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Influence of the convective coefficient on the determination of thermal transmittance through outdoor infrared thermography

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Abstract. Several studies and correlations for the convective heat transfer coefficient (CHTC) are available in literature and in handbooks, depending on type of convection, wind speed range or on the test rigs from which they are derived.
The importance of accurate evaluation of CHTC, especially at the building façades, has been highlighted in the recent years, due to the need for reliable measurement of buildings' heat transfer capability. This study aims at underlining the importance of proper CHTC values for the determination of the building envelope thermal transmittance (U-value) via infrared thermography (IRT). To this scope, firstly an overview on convective heat transfer coefficient is given; then, some CHTC models, chosen from literature, are analyzed at different wind speed classes. Subsequently, such models are employed in two formulas proposed in literature for the U-value measurement via IRT, by using data from previous experimental campaign carried out in controlled environment. Results were compared, and significant deviations were found: one of the employed approaches and formulation is less sensitive to the correlation adopted for the convection expression, amongst those considered and in the wind speed range analyzed. This constitutes an advantage, since one of the weak points of the IRT method is the convection expression itself.

1. Introduction

The need for accurate evaluation of building energy losses has become crucial for reliable energy plan at urban, regional and national scale. The heat loss through the envelope, identified by the thermal transmittance value (U-value), is driven by the three heat exchange mechanisms: convection (due to the air mass flowing near the walls that face the indoor and the outdoor environments); conduction (from surface to surface, and due to materials capability of conducing heat); radiation (that accounts for the thermal radiation flux in the long-wave band) [1,2].
Methods and techniques for reliable measurement of conductive heat flux losses through the building envelope are available [3], and also the radiative contribution is easily retrievable [4].
The main issues concern the evaluation of the convective contribution, for which the knowledge of the convective heat transfer coefficient h_c (CHTC) is needed. Regarding the latter, researchers agree that its evaluation in crucial for reliable U-value measurement, and many studies (performed either in laboratory or in situ) have been carried out up to now [5-7].
The evaluation of CHTC is a complex matter, since it depends on: (i) type of fluid; (ii) type of convection (either free or forced); (iii) type of regime (either laminar or turbulent); (iv) surface layout or displacement (vertical, horizontal, sloped) and shape (flat, cylindrical, etc).
For this reason, several ways to express the h_c are available, both in literature and in handbooks, varying for the limits of applicability, the governing hypothesis, and the set up employed for the evaluation [1, 8-11]. Many expressions for the convective heat transfer coefficient for building evaluation purposes simply refer to windward and leeward facades [12]. This approach aims at being as much general as possible, depending on the wind direction. The challenge, however, is to customize

expressions depending on the shape factor of the structure, which influences the wind flow across the surfaces, as done in [13].
The importance of proper expressions or ways to evaluate the convective heat transfer coefficient occurring at building envelope has been highlighted in several works dealing with the U-value assessment [14]. Particularly, researches that employ the infrared thermography (IRT) for the thermal transmittance evaluation claim the need for accurate correlation for the convective contribution. Such issue, well known by those who employ IRT, is increased when outdoor thermographic campaigns are carried out.
Hence, the aim of this work is the investigation of the influence: (i) of different hypotheses on air speed and (ii) of different expressions for the convective heat transfer coefficient; on thermal transmittance evaluated by IRT outdoor thermography.
In this view, the paper is structured as follows: section 2 describes the outdoor IRT approaches and the methodology followed, section 3 is devoted to the analysis of the convective coefficient correlations adopted, whose influence on thermal transmittance assessment is studied in section 4. Finally, conclusions are drawn in section 5: results show that, depending on the adopted CHTC correlation and on the outdoor IRT approach followed, final thermal transmittance can vary by far from expected values.

2. IRT technique for the U-value assessment

In the last decade, a novel methodology for the U-values assessment has been proposed in literature, based on infrared thermography. This method is mainly referred to as IRT (Infrared Thermography) or ITT (Infrared Thermography Technique).
Many studies have been published on this topic; given a recent review [14], it is possible to identify two main approaches to the technique: performing IRT from inside the structure [15-17], or from the outside [14, 18-20].
According to the IRT method, the indoor and outdoor air temperatures and wall temperature, whether from the inner or from the outer side, are retrieved by employing an infrared camera, that is a device that converts the infrared radiant energy emitted from the target object into an image whose color variation /hues are related to the target apparent temperature distribution. Such temperatures, together with other quantities like wind speed or convective coefficient, wall emissivity and so on, are employed in correlations (formulas) that express the wall's thermal transmittance.
To resolve the debate of the best feasibility between indoor and outdoor measurement campaign is still not possible.
On one hand, performing measurements from indoor ensures quite stable environmental conditions (i.e. air temperature, air speed, reflected temperature) but entails the need for entering the building to be measured with possible bother for the occupants. On the other hand, outdoor IRT has the advantage of performing measurements without entering the structure, but boundary conditions might influence the measurements, and, therefore, the final result.
Whilst in the first approach air movements are reduced, due to the IR camera placement inside the room to be checked, in the second approach acquisitions are taken from the outside, therefore convection might play a key role in the evaluation of the thermal transmittance.
However, those [18-21] who perform outdoor IRT have obtained results under certain environmental conditions or by imposing some practical hypothesis, like for instance the absence of convective movements or negligible wind speed in proximity of the investigated wall.
In [14, 18-20] Equation 1 is employed; the heat balance of the wall is expressed by the sum of the radiative and convective exchange from the wall to the outdoor air. The latter is expressed by a Jürges' equation simplification. Being (T_s) the wall/surface temperature, (T_{ae}) and (T_{ai}) the outdoor and indoor air temperature, respectively, (v) the wind speed, (ε) the wall emissivity and (σ) the Stephan-Boltzmann constant, the equation is:

$$U = \frac{\varepsilon\sigma(T_s^4 - T_{ae}^4) + 3.8054v(T_s - T_{ae})}{T_{ai} - T_{ae}} \tag{1}$$

In the approach followed by Dall'O' et al [21], and expressed by Equation 2, the thermal transmittance is evaluated as:

$$U = \frac{h_e(T_s - T_{ae})}{T_{ai} - T_{ae}} \text{ with } h_e = 5.8 + 3.8054v \tag{2}$$

Starting from the analysis of the correlations proposed in Albatici [20] and Dall'O' [21], two main concerns are evident: (i) the differences in the way the heat balance of the wall is expressed; (ii) the difference in the way the convective contribution is accounted. It is worth mentioning that Equation 2 employs a Jürge correlation for h, while Equation 1 uses its simplification.

2.1. Methodology

The twofold aim of this work is: (i) assessing the influence of different hypotheses on convection in the outdoor IRT approach; (ii) assess the sensibility of Equation 1 and Equation 2 to the convection expression. In other words, one of the scopes is to understand how the thermal transmittance evaluated by using the Jürge's correlation in Equation 1 and Equation 2 can vary when other expressions for CHTC are employed. These expressions can be structured similarly to Jürge's correlation (linear correlations), or can be more complex (exponential correlations). These aims become relevant especially when low air speed are considered [21].
The kickstart of the research has been a reviewer comment on a previously published paper [19], asking to detail the possible influence of convection on results. Therefore, in this contribution such issue has been addressed. Hence, this work widens previous results and outcomes [19].
Particularly, in [19] four approaches were followed, adapting two indoor IRT procedures to outdoor consideration. In the present work, only the two outdoor methodologies (proposed by Albatici [20] and Dall'O' [21]) are considered.
A preliminary analysis of the dependence of convective coefficient on wind speed is given, taking into account some relevant correlations for CHTC proposed in literature.
Then, the correlations are employed respectively in Equation 1 and 2 by substituting the convective term. The final assessment is carried out considering low air speed (less than 0.4 m/s), since the set up employed in [19] allowed to have negligible wind speed at wall surface, being the specimen placed inside a facility that acted as outdoor environment. Therefore, being the conditions at surface level controlled, air speed has been considered negligible [19]. This hypothesis has been supported by a simple proof: under an aluminum foil, that was placed on the wall exposed to air at lower temperature, a slight heat plume rose. This was due to the heating of the air between the foil and the wall. Given the low temperature increase (assessed by infrared thermography) and the vertical layout of the plume, it is reasonable to hypothesize that the air speed in proximity of the wall was negligible.
The procedure followed to assess the impact of the convection expression on the final U-value is detailed below.

1. Each correlation of Table 1 was evaluated for the air speeds considered (0 m/s to 0.4 m/s with a step of 0.1 m/s);
2. Convective contributions evaluated in Step 1 were employed in Equation 1 and Equation 2, for obtaining, with "modified" equations, the U-value;
3. "Modified" Equation 1 and Equation 2 were used for the 24 campaigns of [19];
4. The U-value has been arithmetically averaged on the 24 campaigns, for each air speed class, and each correlation;
5. The obtained U-values have been divided by the corresponding U-values calculated in [19];
6. The ratios obtained in Step 5 have been plot.

This methodology has been summarized in Figure 1.

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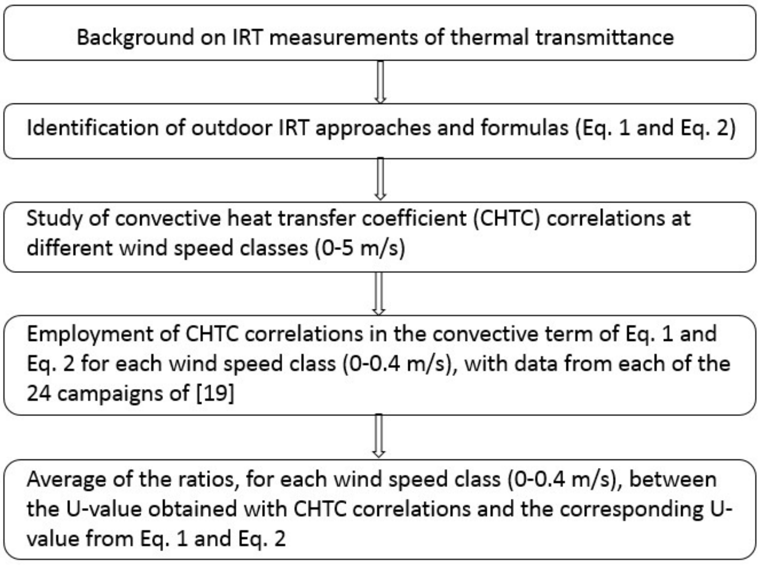

Figure 1. Research procedure.

3. Convective coefficient expressions

Several works in literature concern the way to express convective coefficient; however, there is a paper [22] that aims at collecting the more relevant, grouped as linear or power law expressions of the wind speed, and as expressions involving the Reynolds number.
In the present work, it has been decided to employ only the expressions of the first group, therefore the general expression of the convective coefficient is (Equation 3):

$$h = a + b * v\hat{}n \tag{3}$$

Where (a), (b) and (n) are constants and (v) is the air speed (expressed in m/s).
This, in order to have easy and manageable expressions of the CHTC, to be used in Equation 1 and Equation 2. However, there are literature examples where expressions of the second group are employed in indoor IRT [17].
The chosen correlations, named by a progressive ID, together with the coefficients a, b and n, are listed in Table 1.

Table 1. Values for the CHTC correlations to be used in Equation 3 (h= a +b*v^n).

Ref	ID	a	b	n	Ref	ID	a	b	n
[23]	C1	0.000	2.860	0.617	[41]	C29	7.820	3.500	1.000
[24]	C2	6.220	0.486	1.000	[40]	C30	5.800	3.950	1.000
[23]	C3	0.000	2.380	0.890	[42]	C31	-0.685	11.800	0.500
[25]	C4	0.036	2.200	1.000	[43]	C32	5.820	4.020	1.000
[26]	C5	5.000	1.000	1.000	[44]	C33	5.820	4.070	1.000
[27]	C6	5.100	1.700	1.000	[45]	C34	6.420	3.960	1.000
[27]	C7	5.100	1.700	1.010	[46]	C35	5.800	4.100	1.000
[28]	C8	4.930	1.770	1.000	[43]	C36	6.050	4.080	1.000
[24]	C9	6.220	2.000	1.000	[39]	C37	0.000	7.520	0.784
[29]	C10	5.500	2.200	1.000	[38]	C38	0.000	7.600	0.780
[30]	C11	0.000	6.600	0.600	[41]	C39	8.900	3.710	1.000
[31]	C12	7.000	2.100	1.000	[47]	C40	6.200	4.300	1.000
[32]	C13	2.800	3.000	1.000	[48]	C41	0.000	5.700	1.000
[28]	C14	8.910	2.000	1.000	[49]	C42	0.000	14.820	0.420
[33]	C15	4.500	2.900	1.000	[50]	C43	7.550	4.350	1.000
[20]	C16	0.000	3.805	1.000	[28]	C44	0.000	16.150	0.397
[34]	C17	8.300	2.200	1.000	[51]	C45	10.030	5.000	1.000
[12]	C18	5.800	2.900	1.000	[28]	C46	0.000	16.210	0.452
[35]	C19	0.000	6.970	0.666	[49]	C47	0.000	15.000	0.530
[34]	C20	0.000	9.400	0.500	[41]	C48	10.700	4.960	1.000
[36]	C21	8.550	2.560	1.000	[52]	C49	5.700	6.000	1.000
[37]	C22	4.214	3.575	1.000	[28]	C50	0.000	16.250	0.503
[34]	C23	6.500	3.300	1.000	[48]	C51	11.400	5.700	1.000
[38]	C24	5.700	3.800	1.000	[23]	C52	6.470	7.000	1.000
[39]	C25	0.000	7.110	0.775	[51]	C53	12.200	7.000	1.000
[21]	C26	5.800	3.805	1.000	[53]	C54	0.000	18.650	0.605
[40]	C27	0.000	7.130	0.780	[48]	C55	23.000	5.700	1.000
[38]	C28	0.000	7.200	0.780	[45]	C56	4.470	10.210	1.000
					[12]	C57	8.700	9.400	1.000

As first step, the dispersion of the convective coefficient, calculated according to different expressions and at different wind speed classes ranging between 0 m/s and 5 m/s, has been evaluated. Results are shown in Figure 2, where the CHTC are plotted on the x-axis, according to the expressions proposed in the works labelled in the y-axis. Dots of different colours refer to the wind speed classes (step of 0.5 m/s). Results of the evaluation of the Jürge's equation simplifications adopted in Equation 1 and 2 are also plotted (red labels on y-axis). Finally, a red dotted line marks the value of 25 W/(m^{2}K), that is the value that standard ISO 6946 [54] suggests for external convective heat transfer coefficient when information on the boundary conditions on a plane surface (like walls) are missing, whilst an orange dashed line marks the higher value obtained for wind speed of 0.5 m/s.
The analysis of Figure 2 allows to state the following: (i) some expressions (C1, C2 and C3) provide similar CHTC values (lower than 10 W/(m^{2}K)) by varying the wind speed; (ii) the large majority of the correlations (from C4 to C43) provide CHTC values comprised between 10 W/(m^{2}K) and 30 W/(m^{2}K) for wind speed 5 m/s; (iii) some correlations provide CHTC values spanning up to 56

W/(m^{2}K) for wind speed up to 5 m/s; (iv) half of the considered correlations provide CHTC values lower than 25 W/(m^{2}K) for wind speed up to 5 m/s; (v) for wind speed between 0 m/s and 1 m/s, all the correlations provide CHTC value lower than 18.8 W/(m^{2}K), except for C55 that provides value up to 28.7 W/(m^{2}K).

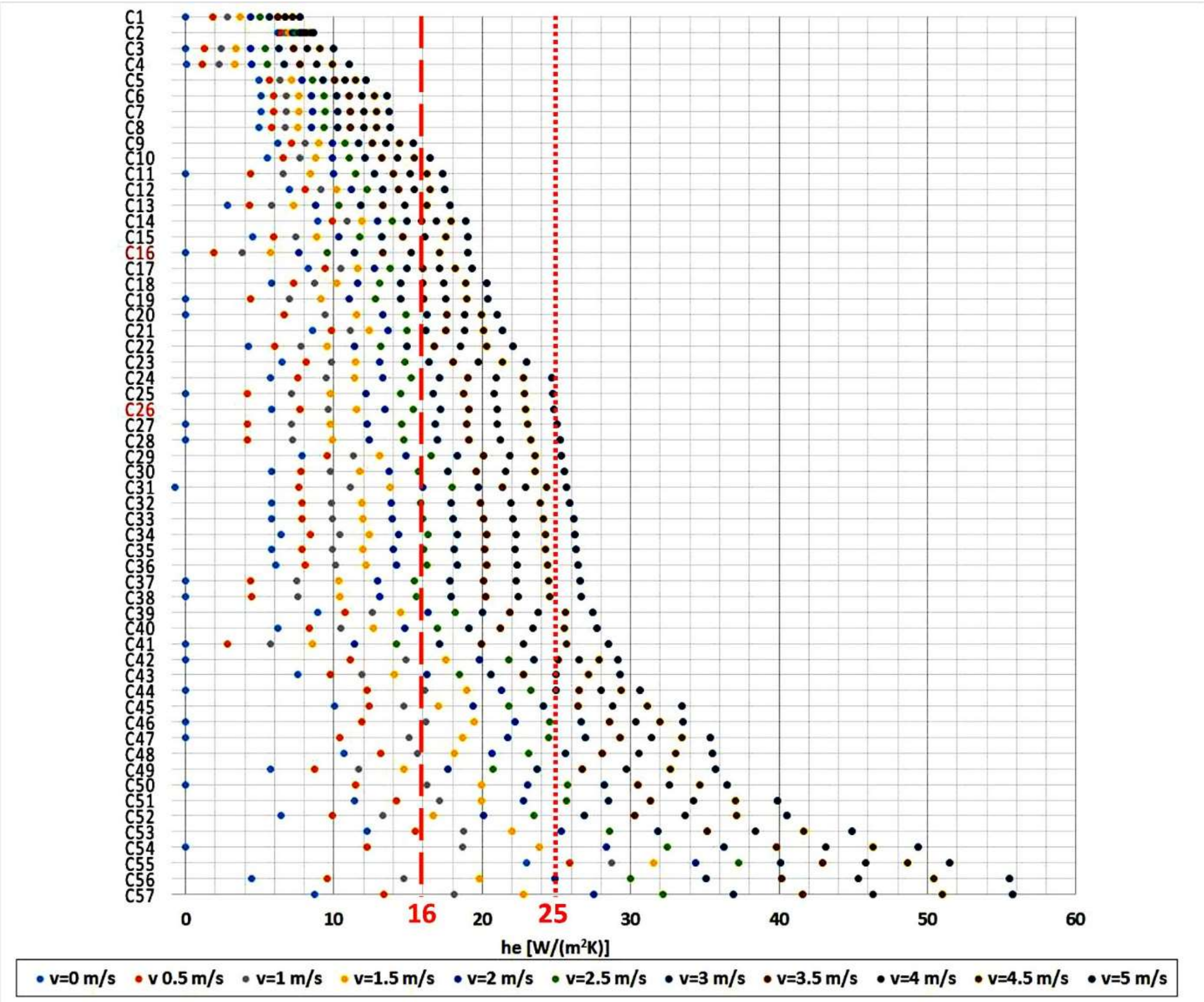

Figure 2. CHTC comparison for wind speed ranging between 0 m/s and 5 m/s.

4. Convective coefficient influence on thermal transmittance

Given the fact that in the experimental set up employed in [19] the air speed in proximity of the wall was negligible, the focus of the research is now the reduced wind speed range 0 m/s – 0.4 m/s. In fact, low wind speed is expected in case of controlled environment set up, like the one of [19]. Therefore, it is reasonable to reduce the wind speed range to 0-0.4 m/s. Finally, for results display, it has been chosen to plot the average of the ratios between the final U-value (once calculated according to Equation 1 - namely U1 - and once according to Equation 2 – namely U2), obtained with data of the 24 experimental campaigns of [19], and the U-value obtained with the original equations.

Therefore, each dot represents, at its specific wind speed, the ratio between the U-value (calculated by substituting in the convective term the given correlation), and the original value (obtained with the equations 1 and 2), averaged on the 24 campaigns. This has been done for values obtained via Equation 1 (therefore, we have the ratio U/U1) and via Equation 2 (therefore, we have the ratio U/U2). Results are shown respectively in Figure 3 and Figure 4, whilst Figure 5 proposes details of results of

Figure 4 focusing in the range of ratio 0-6. The red dashed line in Figures 3 to 5 marks the ratio equal to 1, when the U-value calculated with the CHTC correlation equals the one proposed by the original equation. Therefore, the dots' scattering, and their distance from the red line, represents the deviation from the original condition (i.e. ratio equal to 1).

From the results analysis, the following outcomes can be drawn:

- Correlations that provide CHTC values quite near when the wind speed spans from 0 m/s to 5 m/s (upper part of Figure 2) give the higher U/U1 and U/U2 ratios; this means that such correlations worst represent the convective phenomena at low wind speed.
- Correlations (like C48, C49, C50, C51, C53, C54 and C57) that provide higher CHTC values with wind speed up to 0.5 m/s, are those who provide lower U-value ratios considering Equation1;
- Figure 3 shows that the considered correlations provide U-values that can be up to 5.5 times the expected ones (see C3) when Equation1 is considered. Instead, considering Equation 2, such ratio can be up to 62. Therefore, the correlation C3 should not be preferred for the convective expression;
- Considering Equation 1, several correlations provide results that fit the expected one (C21, C22, C32, C33, C34, C40, C42) in the considered wind speed range. Most of all, the correlations C54, C55 and C57 almost perfectly match the expected one;
- Considering Equation 2, results of Figure 5 show that the correlations C54, C55 and C57 are those who provide results near the expected one;
- Results of Figure 3 are less scattered than their corresponding of Figure 4; this implies that Equation 1 is less sensitive to the correlation adopted for the convection expression, amongst those considered and in the wind speed range analyzed. This constitutes an advantage, since one of the weak points of the IRT method is the convection expression itself.

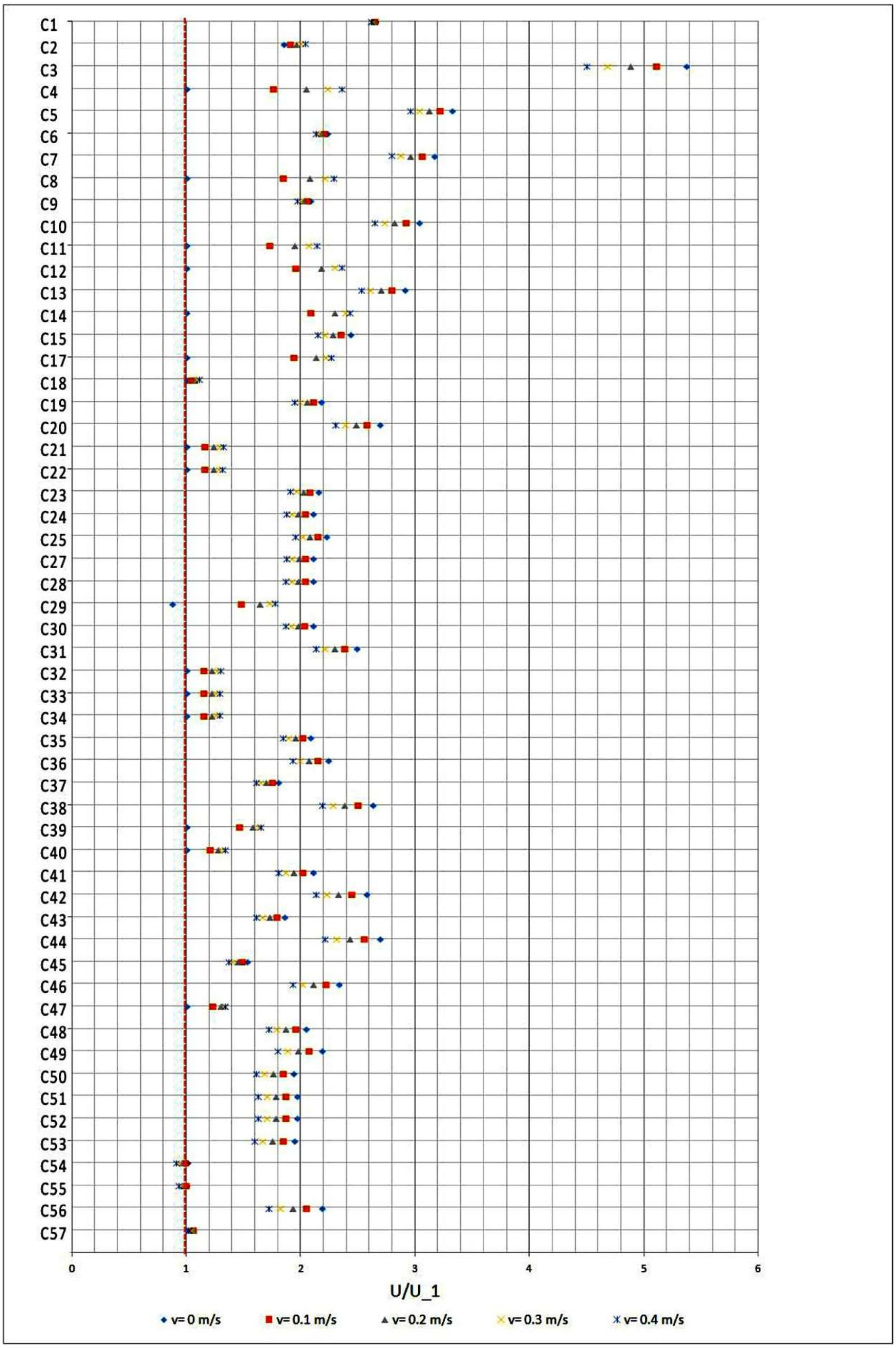

Figure 3. U-value ratios at different wind speed using Equation 1.

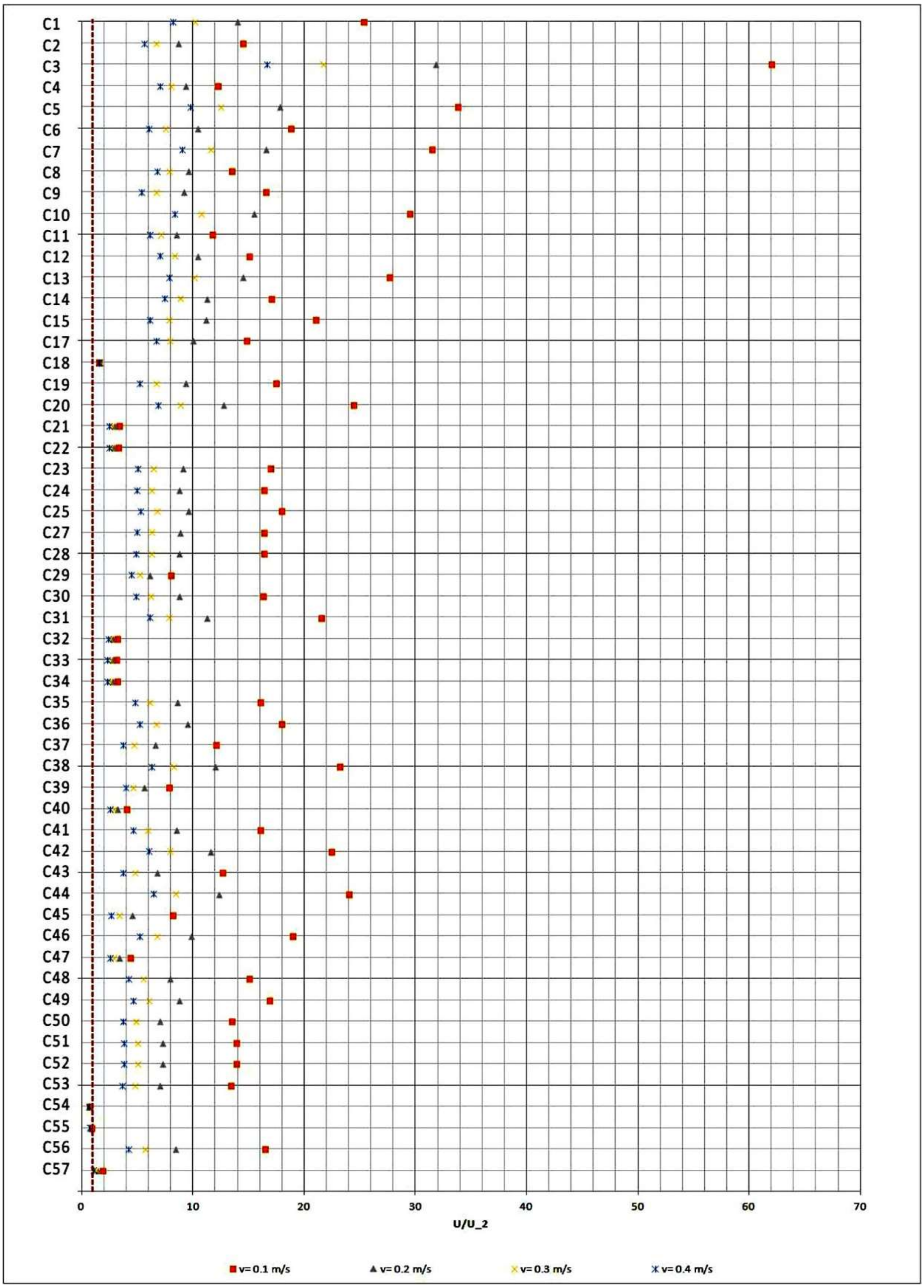

Figure 4. U-value ratios at different wind speed using Equation 2.

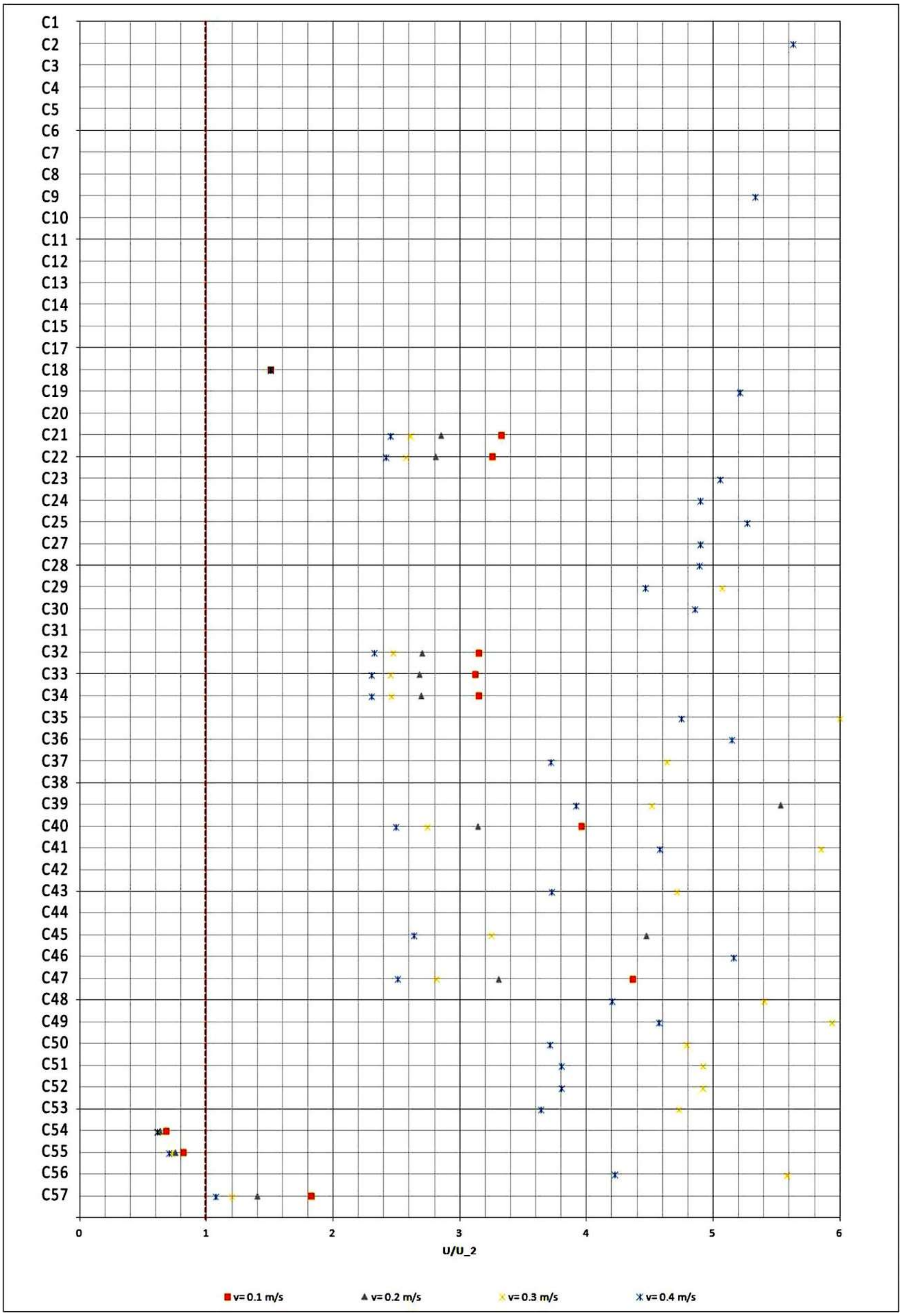

Figure 5. U-value ratios at different wind speed using Equation 2 – detail of the ratio range 0-6.

5. Conclusions

The twofold aim of this work is to assess the influence of convective correlation to be adopted in outdoor IRT measurement of thermal transmittance.
From the comparison of CHCT values at different wind speed classes (ranging from = m/s to 5 m/s), it results that some expressions provide similar CHTC values (lower than 10 W/(m2K) by varying the wind speed, but the large majority of analysed correlations provide CHTC values comprised between 10 W/(m2K) and 30 W/(m2K); half of the considered correlations provide CHTC values lower than 25 W/(m2K) for wind speed up to 5 m/s.
After this preliminary comparison amongst CHTC correlations, it is reasonable to consider the reduced wind speed range 0-0.4 m/s, such as the low wind speed in proximity of buildings' façade during IRT survey (as also recommended by common practice).
In this case, the ratios between the final U-value with, in turn, the CHTC correlations, and the U-value obtained with the original equations (U1 from Eq.1 and U2 from Eq.2), have been compared.
The following outcomes can be pointed out:

- Correlations that provide CHTC values quite near when the wind speed spans from 0 m/s to 5 m/s worst represent the convective phenomena at low wind speed.
- Correlations providing higher CHTC values with wind speed up to 0.5 m/s (like C48, C49, C50, C51, C53, C54 and C57), give lower U-value ratios considering Equation1;
- Correlation C3 should not be preferred for the convective expression (very high U/U1 and U/U2 ratios);

From the Equation point of view, it is possible to state that the approach and formulation proposed by Albatici [20] is less sensitive to the correlation adopted for the convection expression, amongst those considered and in the wind speed range analyzed. This constitutes an advantage, since one of the weak points of the IRT method is the convection expression itself.

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