ESTIMATING THE INFLUENCE OF OUTDOOR CONVECTIVE HEAT TRANSFER COEFFICIENT ON THERMAL LOADS

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ABSTRACT

This research focuses on the influence of outdoor convective heat transfer coefficient on thermal load calculation in Building Energy Simulation programs.

In building energy is commonly used the overall heat transfer coefficient value (U-value) to characterize external walls and windows in terms of heat gain or loss through them. Thus, the higher the U-value the lower the thermal resistance and the larger the heat transfer through the enclosure element and vice versa. Calculating the mentioned value involves not only the layers making up the building element, but also the internal and external surface resistances. The external surface resistance has the greatest level of uncertainty. This resistance is calculated as the inverse of the sum of the outdoor convective and radiant heat transfer coefficients. Regulations and Building Energy Simulation programs in Spain (LIDER and CALENER) use a constant outdoor convective heat transfer coefficient value. This study analyses the importance of a detailed calculation of the outdoor convective heat transfer coefficients on the thermal loads of buildings, distinguishing between two types of envelope elements: facade walls and windows. The extrapolation of the dimensionless numbers quantifying the convective heat transfer to outdoor air velocity and temperature difference between the external surface and outdoor air has been done. Therefore, the corresponding correlation can be selected in order to determine the outdoor convective heat transfer coefficient as a function of easily measurable parameters. Once the outdoor convective heat transfer coefficient has been calculated by using the appropriate correlation, the relative error on the thermal load calculation due to assuming a constant reference outdoor convective heat transfer coefficient value is estimated. Firstly, the maximum possible relative error on the thermal load calculation has been delimited. Then, the estimation of the relative error for different representative cases has been developed for facade walls and windows. The results show that above a certain U-value of reference, the relative error on the thermal load calculation due to assuming a constant outdoor convective heat transfer coefficient can reach 34.66% by overestimation.

Keywords: Building Energy Simulation programs, Overall Heat Transfer Coefficient, Outdoor Convective Heat Transfer Coefficient, Thermal Loads.

INTRODUCTION

In building energy is commonly used the overall heat transfer coefficient value (U-value) to characterize the building enclosure elements in terms of heat gain or loss through them. A high U-value corresponds to a low thermal resistance, that is, an element that allows a large heat transfer through it and vice versa. Calculating the mentioned value involves not only the layers making up the building enclosure element, but also the internal and external surface resistances. The external surface resistance has a greater level of uncertainty. This resistance is calculated as the inverse of the sum of the outdoor convective and radiant heat transfer coefficients. Therefore, the outdoor convective heat transfer coefficient influences on the thermal load through the enclosure elements, that is, on the heat transfer rate through facade walls and windows which are in contact with the outside air. Regulations and Building Energy Simulation programs (BES programs) in Spain (LIDER and CALENER) use a constant value of 20 W/m^2K (IDAE, 2009) for the outdoor convective heat transfer coefficient. Since this coefficient mainly depends on the movement type of the fluid and its physical properties, the above mentioned assumption involves an error that is necessary to quantify in order to assess how it affects the calculation made by these programs to estimate the energy demand of buildings. Estimating this error is especially important under the DIRECTIVE 2010/31/EU (Official Journal of the European Union, 2010) which imposes the certification of existing buildings, whose enclosure elements have a higher U-value. Furthermore, this error is more significant in windows because of its greater U-value, both in new and existing buildings.

Then, this study aims to evaluate the error committed by these BES programs by assuming a constant value of this coefficient instead of calculating it in detail. That is, this paper intends to answer the following question: ¿is it important to calculate in detail the outdoor convective heat transfer coefficient in BES programs? The results are useful to both new and existing buildings.

Firstly, the extrapolation of the dimensionless numbers quantifying the convective heat transfer to outdoor air velocity and temperature difference between the outer surface and outdoor air has been done. Then, nine different regions have been defined depending on convection type and fluid regime, in such a way that the corresponding correlation can be selected in order to determine the outdoor convective heat transfer coefficient as a function of easily measurable parameters. After that, the expected values of outdoor air velocity and outdoor temperature difference between air and outer surface have been estimated by means of Weibull probability density function for facade wall and window under the case study considered in this paper.

Finally, once the outdoor convective heat transfer coefficient has been calculated by using the appropriate correlation from the expected Weibull distributions, the relative error on the thermal load calculation due to assuming a constant outdoor convective heat transfer coefficient value is estimated. Furthermore, the maximum possible relative error on the thermal load calculation has been delimited.

THE OUTDOOR CONVECTIVE HEAT TRANSFER COEFFICIENT

The outdoor convective heat transfer coefficient quantifies the heat transfer rate by convection between the outdoor air and outer surfaces of facade walls and windows. The mechanism of heat transfer by convection occurs between the fluid in motion and solid. It depends on many parameters, but mainly on the movement type of the fluid and its physical properties. Firstly in this study, the extrapolation of the dimensionless numbers quantifying the convective heat transfer to outdoor air velocity and temperature difference between the outer surface and outdoor air has been done. On the other hand, we can distinguish two main types of convection, forced convection and natural convection. The difference between them resides in the origin which causes the movement of the fluid. In turn, within each type of convection, the fluid may have three types of regime, laminar, turbulent or transition. According to the previous classification, nine different regions can be distinguished and the convective heat transfer coefficient calculated by using the corresponding correlation (Incropera, 2011) depending on air velocity and surface-air temperature difference. Figure 1 shows the nine regions above mentioned and table 1 the convection type and fluid regime corresponding to each region of figure 1.

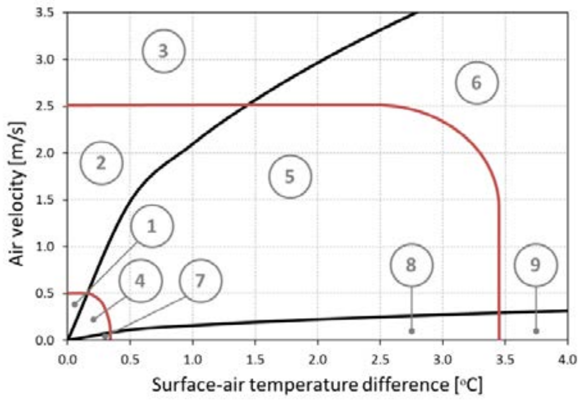

Figure 1 Correlation applicability regions as a function of air velocity and surface-air temperature difference

Table 1
Convection type and fluid regime of correlation applicability regions

Region	Convection type	Fluid regime
1	Forced	Laminar
2	Forced	Transition
3	Forced	Turbulent
4	Mixed	Laminar
5	Mixed	Transition
6	Mixed	Turbulent
7	Natural	Laminar
8	Natural	Transition
9	Natural	Turbulent

CASE STUDIES

In this paper, the results concerned to a hypothetical building located in Madrid are shown for two representative enclosure elements: facade wall and window. A facade wall with a typical composition in Spanish buildings (insulation thickness of 57 cm) and a double glass window are considered, with an U-value of 1 W/m^2K and 3.5 W/m^2K respectively.

These enclosure elements are considered to face to north, south, east and west orientation and can be either free of obstructions or with shading elements blocking the beam solar radiation on its surface. Therefore, it is assumed that the probability of finding a facade wall or window facing to any of above mentioned orientations and free or not of shading elements is the same. The considered period in this study corresponds to winter season: December, January and February. Furthermore, it is considered an ideal system inside the space which maintains the indoor temperature at 20 °C during these months (RITE, 2013).

ESTIMATING THE EXPECTED OUTDOOR AIR VELOCITY AND OUTDOOR TEMPERATURE DIFFERENCE

To assess how the outdoor convective heat transfer coefficient influences on the thermal load, it is necessary to estimate what values of outdoor air velocity and outdoor temperature difference between air and outer surface could be expected under the case study described in the previous section.

It can be done by means of their frequency distributions once have been normalized by adjusting to the Weibull probability density function (Dodson, 2006) by the least squares method.

Outdoor temperature difference: facade wall

A possible method to simulate the transient thermal performance of facade walls is the well-known transfer function (Mitalas, 1972). The transfer function determines the heat transfer rate by conduction in each element surface: outer q_1 and inner q_2 surface (EQUATION 1).

$$q_1 = \sum_{i=0}^{n_a}\big(a(i)\cdot T_{S1}(t-i)\big) - \sum_{i=0}^{n_b}\big(b(i)\cdot T_{S2}(t-i)\big) - \sum_{i=1}^{n_d}\big(d(i)\cdot q_1(t-i)\big)$$
$$q_2 = -\sum_{i=0}^{n_b}\big(b(i)\cdot T_{S1}(t-i)\big) + \sum_{i=0}^{n_c}\big(c(i)\cdot T_{S2}(t-i)\big) - \sum_{i=1}^{n_d}\big(d(i)\cdot q_2(t-i)\big) \quad (1)$$

Where:

q: heat transfer rate by conduction in the outer (1) or inner (2) surface of the enclosure element [W/m^2].

T_S: outer (1) or inner (2) surface temperature of the enclosure element [ºC].

a(i), b(i), c(i), d(i): response factors of the transfer function calculated by finite difference method (FDM). These factors are listed in the table 2.

Table 2
Response factors of the transfer function obtained by FDM

$a(i)$ [W/m^{2}K]	$b(i)$ [W/m^{2}K]	$c(i)$ [W/m^{2}K]	$d(i)$ [-]
1.84E+01	1.51E-04	1.38E+01	1.00E+00
-3.38E+01	1.67E-02	-2.85E+01	-1.38E+00
1.93E+01	6.15E-02	1.85E+01	5.32E-01
-3.95E+00	3.02E-02	-4.02E+00	-5.46E-02
1.88E-01	3.54E-03	2.74E-01	
2.68E-04	5.10E-05	2.84E-04	

The heat transfer rate q_1 and q_2 calculated by the transfer function in each element surface (EQUATION 1), is then made equal to the heat transfer rate by convection, long wavelength radiation and solar radiation (EQUATION 2).

$$q^* = h_{cr}\cdot(T_S - T_{sa}) \quad (2)$$

Where:

q^*: heat transfer rate in the corresponding element surface [W/m^2].

h_{cr}: convective-radiant heat transfer coefficient [W/m^{2}K] calculated as $h_{cr} = h_c + h_r$, where h_c is the convective heat transfer coefficient [W/m^{2}K] and h_r the long-wavelength radiant heat transfer coefficient [W/m^{2}K].

T_{sa}: sun-air temperature [ºC] calculated as follows:

$$T_{sa} = \frac{I\cdot\alpha + h_{cr}\cdot T_{cr}}{h_{cr}} \quad (3)$$

Where:

I: global solar irradiation on the surface [W/m^2].

α: absorptivity of the surface [-].

T_{cr}: convective-radiant temperature [ºC] calculated as follows:

$$T_{cr} = \frac{h_c\cdot T_c + h_r\cdot T_r}{h_{cr}} \quad (4)$$

Where:

T_c: convective temperature [ºC].

T_r: surroundings temperature [ºC].

In matrix arrangement, the surface temperatures can then be calculated as following:

$$\begin{bmatrix}T_{S1}\\T_{S2}\end{bmatrix} = \begin{bmatrix}\frac{-h_{cr2}-c_0}{|A|} & -\frac{b_0}{|A|}\\ -\frac{b_0}{|A|} & \frac{-h_{cr1}-a_0}{|A|}\end{bmatrix}\begin{bmatrix}-h_{cr1}\cdot T_{sa1}+P_1\\ -h_{cr2}\cdot T_{sa2}+P_2\end{bmatrix} \quad (5)$$

Where:

$$a_0 = a(0);\ b_0 = b(0);\ c_0 = c(0) \quad (6)$$

$$|A| = \begin{vmatrix}-h_{cr1}-a_0 & b_0\\ b_0 & -h_{cr2}-c_0\end{vmatrix} \quad (7)$$

$$P_1 = \sum_{i=1}^{n_a}\big(a(i)\cdot T_{S1}(t-i)\big) - \sum_{i=1}^{n_b}\big(b(i)\cdot T_{S2}(t-i)\big) - \sum_{i=1}^{n_d}\big(d(i)\cdot q_1(t-i)\big)$$
$$P_2 = -\sum_{i=1}^{n_b}\big(b(i)\cdot T_{S1}(t-i)\big) + \sum_{i=1}^{n_c}\big(c(i)\cdot T_{S2}(t-i)\big) - \sum_{i=1}^{n_d}\big(d(i)\cdot q_2(t-i)\big) \quad (8)$$

Comparing the outer surface temperature of the enclosure element with the outdoor air temperature, the Weibull probability density function for facade wall is obtained (figure 3).

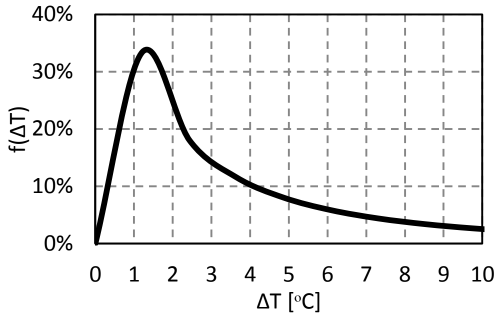

Figure 3 Weibull probability density function for the outdoor temperature difference in facade wall

Outdoor temperature difference: window

The semi-transparent elements, such as windows, can be simulated in steady state, making it possible to use the well-known simplified model of 2 nodes. In this way, the surface temperatures of the enclosure element can be calculated as follows:

$$\begin{bmatrix} T_{S1} \\ T_{S2} \end{bmatrix} = \begin{bmatrix} \dfrac{-h_{cr2} - \frac{k}{e}}{|A|} & -\dfrac{\frac{k}{e}}{|A|} \\ \dfrac{\frac{k}{e}}{|A|} & \dfrac{h_{cr1} + \frac{k}{e}}{|A|} \end{bmatrix} \begin{bmatrix} h_{cr1} \cdot T_{sa1} \\ -h_{cr2} \cdot T_{sa2} \end{bmatrix} \quad (9)$$

Comparing the outer surface temperature of the enclosure element with the outdoor air temperature, the Weibull probability density function for window is obtained (figure 4).

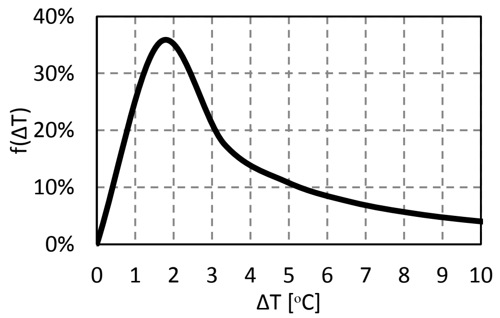

Figure 4 Weibull probability density function for the outdoor temperature difference in window

Outdoor air velocity

Both experimentally and extracted from different characterizations, it is found out that wind velocity above and below the height of buildings differs greatly from each other. On the other hand, due to the greater roughness in urban areas than in rural areas, the wind velocity in the first ones is generally much lower. All this implies the need to translate the available wind velocity measurements at airports ,Barajas in this case (INM, 2004), to urban areas. In this paper, it has been considered that wind velocity in the urban area is approximately 25% of the velocity measurements at the airport (Santamouris, 2001). Figure 5 shows the Weibull probability density function for outdoor air velocity in the location which has been considered in this study.

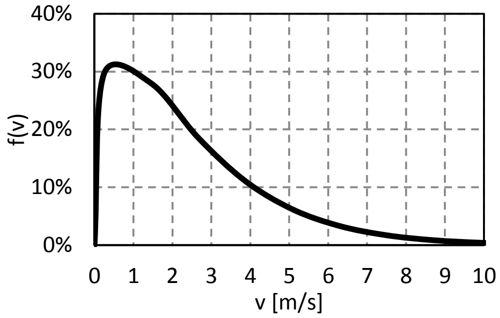

Figure 5 Weibull probability density function for the outdoor air velocity

DISCUSSION AND RESULT ANSLISYS

Estimating the influence of the outdoor convective heat transfer coefficient on thermal loads

Once the expected conditions of outdoor air velocity and outdoor temperature difference have been assessed, the relative error on the thermal load can be estimated. This relative error is obtained as follows:

$$e\% = \frac{\Delta q}{q_{Ref}} \cdot 100 = \frac{q - q_{Ref}}{q_{Ref}} \cdot 100 \quad (10)$$

Where:

q: thermal load through the enclosure element [W/m2] if the corresponding outdoor convective heat transfer coefficient correlations are used under the expected outdoor air velocity and outdoor temperature difference (EQUATION 11).

q_{Ref}: thermal load through the enclosure element [W/m2] if a reference constant value for the outdoor convective heat transfer coefficient is used (EQUATION 12).

$$q = U \cdot \Delta T = \frac{1}{\frac{1}{h_{ce} + h_{re}^{Ref}} + R_{SS} + \frac{1}{h_{ci}^{Ref} + h_{ri}^{Ref}}} \cdot \Delta T \quad (11)$$

Where:

U: overall heat transfer coefficient value [W/m^{2}K] if the corresponding outdoor convective heat transfer coefficient correlations are used under the expected outdoor air velocity and outdoor temperature difference.

ΔT: temperature difference between outdoor air and indoor air [ºC].

R_{SS}: surface-surface resistance of the enclosure element [m^{2}K/W].

h_{ce}: outdoor convective heat transfer coefficient calculated by means of the corresponding correlations under the expected outdoor air velocity and outdoor temperature difference. [W/m^{2}K].

h^{Ref}: outdoor (e); indoor (i); convective (c); long wavelength radiant (r) heat transfer coefficients if a reference constant value is used [W/m^{2}K].

Figure 6 (page 9) shows how the outdoor convective heat transfer coefficient h_{ce} in EQUATION 11 is calculated. For a certain value of outdoor air velocity (v) and outdoor temperature difference (ΔT) the convection type and fluid regime is found. Then, as mentioned in section 2, the appropriate correlation can be selected (Incropera, 2011) and the outdoor convective heat transfer coefficient calculated. Furthermore, the Weibull probability density function gives information about the most likely values of this coefficient and, therefore, of the relative error.

$$q_{Ref} = U_{Ref} \cdot \Delta T = \\ = \frac{1}{\frac{1}{h_{ce}^{Ref} + h_{re}^{Ref}} + R_{SS} + \frac{1}{h_{ci}^{Ref} + h_{ri}^{Ref}}} \cdot \Delta T \qquad (12)$$

Where:

U_{Ref}: overall heat transfer coefficient value [W/m^{2}K] if a reference constant value for every heat transfer coefficient is used.

According to Spanish Regulations, the reference constant values for the different coefficients are the following:

Table 3
Reference constant values for heat transfer coefficients according to the Spanish Regulations

Heat transfer coefficient	**Reference constant value [W/m²K]**
h_{ce}^{Ref}	20
h_{re}^{Ref}	5
h_{ci}^{Ref}	2
h_{ri}^{Ref}	5.7

Thus, the error on the thermal load Δq is calculated as follows:

$$\Delta q = q - q_{Ref} = \left(U - U_{Ref}\right) \cdot \Delta T = \Delta U \cdot \Delta T \qquad (13)$$

Where:

$$\Delta U = U_{Ref}\left(\frac{1}{U_{Ref} \cdot \left(\frac{1}{h_{ce} + h_{re}^{Ref}} - \frac{1}{h_{cri}^{Ref}}\right) + 1} - 1\right) \qquad (14)$$

Where:

h_{cri}^{Ref}: convective-radiant heat transfer coefficient if reference constant values are used [W/m^{2}K], calculated as $h_{cri}^{Ref} = h_{ci}^{Ref} + h_{ri}^{Ref}$.

Introducing EQUATION 12, 13 and 14 in EQUATION 10, the relative error on thermal load can be calculated as follows:

$$e\% = \frac{\Delta U \cdot \Delta T}{U_{Ref} \cdot \Delta T} \cdot 100 = \\ = \left(\frac{1}{U_{Ref} \cdot \left(\frac{1}{h_{ce} + h_{re}^{Ref}} - \frac{1}{h_{cri}^{Ref}}\right) + 1} - 1\right) \cdot 100 \qquad (15)$$

Once the relative error has been defined, then the limit corresponding to the maximum overestimation and maximum underestimation can be calculated for each type of enclosure element under consideration. The maximum overestimation is obtained when the outdoor convective heat transfer coefficient value h_{ce} is zero. The maximum underestimation is obtained when the value of this coefficient h_{ce} tends to an infinite value. Substituting these values in EQUATION 15, the described limits for the relative error can be obtained. The following table shows the limit values for both enclosure elements. These limits are independent of the location, orientation and solar radiation.

Table 4
Reference constant values for heat transfer coefficients according to the Spanish Regulations

	Facade wall	**Window**
Maximum Overestimation	-13.78	-35.90
Maximum Underestimation	4.16	16.28

Once the possible maximum relative error has been delimited, the relative error on thermal load for the case study described in this paper can be calculated according to the expected values of the parameters which quantify the outdoor convective heat transfer coefficient.

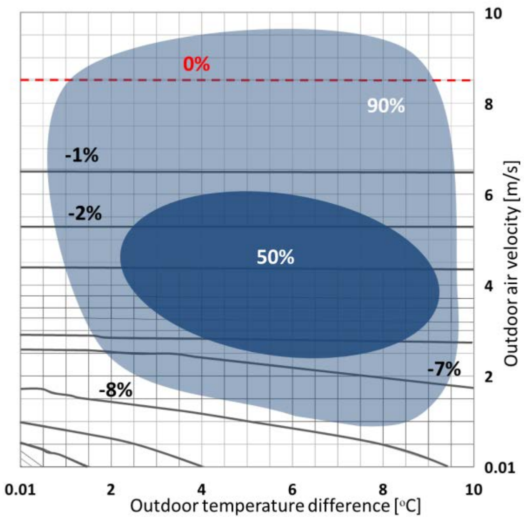

Figure 7 Relative error on the thermal load through facade wall as a function of outdoor air velocity and outdoor temperature difference

Figure 7 shows the relative error committed on the thermal load through facade wall versus outdoor air velocity and temperature difference between the outer surface and outdoor air. Dashed line shows the values of outdoor air velocity and outdoor temperature difference for which the relative error committed by the simulation programs is zero. Above this line, the simulation programs underestimate the thermal load through the element, according to the definition of the relative error (EQUATION 10). Below this line, the simulation programs overestimate the thermal load through the element. For facade wall, figure 7 shows that 90% of cases the relative error committed on the thermal load is less than 8% by overestimation and less than 1% by underestimation. In 50% of cases, the simulation programs overestimate the value of the thermal load through facade wall between about 7 and 1%.

The same methodology was carried out for window, Figure 8. The relative error by underestimation is not significant and less than 2%. However, the relative error by overestimation may be close to 24%. In 50% of cases, the simulation programs overestimate the thermal load through the window between 4 and 14%.

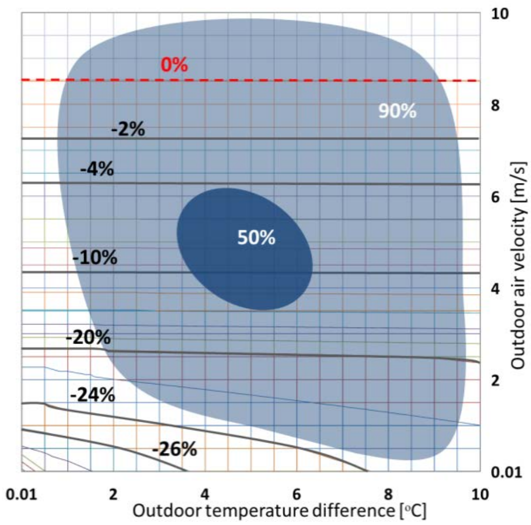

Figure 8 Relative error on the thermal load through the window as a function of outdoor air velocity and outdoor temperature difference

Figure 9 (page 8) shows the relative error on thermal load versus the overall heat transfer coefficient value of the element (U-value). This figure shows how the relative error committed on the thermal load by simulation programs increases as does U-value of the elements used in building construction. For each element, the relative error on thermal load under the expected conditions has been represented. Dashed lines represent the mean relative error by underestimation and overestimation as a function of the U-value. For facade wall this mean value is 0.35% by underestimation, and 3.98% by overestimation. For window, the mean value by underestimation is also negligible and equal to 1.22%. However, the mean relative error which is committed by overestimation is 12.04%.

CONCLUSION

This paper aims to estimate the relative error committed by Building Energy Simulation programs on thermal loads by assuming a constant value of the outdoor convective heat transfer coefficient. That is, this paper intends to answer the following question: ¿is it important to calculate in detail the outdoor convective heat transfer coefficient in these programs? For this purpose, two types of enclosure elements have been considered: facade wall and window. Then, thermal load by using a constant outdoor convective heat transfer coefficient is compared with those calculated by means of empirical correlations under the expected conditions of outdoor air velocity and outdoor temperature difference for a specific case study. The results are useful to both new and existing buildings.

The results show:

- The maximum possible relative error on thermal load increases as does U-value of the enclosure elements. For a facade wall with an U-value of 1

W/m^{2}K the maximum possible relative error is 13.78% by overestimation and 4.16% by underestimation. For a window with an U-value of 3.5 W/m2K the maximum possible relative error is 35.90% by overestimation and 16.28% by underestimation. These maximum possible relative errors are independent of location, orientation and solar radiation.

- For a facade wall under the expected conditions in the considered study case, a relative error less than 8% by overestimation and 1% by underestimations is obtained in 90% of cases. A relative error between 1% and 7% by overestimation is obtained in 50% of cases. On the other hand, the mean relative error is 3.98% by overestimation and 0.35% by underestimation.
- For a window under the expected conditions in the considered study case, a relative error less than 24% by overestimation and 2% by underestimations is obtained in 90% of cases. A relative error between 4% and 14% by overestimation is obtained in 50% of cases. On the other hand, the mean relative error is 12.04% by overestimation and 1.22% by underestimation.

As extracted from the results, the relative error on thermal load by assuming a constant value of the outdoor convective heat transfer coefficient can become significant. In general, for an enclosure element with a U-value greater than or equal to 3.5 W/m2K, the relative error on thermal load could be significant. In both types of considered enclosure elements, the highest relative error is obtained by overestimation of the thermal load.

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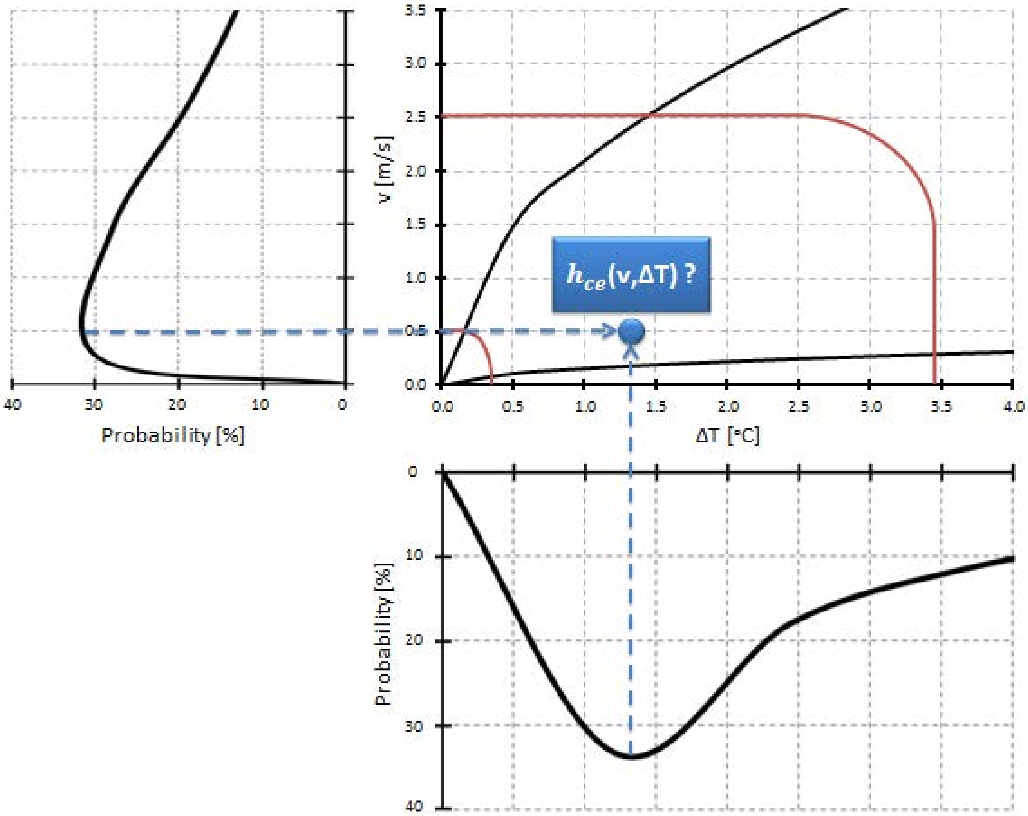

Figure 6 Outdoor convective heat transfer coefficient as a function of the expected outdoor air velocity and outdoor temperature difference between air and enclosure surface

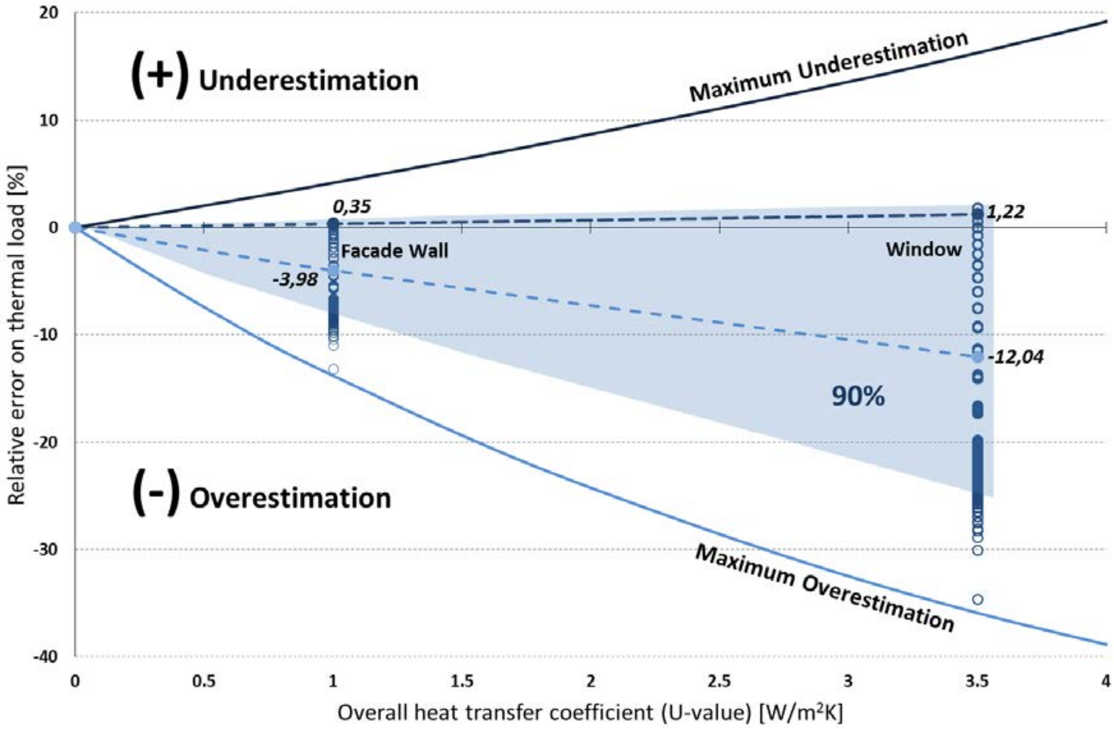

Figure 9 Relative error on the thermal load as a function of the overall heat transfer coefficient