VARIABILITY OF EXTERNAL CONVECTIVE HEAT TRANSFER COEFFICIENTS AND EFFECTS ON THE COOLING ENERGY CONSUMPTION OF BRAZILIAN ISOLATED LOW-RISE BUILDINGS

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Abstract. *Building energy analysis are sensitive to external convective heat transfer coefficients so that some researchers have conducted sensitivity calculations and proved that depending on the choice of those coefficients, energy demand estimated values can vary from 20 to 40 %. In spite of this variability, current Standards such as the Brazilian Standards Project NBR 15220-2 recommends the use of a single constant value in the calculation methods of thermal transmittance whatever are the building surface orientation and their location. The aim of the present analysis is to evaluate the variability of the external convective heat transfer coefficients in Brazil and the induced effects on the energy consumption in the case of isolated low-rise buildings. In a first part, the variability of wind characteristics is presented for several Brazilian locations. Then, the external convective heat transfer coefficients for the vertical walls and roof by recent correlations that account for wind velocity and direction are evaluated and the cooling energy consumption is calculated for an isolated low-rise building in different locations. External convective heat transfer coefficient single constant value is then determined in order to obtain the same yearly cooling energy consumption. Results show that this single value depends on the building location and that is much lower than the value proposed by the Standards Project NBR 15220-2 for Brazilian locations.*

Keywords*: external convective heat transfer coefficient, cooling energy, low-rise building, simulation.*

1. INTRODUCTION

Building Simulation tools need to better evaluate convective heat exchanges between external air and wall surfaces. Previous analysis demonstrated the significant effects of convective heat transfer coefficient values on the room energy balance. Awbi (1998) and Beausoleil-Morrison (1999) have pointed out that large discrepancies observed among widely used building thermal models can be attributed to the different correlations used to calculate or impose the value of the convective heat transfer coefficients. By performing sensitivity calculations, Beausoleil-Morrison (1999) proved that the choice of convective heat transfer coefficient values can lead to differences from 20 % to 40 % of energy demands.

Many research works have been conducted since early eighties focused on the convection heat transfer problems inside buildings. On the other hand, not much research has been focused on the determination of convective heat transfer coefficients (CHTC) at external walls. The main reason lies in the variability of wind characteristics in urban environments and more precisely around buildings. Nevertheless, experimental works have been conducted by McAdams (1954), Sturrock (1971) and, especially, Ito (1972), whose results have been incorporated for energy calculation algorithm of ASHRAE Task Group (1975). These relationships that are commonly used in building energy simulations link convective heat transfer coefficient values to local wind velocity near the surface (evaluated from the meteorological wind velocity at 10m) and surface tilt (horizontal or vertical) and, for some of them, to the wind incidence angle to the considered surface.

These last fifteen years, with the increase of computational resources, the use of CFD became more and more popular to study and solve the physical problems encountered in the built environment. In this way, Emmel *et al.* (2007) numerically studied the variation of the external CHTC related to the wind velocity (1, 5, 10 and 15m/s), the wind-to-surface incidence angle (all wind direction using a angle step value of 45°) and the temperature difference between the surface and the external air (5, 10, 15 and 20°C). Results show that external CHTC essentially depends on the wind velocity and direction, and that the temperature difference has a negligible effect for wind velocities higher than 2m/s.

The present study aims to analyze the effect of the external CHTC variability on the cooling energy consumption of an isolated low-rise building (lower than three floors) located in Brazil. In a first part, the configuration of the studied building, the correlations used to calculate the external CHTC that have been implemented in the Building Energy Simulation program PowerDomus (Mendes *et al.*, 2003) and the wind characteristics of five Brazilian locations are presented. In a second part, the cooling energy consumption of the five tested cases is then calculated taking into account the wind effect. To finish, the external CHTC single constant value is then determined in order to obtain the same yearly cooling energy consumption. Results are discussed in the last part.

2. METHODOLOGY

2.1. Building configuration and simulation parameters

For the present analysis, the studied building has been chosen according to the BESTest methodology (Judkoff and Neymark, 1995) that is a classical methodology used tot test the Building Energy Simulation programs. The building is a parallelepipedic one-zone volume of dimensions 8.0 × 6.0 × 2.7m. Compared to the original configuration, the only distinction is that the building envelope has been modified according to a wall structure more commonly found in Brazil. In this way, the vertical walls and roof are made of brick (10cm) with plaster layer on each surface (2cm). The floor (and soil) layers are: wood (1.4cm), concrete (50cm) and sandy soil (200cm). The north wall (instead of the south one in the BESTest configuration that is defined for the north hemisphere) presents two double-glazed windows whose characteristics are: surface area of $6m^2$ (each window), overall heat transmittance of $3W/m^2.K$ and a Solar Heat Gain Coefficient at normal incidence of 0.76. The ventilation system provides a constant and permanent air renewal of 1.0/h. A residential air conditioning system (described in the next section) keeps the temperature of the air lower than 24 ± 1°C. Internal heat gain of 200W is also constant and permanent. The internal CHTC is considered equal to $3W/m^2.K$. The external CHTC is calculated according to two relationships that take into account the wind velocity at a height of 10m (meteorological height), U_{10}. The first one is the MoWiTT algorithm (Yazdanian, 1994) and is used when U_{10} is lower than 1m/s.

$$h_c = \sqrt{\left(0.84 \Delta T^{1/3}\right)\left(0.84 \Delta T^{1/3}\right)^2 + \left(aU_z{}^b\right)^2} \tag{1}$$

where h_c is the external CHTC ($W/m^2.K$), ΔT is the temperature difference between the wall external surface and the ambient air (ºC), U_z is the wind velocity at altitude z (m/s) and a and b are constant values that depend on the wind incidence angle to the considered surface. Values are a=2.38 and b=0.89, and, a=2.86 e b=0.617, for incidence angle lower and higher than 90º, respectively.

The wind velocity at altitude z can be evaluated through the expression given by Counihan (1975):

$$\frac{U_z}{U_{10}} = \left(\frac{z}{z_{10}}\right)^{\alpha} \tag{2}$$

where U_{10} is the wind velocity at altitude z_{10}=10m (m/s) and α is a constant that depends on the ground roughness at the location of the building. This roughness is a function of the neighboring building density. In the present case of an isolated building, α is considered equal to 0.14.

When U_{10} is higher than 1m/s, the external CHTC is evaluated by the correlations of Emmel *et al.* (2007):

$$h_c = aU_{10}{}^b \tag{3}$$

where a and b are coefficients that depend on the wind incidence angle to the considered surface, θ, and the inclination of the surface (vertical or horizontal such as roof). Table 1 presents the values of the two coefficients; those correlations are valid for wind velocity from 1 to 15m/s and temperature difference between the wall external surface and the ambient air lower than 10°C.

Table 1. External CHTC (Emmel *et al.*, 2007).

	θ (°)	a	b
Vertical wall	0	5.15	0.81
	± 45	3.34	0.84
	± 90	4.78	0.71
	± 135	4.05	0.77
	± 180	3.54	0.76
Roof	0	5.11	0.78
	± 45	4.60	0.79
	± 90	3.67	0.85

The spatial and temporal discretizations, required by the Building Energy Simulation (BES) program PowerDomus (Mendes *et al.*, 2003) to solve the one-dimensional heat transfer through the building envelope using the finite-volume methodology, have been defined according to Abadie and Mendes (2006) for pure heat transfer problems (without combined moisture transfer). A finite-volume length of 1cm and a time step of 1min have been chosen for the present analysis. In order to remove the unwanted effect of initial conditions on the results, simulations have been performed for 2 years, the last one being used to extract the actual results.

2.2. Characteristics of the air conditioning system

BES programs such as PowerDomus (Mendes *et al.*, 2003) usually employ empirical modeling of air conditioning equipment based on performance data tables provided by manufacturers. However, manufacturers of residential system usually do not give such information but present the system performance for a unique normative condition (ISO 5151, 1994). This fact has encouraged the development of empirical models appropriated for integration into BES programs. Those models, obtained by regression analysis, provide the total cooling capacity (*CT*), the sensible cooling capacity (*CS*) and the energy efficiency ratio (*EER*). Those characteristics are calculated as functions of the wet-bulb (tw_{in}) and dry-bulb (t_{out}) temperatures of the indoor and outdoor air, respectively.

The modeled air conditioning system is a window-type equipment with rotating compressor: *CT*=9900Btu/h, *CS*=5871Btu/h and *EER*=9.4Btu/hW at standards conditions (tw_{in}=19.4±0.2°C and t_{out}=35.0±0.3°C). The system performance is determined for other conditions through the use of dimensionless coefficients (*Z*) for the total cooling capacity, the sensible cooling capacity and the energy efficiency ratio, defined by:

$$Z_{CT}, Z_{CS}, Z_{EER} = \frac{(CT, CS, EER)^{tw_{in}, t_{out}}}{(CT, CS, EER)^{19.4°C, 35.0°C}} = a_0 + a_1 tw_{in} + a_2 tw_{in}^2 + a_3 t_{out} + a_4 t_{out}^2 + a_5 tw_{in} t_{out} \quad (4)$$

where the coefficients a_i (*i*=0 to 5) are given in Table 2.

Table 2. Coefficients of Eq. (4).

Z	a_0	a_1	a_2	a_3	a_4	a_5	R^2
CT	-0.64923733	0.06520502	-0.00109588	0.04668802	-0.00101406	0.00058685	0.989
CS	0.25358180	-0.26485570	0.00494079	0.16734804	-0.00261926	0.00184341	0.701
EER	-0.38608209	0.13043817	-0.00139126	0.01649467	-0.00044456	-0.00094456	0.989

Figure 1 presents the dimensionless energy efficiency ratio (Z_{EER}) variation according to the ambient conditions. As illustrated in the figure, the energy efficiency of the chosen air conditioning system increases with a decrease of t_{out} and an increase of tw_{in}. This energy efficiency increase is due to the higher difference between the evaporation temperature and the air temperature at the evaporator inlet and, to the higher latent load when the indoor wet-bulb temperature is high.

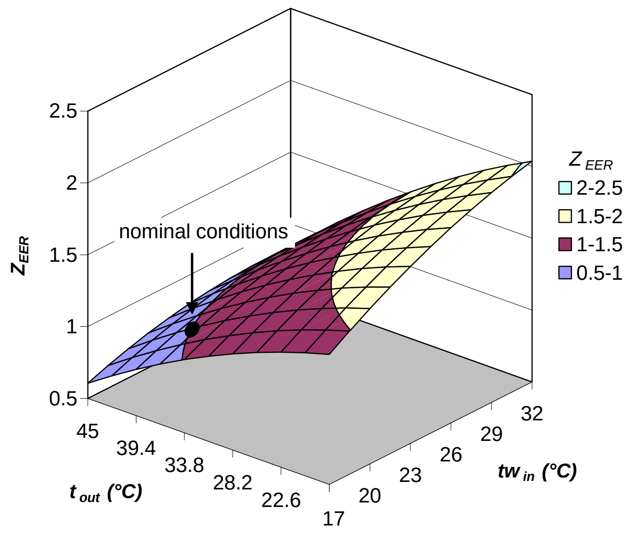

Figure 1. Dimensionless energy efficiency ratio (Z_{EER}).

2.3. Wind characteristics for the chosen Brazilian locations

For the present study, five locations have been chosen: Belém, Brasília, Cuiabá, Curitiba and Florianópolis,. They have been chosen to represent a good variation of weather (essentially focused on wind velocity) encountered in Brazil. The TMY weather files available on the BES program Energy Plus website (2008) have been used here. Table 3 presents the wind mean velocity and most frequent direction for those five locations. Wind velocity varies from 3.3m/s for Florianópolis to 2m/s for Cuiabá. The predominant direction is north for all locations except for Curitiba where east is as frequent as north.

Table 3. Wind velocity and direction.

	Belém	Brasília	Cuiabá	Curitiba	Florianópolis
Mean velocity ± standard deviation (m/s)	2.4 ± 2.2	2.1 ± 2.5	2.0 ± 2.1	3.0 ± 2.4	3.3 ± 3.0
Wind direction (frequency)	N (42%) NL (21%) L (20%)	N (44%) NL (11%) L (16%)	N (62%) NL (6%) NO (10%)	N (24%) L (25 %) SL (20%)	N (40 %) SL (9%) S (14%)

2.4. Simulated cases

A first phase of simulations aims to calculate the cooling energy consumption of the air conditioning system presented above for the five locations accounting for the effect of the wind on the external CHTC values (through Eqs. (1) and (2)). A second phase has the objective of determining an external CHTC single constant value that leads to the same yearly cooling energy consumption obtained in the first phase. So a parametric study is performed to analyze the variation of the cooling energy consumption with the external CHTC varying its value from 5 to 25W/m^2.K, using an increment of 2W/m^2.K.

3. RESULTS

3.1. Cooling energy consumption

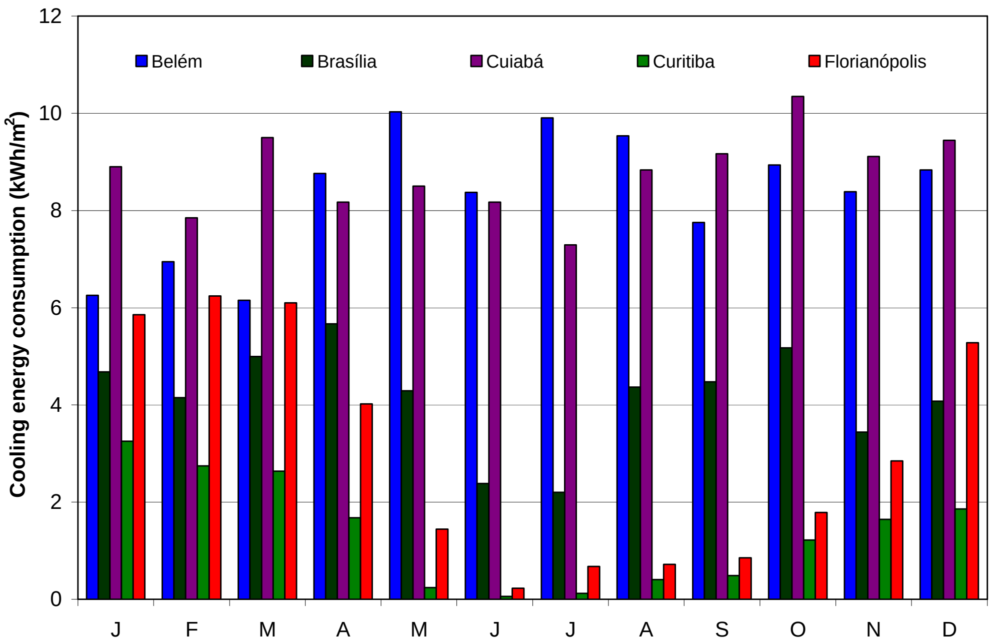

Figure 2. Monthly cooling energy consumption.

Table 4. Yearly cooling energy consumption (per square meter of floor area).

	Belém	Brasília	Cuiabá	Curitiba	Florianópolis
Yearly cooling energy consumption (kWh/m^2)	99.87	49.89	105.29	16.35	36.05

Figure 2 presents the monthly cooling energy consumption for the five locations accounting for the effect of the wind on the external CHTC values. As observed in this graph, the southern locations (Curitiba and Florianópolis) present a real winter and summer seasons. For the last period, the second location presents consumption twice as high as the first one. In the case of Brasilia, the mid-seasons (spring and autumn) are the ones that require cooling. The two northern locations need the higher and mostly constant cooling energy during the entire year.

Table 4 presents the yearly cooling energy consumption. Cuiabá and Belém present the highest cooling energy consumptions that are twice as high as that of Brasília. Smaller values are observed for the two southern locations.

3.2. External CHTC effect

Figure 3 presents the variation of the yearly cooling energy consumption as a function of the external CHTC value (one constant single value imposed to all the envelope external surfaces). The filled-circle symbols represent the yearly cooling energy consumption obtained using the wind-dependent external CHTC. The dotted line shows the minimum value of the external CHTC imposed by the Brazilian Standards Project NBR 15220-2 (ABNT, 2004). This value has been calculated from the Standards value of 25W/m^2.K that accounts for both convective and radiative heat transfer. The maximum value of the linearized radiative coefficient has been calculated using the following equation:

$$h_r = 4\sigma\varepsilon\left(\frac{T_{surf} + T_{out}}{2}\right)^3 \tag{5}$$

where σ is the Stefan-Boltzmann constant (5.67×10^{-8}W/m^2.K^4), ε is the envelope external surface emissivity (assumed to be close to 0.9), T_{surf} is the envelope external surface temperature (K) and, T_{out}, the outdoor air temperature (K) .

The mean temperature between the envelope external surface and the outdoor air has been obtained from the simulations with wind-dependent external CHTCs. For example, in the case of Curitiba, the maximal mean temperature is 21±6°C with a maximum value of 40°C. Those values lead to the maximum value of the linearized radiative coefficient of about 6W/m^2.K and, as a consequence, to a minimum value of the external CHTC of 19W/m^2.K.

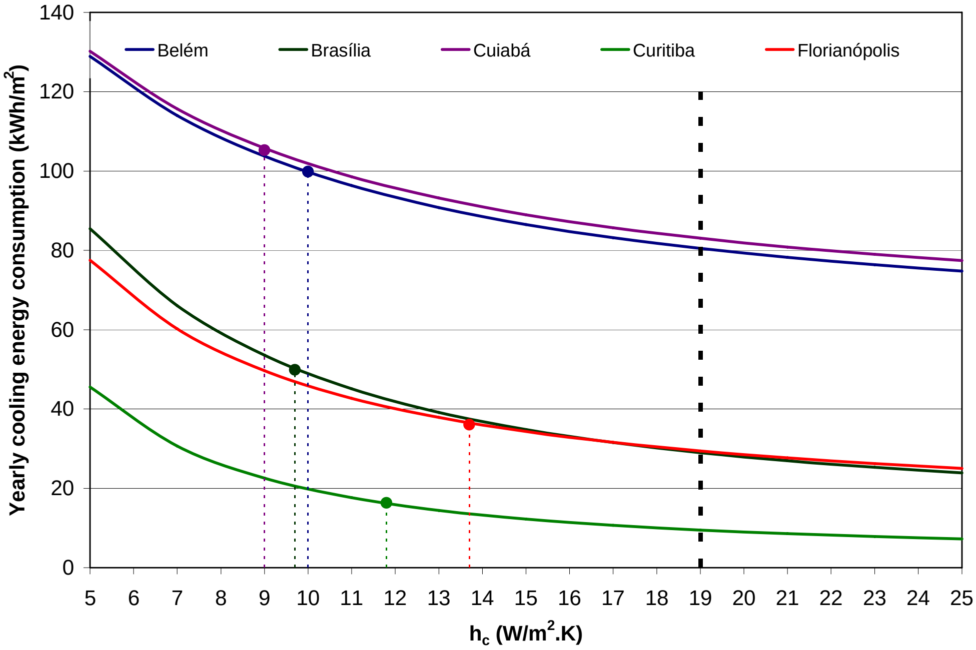

Figure 3. Yearly cooling energy consumption as a function of the external CHTC imposed value.

As observed in Fig. 3, the yearly cooling energy consumption is a decreasing function of the external CHTC imposed value. This is due to the fact that the outdoor air temperature is almost always lower than the envelope external surface temperature (especially when there is important solar radiation, for which cooling is needed); hence the external convective transfer helps cooling down the building envelope and reducing the air conditioning energy consumption.

This passive cooling of the wind is particularly efficient for external CHTC low values (external CHTC lower than 19W/m^2.K i.e. for wind velocity lower than about 3.5m/s). Note that the trend would be inversed in the case of heating energy.

Figure 3 illustrates also the relatively high variability of the constant single external CHTC needed to be imposed to all envelope external surfaces to obtain the same value of yearly cooling energy consumption. As shown in Table 5, values vary from 9.0 to 13.7W/m^2.K for the chosen Brazilian locations. Another observation is the large difference between the obtained values and the nominal one. This difference would lead to an underestimation of 20 to 40% of the yearly cooling energy consumption.

Table 5. Constant single external CHTC.

	Belém	Brasília	Cuiabá	Curitiba	Florianópolis
Constant single external CHTC value (W/m^2.K)	10.0	9.7	9.0	11.8	13.7

4. DISCUSSION

The results presented in the previous section are limited to the studied isolated low-rise building. Additional simulations have been done including a 5cm-thick insulation layer between the brick and the internal plasterboard ones in order to decrease the envelope thermal transmittance as the chosen studied building presents what can be considered as a higher thermal transmittance. Table 6 presents the obtained values. Compared to the original studied building, there is a small but notable decrease of the constant single external CHTC. Note that the variability also decreases from 4.7 to 1.3W/m^2.K in this case.

Table 6. Constant single external CHTC – studied building with insulation layer.

	Belém	Brasília	Cuiabá	Curitiba	Florianópolis
Constant single external CHTC value (W/m^2.K)	8.9	8.8	8.2	9.7	10.2

Hence, it can be concluded that the normative value for external CHTC is too high to evaluate the cooling energy consumption of isolated low-rise buildings. At this point, it is important to recall that the Brazilian Standards Project NBR 15220-2 is based on the ISO 6946 (ISO, 1996) Standard. This Standard recommends the use of an already mentioned combined convection and radiation heat transfer coefficient of 25W/m^2.K in the absence of specific information on the boundary conditions, which leads to an external CHTC value of about 19W/m^2.K. This Standard also provides a note that this value is based on a wind velocity between 4 and 5m/s. Considering the wind velocity values presented in Table 3, for the five chosen Brazilian locations, the external CHTC value of 19W/m^2.K actually seems unreasonably high. The higher ISO value is actually correlated to the actual wind velocity encountered in the northern hemisphere regions. Figure 4 presents the annual 10m wind velocity for terrain similar to airports averaged over the July 1983-June 1993 period. This world wind map is derived from the Surface meteorology Solar Energy (SSE) data (NASA, 2004). One can observe that Brazil presents wind velocities between 0 and 4.5m/s whereas the United States of America and Europe are locations with higher velocities, from 2.7 to 7.0m/s.

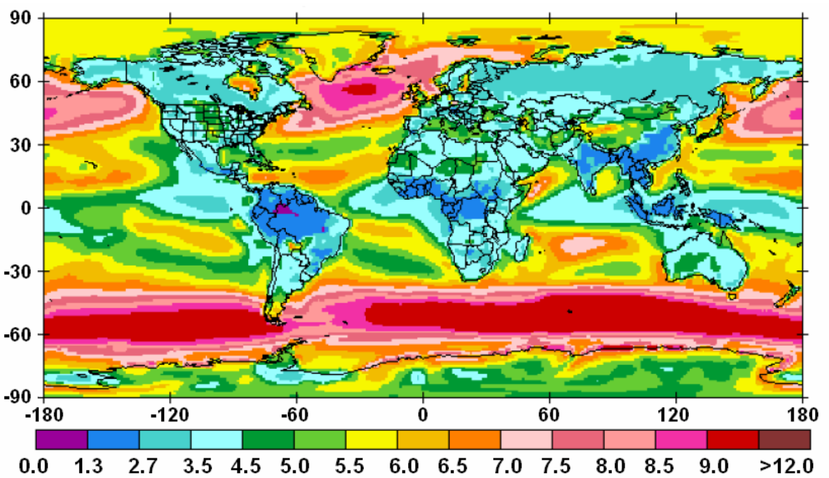

Figure 4. Annual 10 wind velocity for terrain similar to airports (July 1983-June 1993).

More precisely, Table 7 presents a comparison of the wind mean velocity at 10m high for the three mentioned world regions: Brazil, USA and Europe. These statistics have been calculated from the TMY files available on the EnergyPlus BES program's website (EnergyPlus, 2008) using 24 locations for Brazil, 275 ones for USA and 179 ones for Europe (34 countries). As observed, there is a huge difference of wind resources between Brazil and the two northern hemisphere regions. In fact, those statistics can explain the ISO Standard value of 19W/m^2.K.

Table 7. Wind mean velocity around the world.

	Brazil	USA	Europe
Mean velocity ± standard deviation (m/s)	2.4 ± 1.0	4.1 ± 1.2	3.8 ± 1.7

In order to test that possible reason, three additional simulations have been performed for three locations of USA: Miami, Oklahoma City and Dodge City. Those three locations have been chosen because they present wind mean velocity equal or higher than the mean value found in USA. In those simulations, the windows have been placed on the southern wall in order to enable direct solar loads. Table 8 presents the obtained constant single external CHTC values along with the wind mean velocity and cooling energy consumption ones. It can be observed the external CHTC values are much closer to the standardized value than those found for Brazilian weather files.

Because of the high thermal transmittance of typical Brazilian building envelopes, the behavior of the indoor environment, its cooling energy consumption in particularly, is more dependent on the CHTC values than the more isolated building envelopes encountered in Europe and USA. Then, it can be concluded that a more suitable external CHTC value for Brazil would be around 14W/m^2.K so that the combined (convective and radiative) surface resistance should be changed to 0.05m^2.K/W, instead of the current value of 0.04m^2.K/W.

Table 8. Constant single external CHTC – studied building located in the USA.

	Miami	Oklahoma City	Dodge City
Mean velocity ± standard deviation (m/s)	4.1 ± 2.2	4.7 ± 2.5	6.3 ± 2.8
Yearly cooling energy consumption (kWh/m^2)	145.7	64.9	41.9
Constant single external CHTC value (W/m^2.K)	15.0	16.0	19.5

5. CONCLUSION

The present study intended to analyze the variability of the external CHTC and its effects on the cooling energy consumption of a Brazilian isolated low-rise building.

It has been shown that the yearly cooling energy consumption is a decreasing function of the external CHTC and that, because the external CHTC is an increasing function of the wind velocity, buildings located in region that presents high wind velocity can benefit of this passive cooling effect.

More importantly, the present analysis showed that the single constant value to be applied to all external surfaces in order to obtain the same cooling energy than the one calculating with wind-dependent external CHTC varies from location to location and that it is much lower than the Brazilian Standards Project NBR 15220-2 (ABNT, 2004). Results showed that this difference would introduce an underestimation of the cooling energy consumption higher than 20% for the studied cases using the standardized values.

The main conclusion is that a correction to the current value of 0.04m^2.K/W used for the combined surface resistance by the Brazilian Standards Project NBR 15220-2 (ABNT, 2004) should be done to increase it to 0.05m^2.K/W.

The limitation of the present study essentially lies in the studied building configuration, which is an isolated low-rise building. Results for high-rise buildings may differ as the wind velocity (and the external CHTC) will increase with height. Additional simulations with *ad hoc* external CHTC are then required to complete the present analysis. The effect of neighboring buildings on the wind velocity should be also included in the study to evaluate the variation of the external CHTC for city centers and take into account the urban canyon effect.

6. ACKNOWLEDGEMENTS

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5. RESPONSIBILITY NOTICE