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Thermal simulation of a double skin façade with plants

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Abstract

Using plants in building walls is a bioclimatic strategy to obtain savings in building energy consumption, between other important benefits of aesthetic, psychological and economic origins. The plant, as a living component of the facade, responses to the environment conditions in a very complicated way. The simulation of this response is not straightforward and some simplifications are needed in order to include it as a building component. The aim of this paper is to present two alternative simplified models to simulate a green wall with EnergyPlus. A discussion about why the green roof model cannot be used in a vertical green façade is also included. Both models are used to simulate a prototype with a green façade. Inside and outside glass temperatures, plant foliage temperature, and window heat gain and losses are calculated. The results are discussed and recommendations for simulating green façades are done.

Keywords: double skin façade; green façade; plants; thermal simulation

1. Introduction

The popularity of vertical greenery is growing up because it is certainly an alternative to roof greenery in big cities where tower blocks predominates. The high wall to roof ratio implies a large potential surface area for greening. Moreover, facade walls, unlike rooftops, usually have no insulation layer against solar heat [1]. Using plants as shading devices is better than using conventional devices because the surface temperature of leaves is lower than the surface temperature of the shading material. The reason lies in the solar radiation absorbed by plants: around 60% of the absorbed radiation is turned by plants into the latent heat. Thus, plants transform the absorbed solar radiation into sensible and latent heat, while a conventional device transforms the absorbed solar radiation in sensible heat, that is, its temperature increases more than in a plant. Pérez *et al.* [2] summarizes the mechanisms of green facades when are

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used as passive system for energy savings: interception of solar radiation by the shadowing effect of the vegetation, thermal insulation provided by vegetation, evaporative cooling that occurs by evapotranspiration from the plants and the substrate, and variation of the effect of the wind on the building.

The plant, as a living component of the facade, responses to the environment conditions in a very complicated way. The simulation of this response is not straightforward and some simplifications are needed in order to include it as a building component. Significant contributions were made in the last years, and only a few are cited here. Kontoleon and Eumorfopoulou [3] investigated the thermal behaviour of a building zone that incorporates a plant-covered wall by employing a thermal-network model. Ip *et al.* [4] studied the solar transmittance during the year of a vertical deciduous climbing plant canopy and they proposed the use of a dynamic Bioshading Coefficient Function representing the shading performance of the climbing plant canopy over a year. Stec *et al.* [5] developed a simulation model of a double skin facade with plants in the interior of a cavity that was validated with experimental data obtained in a laboratory test facility.

EnergyPlus is a free software developed by LBNL (Lawrence Berkeley National Laboratory) and it is currently the official software for building simulation of the USA Department of Energy. The version 7.1 includes a module to estimate the thermal behavior of a green roof but the simulation of a green wall is not included. The aim of this paper is to present two alternative simplified models to simulate a green wall with EnergyPlus. A discussion about why the green roof model cannot be used in a vertical green façade is also included. Both models are used to simulate a prototype with a green façade. Inside and outside glass temperatures, plant foliage temperature, and window heat gain and losses are calculated. The results are discussed and recommendations for simulating green façades are done.

2. Modeling a green wall with EnergyPlus

2.1. Breaf description of the heat transfer mechanisms in a green wall

The energy balance of a green wall is complex because the plants are living beings and they suffer adaptations to the environment, which are not simple to predict. The temperature of plants depends on non-biotic (physical) parameters (i.e. the boundary layer resistance for heat transfer by convection and radiation and the boundary layer resistance to water vapor), as well as with the biological parameters (i.e. the actual stomatal resistance, water content of leafs, etc. [6]. The heat transfer processes involved in the energy balance of the leaf are: solar radiation absorption, sensible heat exchange by convection between the leaf and the surrounding air, infrared energy exchange between the leaf and the surroundings, latent heat expelled by the plant by transpiration, store of energy in tissues, conduction through the leaf (usually negligible), and energy for metabolic processes necessary for photosynthetic or catabolic reaction (for most situations in nature the energy losses due to metabolic processes are relatively small and neglected in the calculations). Because the high thermal conductivity of the leaf tissue, the upper and lower surface temperatures of a leaf can be assumed identical. From the energy balance perspective, a green façade can be simplified if it is thought as a unique "big leaf". Thus, a green façade can be considered as a vertical element involved in the energy balance of a glazed or opaque wall as shown in Fig. 1 for a glazed wall. An air channel is formed between the building and the green façade, with the air in the cavity being represented by a temperature T_c. The solar radiation I_s incident on the green façade is partially absorbed by the foliage and partially transmitted. Part of the absorbed energy is transformed into latent heat, causing transpiration to appear in the leaves' surfaces, and part into sensible heat, causing an increase in the foliage temperature. Heat is transferred by convection from both sides of the foliage layer to the adjacent air, described by the heat transfer coefficients h_f and h_{glass}. Heat exchange of the foliage with surrounding surfaces by radiation is represented by I_{ir}.

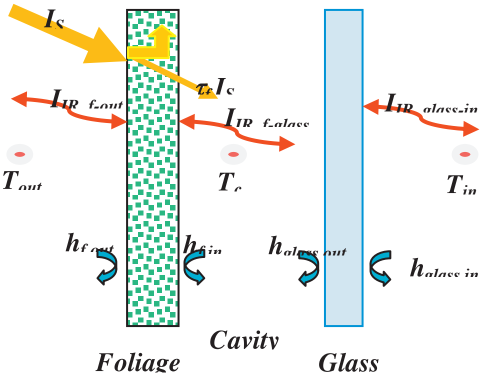

Fig 1. Heat transfer mechanisms in the double facade with plants.

2.2. Why the green roof model cannot be used for a green façade?

EnergyPlus include a module to estimate the thermal behavior of a green roof, based on the energy balance in the foliage layer given by [7]:

$$F_f = \sigma_f \left[I_s (1-\rho_f) + \varepsilon_f I_{ir} - \varepsilon_f \sigma T_f^4 \right] + \frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_g + \varepsilon_f - \varepsilon_g \varepsilon_f} \left(T_g^4 - T_f^4 \right) + H_f + L_f \qquad (1)$$

where F_f is the net heat flux to foliage layer (W/m^2), σ_f is the fractional vegetation coverage of the soil, ρ_f and ε_f the short wave reflectivity and emissivity of the canopy, I_s and I_{ir} the total incoming short wave and long wave radiation (W/m^2) respectively, σ the Stefan-Boltzmann constant (5.699x10^{-8} Wm^{-2}K^{-4}), ε_g the emissivity of the ground surface, T_g the ground surface temperature (K), T_f the leaf temperature (K), H_f the sensible heat transfer between the leaf surface and near-canopy air, and L_f the latent heat flux in the foliage layer. Eq. (1) shows that the heat flux between the ground and the foliage layer depends on: the ground albedo, the radiative long wave exchange between the ground and the foliage, the sensible heat H_f (through the dependence with T_g of the air temperature within the canopy), and the latent heat T_f (through the dependence of the soil moisture content at the root level). The interested reader can find more details of the governing equations in the software manual. Thus, an EnergyPlus user could think that a green façade could be modeled by using the green roof model in a vertical fashion, and making the soil properties (conductivity, density, specific heat at constant pressure, thermal emissivity and albedo) similar to the wall properties, but this is not true. When inspecting Eq. (1), it is evident that this model cannot be used in a vertical fashion to simulate a green facade because of the following reasons:

- All sun exposure of surfaces behind the green roof is eliminated by the model, thus, it is not possible to simulate the solar radiation transmitted by the green facade.

- The radiative heat exchange between the foliage and the soil is calculated for a soil temperature T_g and emissivity ε_g. Making the soil properties similar to the wall properties only changes ε_g, but the temperature T_g is still the ground temperature defined during the input stage and it does not represent the wall surface temperature.
- Finally, the convective heat transfer coefficients between the foliage and the soil are automatically calculated by the code (the user is not allowed to change them) from special relationships that are valid for horizontal grass. These coefficients are not adequate for vertical plants.

2.3. Can a shading element placed in front of a wall/glass simulate the behavior of a green façade?

2.3.1. Model 1: using a Building Shading Object (BS)

A first approximation to the problem is to simulate a green wall is to consider the green wall as a building shading device (BS), with the transmittance of the foliage layer. We named this situation as “Case BS”. In EnergyPlus, a Building Shading object is defined by its geometry (it can be a simple rectangular shape or a more complicated one) and a transmittance schedule (transmittance is assumed to be the same for both beam and diffuse solar radiation). The user can optionally input constant values of visible and solar reflectivities. The most important effect of shading surfaces is to reduce solar gain in windows or surfaces that are shadowed. Shading surfaces also automatically shade diffuse solar radiation (and long-wave radiation) from the sky. This element does not typically have enough thermal mass to be described as part of the building’s thermal makeup, that is, it is not involved in heat transfer calculations.

Because the presence of the green façade modifies the wind velocity near the covered wall, the convective heat transfer coefficient must be calculated previously fom correlations between Nusselt, Grashoff and Reynolds numbers, as proposed by [5]:

$$Nu=0.405\,(Pr\,Gr + 6.92 Pr Re^{2})^{0.25} \tag{2}$$

EnergyPlus assumes that shading devices are opaque to long-wave radiation no matter what the solar transmittance value is. Because plants have large long-wave absorptance (around 0.95) they can be roughly treated as opaque elements in the infrared range. The view factors to the sky and ground for thermal infrared (long-wave) radiation are not user inputs; they are calculated within the software based on surface tilt and shadowing surfaces. Shadowing surfaces are considered to have the same emissivity and temperature as the ground, so they are lumped together with the ground in calculating the ground IR view factor.

Another important observation in relation to using a Building Shading Object is that the shading of ground diffuse solar radiation is not calculated by the program (even if transmittance is set to 1). EnergyPlus Manual warns that *it is up to the user to estimate the effect of this shading and modify the input value of the surface-ground view factor accordingly* [7]. This mean that reflected ground diffuse solar radiation will not be transmitted by the foliage layer if the user does not take the corresponding precautions. To include this transmission, the wall and window view factor must be calculated and multiplied by the transmittance of the plant foliage. This value must be used as a “ficticious” view factor F_{sg} to account for the transmittance of ground diffuse solar radiation (to allow the code using the user-input view factor, FullInteriorAndExterior option for Solar Distribution should be used).

Thus, the BS model simulates the green façade as a building shading surface placed parallel to the wall (or window), with a solar transmittance equal to the green façade transmittance, solar and visible reflectances equal to those of the green façade, with a modified convective heat transfer coefficient *h* for the covered glazed surface, and with a "ficticious" view factor of the covered wall equal to the real view factor value multiplied by the solar transmittance of the green façade.

2.3.2. Model 2: using a Window Shading Device Object (WSD)

A second option to simulate the thermal behavior of a green façade is by using a Window Shading Device. Shading devices affect the system transmittance and glass layer absorptance for short-wave radiation and for long-wave (thermal) radiation. The effect depends on the shade position (interior, exterior or between-glass), its transmittance, and the amount of inter-reflection between the shading device and the glazing. Also of interest is the amount of radiation absorbed by the shading device and its temperature. A window shading in EnergyPlus is a layer assumed to be parallel to the glazing and it is defined with the object WindowMaterial:Shade (Fig. 2). The soft calculates the natural convective air flow between the glass and the shade produced by buoyancy effects and the corresponding convective heat transfer coefficient, and the radiative heat transfer between the shade and the glass. Shades are considered to be perfect diffusers (all transmitted and reflected radiation is hemispherically-diffuse) with transmittance and reflectance independent of angle of incidence. The program calculates how much long-wave radiation is absorbed by the shade and by the adjacent glass surface. Reflectance and emissivity properties are assumed to be the same on both sides of the shade.

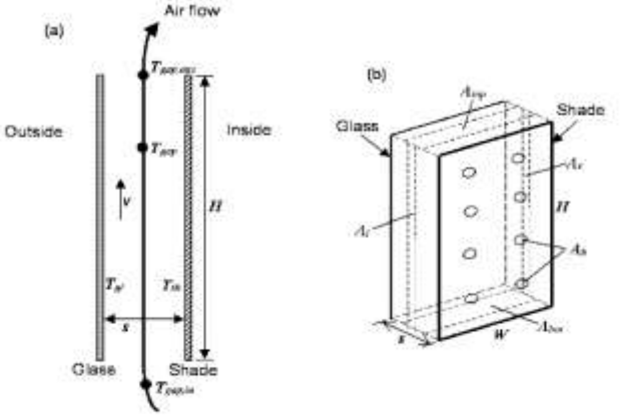

Fig 2. Vertical section (a) and perspective view (b) of glass and interior shade layers showing variables used in the gap air flow analysis. In (b), the air-flow opening areas A_{bot}, A_{top}, A_l, A_r and A_h are shown schematically. Source: Manual of EnergyPlus [7].

WindowMaterial:Shade requires the following inputs: solar and visible transmittances and reflectances, thermal hemispherical emissivity, thermal transmittance, thickness, conductivity, shade to glass distance, top/bottom and left/right opening multipliers (effective areas for air flow at the top/bottom or left/right of the shade divided by the horizontal or vertical area between glass and shade, respectively), and airflow permeability (the total area of openings in the shade surface divided by the shade area).

Because around 60% of the short wave radiation absorbed by the leaf is transformed into latent heat [5], a very simplified way to simulate this behavior is to consider that the 40% of the absorbed energy is transformed into sensible heat. That is, the absorptance of the shading element should be corrected to 0.4 α_f, where is the real absorptance of the green façade. Because inputs for the WindowMaterial:Shade element is reflectance (instead absorptance), the value to be entered is ρ=1-0.4$\alpha_f - \tau_f$.

This model allows estimating the thermal resistance of the green façade. The conductive thermal resistance $R_{cond,glass}$ (m^2 K/W) of a single glass layer is defined as e_{glass}/k_{glass} where k_{glass} is the thermal conductivity of the glass in W/(m K) and e_{glass} its thickness in m. Alternatively, it can be calculated as $R_{cond,\, glass} = \Delta T/q$, where ΔT is the temperature difference (K) between outside and inside glass surface temperatures and q the heat transferred (W/m^2) in steady state, that are variables available as simulation outputs. In the case of adding a green façade, the resulting equivalent thermal-electric circuit is shown in Fig. 3, where the dots represent the nodes of temperature: $T_{glass,in}$ and $T_{glass,out}$ are the indoor and outdoor glass surface temperatures, T_c the air temperature inside the cavity, and T_f the temperature of the green façade. Convective and radiative resistances are defined as usual in the literature [8]. The effective thermal resistance of a wall (o glass) with a green façade can be calculated as:

$$R_{eff} = R_{cond,glass} + R_{green\_facade} = \frac{Tf - T_{glass,in}}{q} \tag{4}$$

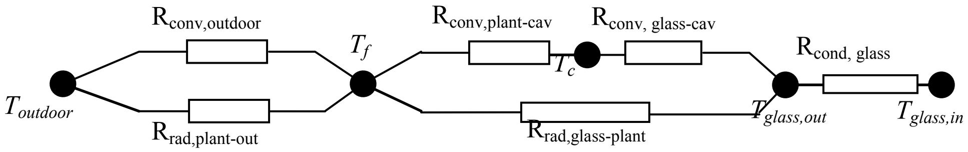

Fig. 3. Thermal-electric equivalent circuit of the green façade.

3. Results

3.1. Description of the simulated prototype

A prototype of 2.4m height, with a floor area of 5m x 5m, was simulated with EnergyPlus V7.1. The prototype was placed in Salta city (24.85º S, 65.48º W, 1216 m o.s.l.) in the Northwest region of Argentina. The West façade is a single-glazed wall with a plant façade covering the whole window at a distance of 0.03m (glazed area A_f= 10.56m^2). Air renewals per hour were set to 1 and the thermal zone was thermostatized at 20ºC. The green façade solar and visible transmittance, absorptance and reflectance changes during the year because the foliage is denser in summer than in winter, and because the intrinsic properties of the leaves also change. In this case the simulation is performed in summer and these properties are assumed constant for the simulation period, with average values given by the literature [9]: $\tau_{f,solar}$ =0.2, $\alpha_{f,solar}$=0.5 and $\rho_{f,solar}$ = 0.3, $\tau_{f,vis}$ =0.06, $\alpha_{f,vis}$=0.85, $\rho_{f,vis}$ = 0.09. The thermal emissivity and reflectance of the plant were ε_f = 0.95 and $\rho_{f,ir}$ = 0.05. The prototype was simulated under average summer conditions, in December. The mean summer climate conditions of the location provided by the National Meteorological Service are: mean minimum and maximum temperatures of 15.2 and 28.3ºC, respectively, absolute maximum temperature of 38.4ºC, mean daily solar irradiance on horizontal surface of 19.2 MJ/(m^{2}day), heliophany of 0.4, mean wind velocity of 1.7 m/s, and mean relative humidity of

71%. Fig. 4 shows the hourly temperature and solar irradiance on horizontal surface and on vertical surface facing West, for an average day of December.

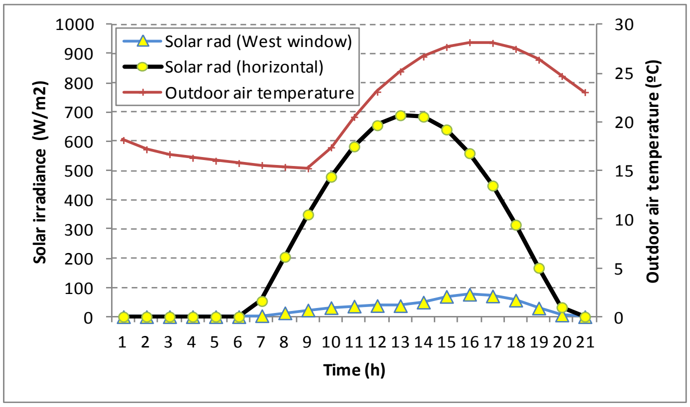

Fig. 4. Hourly outdoor air temperature (ºC) and solar irradiance (W/m^2) on a horizontal surface and on a vertical surface facing West, for an average day of December in Salta city, Argentina (24.85º South latitude, 65.48º West longitude, 1216 m o.s.l.).

Table 1. Optical and thermal properties of the green wall simulated with the BS and WSD models.

Properties for the BS model

4. Shading Building Object	Solar transmittance	0.2
	Solar reflectance	0.3
	Visible reflectance	0.09
5. Window glass surface	View factor to ground	0.1
	Convective coefficient W/(m^{2}K)	6

Properties for the WSD model

Property	*Value*
Solar transmittance	0.2
Solar reflectance	0.3
Visible transmittance	0.06
Visible reflectance	0.09
Thermal emissivity	0.95
Thermal transmittance	0
Thickness	0.001
Conductivity (W/mºC)	0.59
Shade to Glass Distance (m)	0.3
Top Opening Multiplier (m)	1
Bottom Opening Multiplier (m)	1
Left-side Opening Multiplier (m)	1
Rigth-side Opening Multiplier (m)	1
Airflow permeability	0

The green façade was simulated with both models (BS and WSD), and the optical, geometric and thermal properties of these elements are given in Table 1. In the BS model, the convective coefficient was estimated from Eq. (2). The view factor F_{sg} between the vertical glazed surface and the ground is 0.5. Because the solar transmittance of the green façade is 0.2, a “ficticious” view factor of 0.1 was used for the glazed surface.

5.1. Simulation

For both models (BS and WSD), the solar energy transmitted by the window, the window heat loss, outside and inside glass surface temperatures, and green façade temperature resulting from de WSD model, are shown in Figs. 5 to 8. The results corresponding to a bare window are also shown.

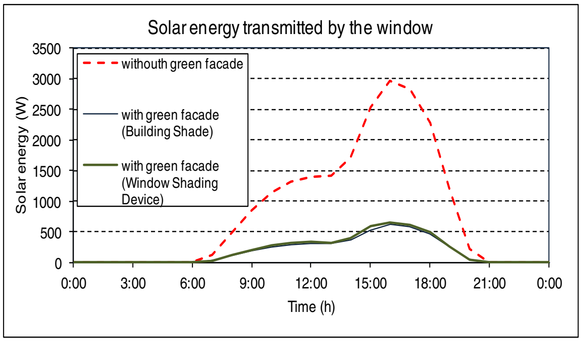

Fig. 5. Solar energy (W) transmitted by the window for both models. The solar energy transmitted by a bare window (without the green façade) is also shown.

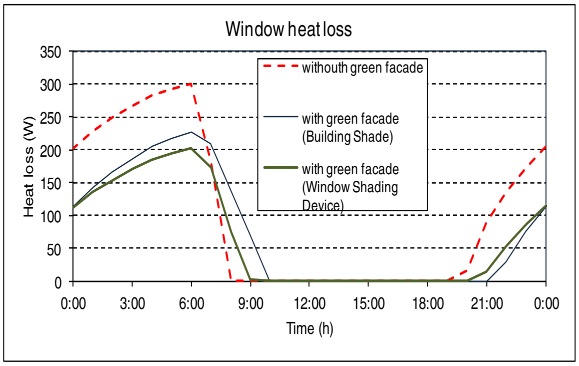

Fig. 6. Window heat loss (W) predicted by BS and WSD models. The window heat loss of a bare window (without the green façade) is also shown.

Fig. 5 shows that both models predict similar amounts of solar energy transmitted by the window to the zone, with the maximum value at 16:00 due to the West orientation of the vertical façade. The energy transmitted by a bare window is around 6.9 MJ/(m^{2}day) while the energy transmitted by the window covered by the green façade is around 1.4 MJ/(m^{2}day). Fig. 6 shows the window heat losses: for the bare window, heat loss is negligible during the sun hours, reaching a maximum value of 300W (equivalent to 28W/m^2) immediately after the sunrise. When comparing the heat losses predicted by both models, it is evident that modeling the green façade as a Building Shade results in 12% higher window heat losses when compared with the WSD model. The reason is that higher in the BS model the radiative exchange is calculated for the glass facing an isothermal surface with emissivity and temperature equaled to the ground emissivity and the ground temperature (assumed constant), while the real exchange is between the glass and the plant façade. In the WSD model the radiative heat transfer is calculated in a more realistic way as occurring between the glass and the shading device (the plant), where the emissivity of the plant was defined by the user, and the plant temperature is variable and calculated by the code. Also there are differences in the heat convection coefficient of the glass for each model. It can be concluded that window heat loss (0.8MJ/m^2-day) is higher for bare window than for a plant covered window (0.5 MJ/m^2-day), and that covering a single-glazed window with plants reduces the heat losses around 37% with respect to the bare window.

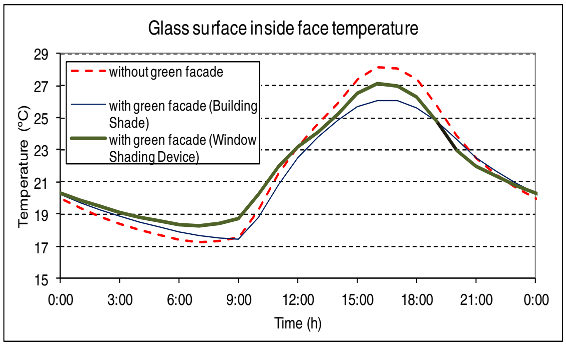

Fig. 7. Inside face temperature of the glass (ºC) predicted by BS and WSD models. The behavior of a bare window (without the green façade) is also shown.

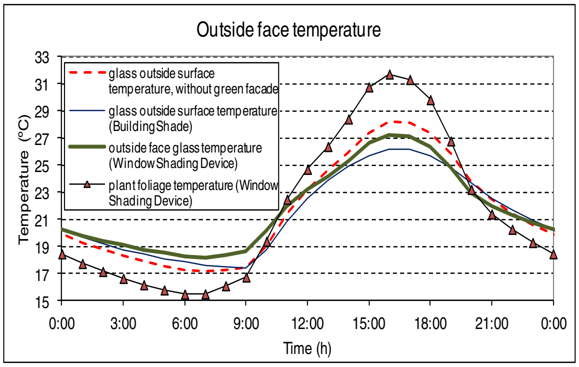

Fig. 8. Outside face temperature of the glass (ºC) predicted by BS and WSD models, and plant temperature predicted by the WSD model. The behavior of a bare window (without the green façade) is also shown.

Figures 7 and 8 show the simulations of the glass surface temperatures for the bare window and for both models. In all cases the highest temperature is reached in the afternoon when the incident solar radiation is maximum. When the window is covered by the green façade, both the inside and outside glass surface temperatures in the afternoon are around 1.5ºC lower due to the shading effect of the green façade. Because the glass pane absorbs around 15% of the incident solar radiation, the decrease of the surface temperature is significantly lower in transparent materials than in opaque ones (absortances between 50% and 80%), where decreases down to 10ºC were reported in the literature. During the night, the temperature of the glass simulated by the BS model is similar to that of the bare glass and lower than the predicted by the WSD model, due to the higher radiative thermal losses of the first model. Fig. 8 shows also the plant foliage temperature that reaches the maximum values (31ºC) during the afternoon.

The estimation of the green façade thermal resistance gives values of $R_{green\_façade}$ around 0.15 m^{2}K/W, value equivalent to the thermal resistance of a 6mm thick layer of expanded polystyrene or 89mm of a quiet air layer. This value is in accordance with other values found in the literature: [3] estimated the thermal resistance of a 25cm plant foliage in 0.5m^{2}K/W (thermal conductance of 2 W/m2K), while [10] estimated an additional resistance of 0.09 m^{2}K/W.

6. Conclusions

The use of plants in building facades is a useful bioclimatic strategy providing many benefits to the thermal, acoustic and psychological comfort of the inhabitants. Also there are benefits on the environment through the reduction of energy for air heating/cooling of interior spaces and CO_2 emissions. This paper presents the study of a double skin façade with plants and provides two models to simulate it in Energy Plus. As pointed out by [10] an abstraction of reality, modeling is an abstraction of reality and it will always have some shortcomings. Nevertheless, we have employed simulations to anticipate future implications of current decisions.

The proposed models were used to predict the thermal behavior of a double skin façade with plants for the climate of Salta, a city in the North West of Argentine. It was shown that the heat gain of a bare window oriented to West is around 6.8 MJ/m2-day and its heat loss is 0.8MJ/m2-day. Covering the window with a plant façade lowers the window heat gain down to 2.1 MJ/m2-day and the heat loss down to 0.5 MJ/m2-day. That is, heat gain and heat loss are reduced to a 30% and 63%, respectively, of the values for the bare window. Both models predicted similar amounts of solar energy transmitted by the window to the zone, and there is a mean diference of 10%-12% between the window heat gains and heat losses predicted by them. A maximum difference of 1.3ºC was found between surface glass temperatures predicted by BS and WSD models. BS model results in lower glass temperatures than WSD model. WSD model is recommended as the model to simulate a green façade because:

- It allows varying the cavity depth and it calculates the air cavity temperature, thus the convective heat transfer is correctly accounted for.
- It estimates the heat transfer coefficient for the surfaces facing the cavity.
- Buoyancy effects are accounted for.
- The model calculates the radiative heat transfer between the glass and the plant (shading) façade and between the plant and the outdoor environment.
- It roughly estimates the plant temperature. It is an important parameter of the simulation.
- The model allows estimating the equivalent thermal resistance of the plant façade.

Aknowledgements

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