factor, based on an analysis pixel-by-pixel. The approach has been tested on glazing [71], in situ [210], with a hot box with different specimens [213] and under different convective solicitations [211], and with thermal images enhancement for more accurate results [215]. Different numerical models have been proposed to overcome the perturbations caused by the climatic parameters on the external T_s that might occur especially during in situ IRT surveys [217]. These models are mainly focused on linear thermal bridges for their large spread both in existing and new buildings. Due to the impact of boundary conditions, the studies do not consider the risk of surface condensation [209]. Furthermore, to reduce completely the impact of weather conditions, a simulation model has been defined without considering detailed meteorological observations [217].

4.5. Surface ε-value determination of building materials

The ε-value characterizes the optical properties of materials, in fact it can be defined as the amount of energy emitted by the investigated object in comparison with an ideal black body kept at the same temperature [218; 219]. For this reason, the emissivity value can range between 0 (perfect reflector or mirror) and 1 (perfect emitter or black body). Emissivity depends on parameters like object temperature, wavelength, and surface condition. Thus, the determination of this value for the most important building materials is an important topic for the IRT surveys in the building and cultural heritage sectors. In fact, the knowledge of the proper ε-value allows the correct T_s reading via thermal images, since the thermal pattern is created based on the IR-camera working principle illustrated in Figure 2.

Several works were published proposing different ε-value determination techniques, to avoid the errors due to reflection and absorption matters. Semi-transparent materials [219], building materials (both historic and modern) [220] were investigated at various T_a and by using different approaches both for mid and long-wavelength regions of the IR spectrum. The empirical approach and the ASTM standard E1933 procedure [105] are proposed, both for in situ and laboratory measurements. A method for emissivity estimation via IR camera has been proposed in [221], where the procedure allows to avoid the employment of emissivity references and the knowledge of reflected temperature. A technique based on IRT for the determination of emissivity has also been proposed [222], to ensure the correct in situ determination. These applied researches noted that the final results are influenced not only by the materials but also by the surface conditions (i.e. age, roughness, exposure to environment, presence of damage, etc.) and the shape of the specimen (i.e. concave and convex shape). Therefore, they suggested to measure this value for each test.

5. IRT PERSPECTIVE IN THE BUILDING SECTOR

Low price, reducing weight, lowering profile, miniaturization, high resolution and sensitivity are the most important factors for driving commercial market. The new frontiers of IRT concern the quantitative study of building behavior, especially in terms of energy losses, witnessed by the recent increase in number of researches on quantitative measurements. Similarly, the foundation of an Italian working group for drafting a national technical report concerning the use of IRT for the U-value assessment of building elements is a significant step in this process [111]. However, it is worth recalling that the International Standard ISO 9869:2 [63] has been draft in 2017 for public comments [224]. By now, the possibility of using and integrating GIS-based approaches can speed the procedures, although they require high technical specialization in the field. An interesting perspective is given by the equipment of high-definition IR-cameras on drones, since the low speed of such device allows to take clear images of large areas in a short time [179; 225]. They can be equipped with a range of sensors including also laser scanners and radar, improving the building IRT survey. By now, IRT mounted on drones are used only for qualitative surveys [20; 25; 179], but the improvement of accuracy of sensor could develop new future markets.

6. CONCLUSIONS

The critical review of the scientific literature shows that the U-value can be calculated via IRT, but different (and sometimes conflicting) procedures have been presented. The most analyzed topic concerns the analysis of the façade, where several procedures have been presented. Windows, glazing and roofs are less treated topics for the difficulties concerning the measurements, since they building elements revealed the greater deviation [27; 57]. For thermal bridges, research activities are still ongoing in controlled environment. The good agreement between simulation and experimental data encourage further efforts in the investigation and development of new techniques based on IRT. The technique has become an important field of interest due to its pros, like:

- Short measurement times varying from minutes to days, as shown in Table 1;
- Reduced costs, compared to the most used in situ technique;
- Possibility of investigating wide portion of the building fabric, also thanks to the possibility of integrating the IR cameras on drones.

As counterparty, some factors could affect the accuracy of results. Particularly, the scientific literature underlines the following elements:

- The accuracy of the IR-camera (defined by its FOV e NETD) can affect the final results; for this reason, good quality instrumentation should be employed;
- The boundary conditions influence the measurements, particularly:
  - The convective heat transfer coefficients have an impact on the performance of the building components, therefore their evaluation should be careful performed; in this sense, studies on approximating equation have been carried out, in order to speed up the in situ assessment when certain conditions (mainly related to wind speed and direction) occur;
  - The reflected contribution cannot be neglected in the quantitative approach, but it should be evaluated for each measurement;
- Surfaces should not be exposed to wetting, frosting of direct solar irradiation in the hours that preceded the survey.

The following operative details have been defined for improving the results reliability:

- Specific skills and competences of the IRT personnel (by now the skill requested are the same for qualitative IRT);
- Control of the influence of the boundary conditions, and particularly reduction of the impact of weather conditions during outdoor surveys [57; 120; 146; 147];
- Presence of high ΔT_a [6; 57; 120; 146];

- Correct determination of the h-values and compensation parameters (ε, T_{refl}, etc.) [57; 120; 130; 147];
- Presence of conditions similar to the steady-state [57; 120]. Experiences, however, show reliable results even when unsteady state occurs [113];

Possible solutions have been outlined to obtain more reliable data, such as:

- Surveying when well defined and stable weather condition occur [6; 120; 146], (avoiding for instance rainy and sunny days);
- Considering an average υ to calculate the h_e value [120; 112];
- Acquiring compensation parameters, even by using simple devices [120];
- Using the same IR-camera to detect surfaces, indoor and outdoor temperatures [120];
- Conducting a sensitivity analysis for considering the effects of radiations and boundary conditions [57].

The technique is getting more and more mature as long as the case studies grow and laboratory experiences are carried out. It is possible to infer the development of the technique looking at the kind and number of variables and operating parameters involved in the assessment procedure, summarized in Table 1: the first study [114] does not take into account reflection compensation, wall emissivity, or local convective heat flow. In the works published in the years after, the importance of T_{refl} compensation has been underlined, and the papers that followed began to consider this parameter. The suggestion of procedural hints helped to define some better conditions for the assessment (time of the day, ΔTa). Simultaneously, the importance of the ε-value was also revealed [57], till the definition of the impact of local convection due to air mass movement. Then, also thanks to the sensitivity analyses carried out, the evaluation of the air speed was taken into account more methodically.

Although the definition of the procedure is encouraging the research activities, some questions on the technique are still open, and they will be deepened in further studies. For instance:

- Does the technique provide reliable results for all building fabric types, or is it influenced by the walls' thermal mass? Some attempts to give an answer have been done [129; 130], but more cases studies are needed;
- Does the technique provide reliable results for wall assemblies with air gaps?
- Is it possible to define a simplified method for determining the convective heat transfer coefficient during in situ measurement?
- Is it possible to carry out a whole sensitivity analysis that includes the influence of operating parameters (like humidity, distance, viewing angle) and influencing parameters (like T_{refl}, ε-value, υ)?
- How relevant is the expertise in infrared thermography of the personnel in the quantitative assessment?

This review could help to contribute to future researches showing main topics treated, different procedures, factors that could affect the results accuracy (and their possible solutions), and question still open for further studies.

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