Hygrothermal Potential of Applying Green Screen Façades in Warm-dry Summer Mediterranean Climates

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Abstract

Green screen façades (GSF) remain an unexplored field of study in warm-summer climates with Mediterranean conditions.
This research aims to establish whether or not these thermal comfort façade systems are worth developing in cities with dry summers and a high range of thermal oscillation.
A comparative study of four buildings´ green screen façades in Santiago de Chile was carried out, with different orientations and plant species, both in type and state of maturity.
Temperature and relative humidity outside and inside the cavity were measured during summer days. It was observed that, during the day, interior relative humidity was higher while the temperature was lower, reverting this behaviour during the afternoon and night. This result accounts for the existence of two different daily periods: passive cooling through evapotranspiration in the presence of solar radiation - reaching up to an 8°C temperature reduction and a 30% increase of the relative humidity - and passive heating in its absence.
The results show that the determining parameters in the behaviour of a green screen façade in a temperate-warm climate are, first, the orientation of the façade, and second, the density of foliage. Regarding orientation, it was also found that the sun exposure was directly proportional to the performance of a green screen façade.

Keywords

Green façade, green screen façade, thermal comfort

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1 INTRODUCTION

Global warming has a high impact in densely populated urban areas. In the coming years, temperatures are expected to increase in all major cities, including Santiago de Chile. Projections suggest an increase in temperatures of 2° to 4°C throughout the country, and a reduction of around 40% of the rainfall in the central area, where the city of Santiago is located (Cifuentes & Mesa, 2008). Among the strategies to mitigate the effects of climate change, the increase of urban green areas is widely accepted, since they promote the creation of microclimates capable of regulating the phenomenon of urban heat islands (Cheng, Cheung, & Chu, 2010; Hunter et al., 2014; Mohamed & Magdy, 2012), due to the evapotranspiration of plants. Evapotranspiration is defined as the loss of moisture from a surface, in this case the soil in which the plant is supported, by direct evaporation together with the loss of water by transpiration from vegetation. It is an organic process that can be used as a passive regulator of temperature and the relative humidity of the environment, depending on the application conditions of the plant material.

Increasing urban green areas by 10% allows a temperature reduction of 2.5°C locally, due to their contribution to shade and humidity (Cameron, Taylor, & Emmet, 2014), thus promoting the reduction of environmental pollution and preservation of biodiversity. In buildings, green façades and roofs allow greater urban vegetation, reducing heat loss in winter and avoiding overheating in summer (Schettini et al., 2016; Cameron et al., 2014; Pérez, Rincón, Vila, González, & Cabeza, 2011). By regulating the surface temperature of the walls, green façades hold the potential to improve the energy performance of buildings (Carpenter & Sikander, 2015).

Green walls, or vertical greening systems (VGS), can be subdivided into two main systems: living walls and green façades. Living walls allow plants to grow through the direct reception of moisture provided by a substrate adhered to the wall in a continuous or modular way, creating a regular growth along the surface; on the other hand, green façades consist of climbing plants which grow along the wall covering it, in a direct or indirect manner (Hunter et al., 2014; Manso & Castro-Gómez, 2016). Direct green façades are those in which the vegetation grows attached to the wall through self-clinging climbers or self-adhesive pads that adhere to the building's exterior walls. Indirect green façades are those in which the vegetation is arranged at a distance from walls and openings using support structures that assist the upward growth of a wider variety of climbing plants (Hunter et al., 2014), working as a solar screen that generates a camera or thermal buffer that blocks the incidental solar radiation, while at the same time reducing the effect of wind on the surface of the façade.

Solar screens are external shading devices, built with different materials configurated as plans arranged parallel to the windows or transparent surfaces of a façade, with the purpose of protecting them from solar gains and visual discomfort produced by glare. Indirect green façades are a special kind of solar screen that contributes to the thermal control of the building through the use of biomaterial, such as plants, and can therefore be considered as a green screen façade (GSF).

Unlike conventional sunscreens, GSF work passively and dynamically. Only a small proportion of the incidental sun radiation is destined to photosynthesis and the rest contributes to evapotranspiration that regulates temperature within the cavity. Research results have shown that, with the same incidental sun radiation, the use of GSF can reduce to a half the surface temperature on the walls, in comparison to that of conventional sun protection. Vegetation surface temperature never exceeds 35°C and sun protection can easily reach 55°C. The use of vegetation allows for the reduction of cooling demands of up to 20% in comparison to that of conventional sunscreens (Mohamed & Magdy, 2012).

For the design of GSF, the vegetation must consider the density of the foliage, its evapotranspiration potential and the planting substrate (Pérez et al., 2011). Different plant species have their own coverage capacity and leaf area index, and therefore their own light and solar transmission coefficients (Susorova, Angulo, Bahrami, & Stephens, 2013; Dahanayake, Chow, & Hou, 2017; Hoelscher, Nehls, Jänicke, & Wessolek, 2016; Susorova et al., 2013; Pan, Wei, Lai, & Chu, 2020). It is important to select species with a high moisture retention capacity and a high leaf density to optimise water use (Pérez et al., 2011). At the same time, the availability and local adaptation of plants must also be considered (Hoelscher et al., 2016) (Cameron, Taylor, & Emmet, 2014). In GSF, species that allow the growth of vertical foliage and the least irrigation substrate requirements are usually used. The support structure is decisive in their growth and in the density of their foliage, since plants tend to increase their biomass in the roots, so adequate vertical support becomes fundamental to their growth (Den Dubbelden & Oosterbeek, 1995).

In experimental studies of GSF, the most widely used indicators are: exterior and interior surface temperature of the walls; relationship between the leaf surface and the planting substrate; foliage density; orientation; plant density; incidental sun radiation; outdoor air temperature; cavity air temperature; and wind speed (Safikhani, Megat, Remaz, & Baharvand, 2014; Hunter et al., 2014). In hot and humid climates, studies have recorded that temperatures on green façades can decrease to 20.8°C on the exterior surface of the façade and 7.7 °C in the interior space, showing reductions of 3.1°C within the cavity (Chen, Li, & Lui, 2013). In Mediterranean climates, reductions between 3°C and 4.5°C during the day and increases between 2°C and 3°C during the night have been recorded (Schettini et al., 2016). This type of study requires laboratory infrastructure in order to control the various parameters on a regular and controlled basis.

Studies based on digital modelling face various difficulties due to the indeterminate geometry and density of vegetation and the difficulty of incorporating evapotranspiration in the model. The most common method used is to experimentally calibrate the models (Safikhani et al., 2014; Šuklje, Medved, & Arkar, 2016). This allows for the prediction of the optical properties of the vegetation and adjustment of the energy balance from the metabolism of the plants, which is associated with the reference climate of the experiment (Allan & Kim, 2016). Experimentally verified calculation modules in the TRNSYS software have shown that green façades have a greater impact in hot climates, since they reduce the cooling demands if provided with an efficient irrigation system (Djedjig, Bozonnet, & Belarbi, 2015). A model based on vegetation morphology has also been proposed and experimentally verified, determining that, in order of importance, the relevant climatic variables are: solar radiation; wind speed; relative humidity; and outdoor air temperature exposure (Susorova et al., 2013). This method also requires a laboratory infrastructure to control the calibration process accurately.

Measurements in buildings are more usual, as the results are variable and valid only to the specific climates and orientations of the case, since they determine the temperature, relative humidity, and solar radiation, which are, in these cases, the most usual variables to be tested. However, orientation is decisive in the performance of green façades since it determines the incidental solar radiation, its duration and intensity throughout the day (Djedjig, Bozonnet, & Belarbi, 2015; Pérez et al., 2017). In Berlin - marine coast climate, Cfb - measurements were conducted in buildings with different orientations, shading being determined as the main factor, followed by evapotranspiration (Hoelscher et al., 2016). In Shanghai - humid subtropical climate, Cfa - the performance before and after the installation of GSF for south and north orientations was compared, determining an average daily reduction of 0.4°C and 0.2°C, and a maximum of 5.5°C and 3.3°C, respectively (Yang, Yuan, Zhuang, & Yao, 2018). In Hong Kong -humid subtropical climate, Cwa - it was determined that on sunny, cloudy or rainy days, 1.30, 0.84, and 0.71 kW/h could be saved in air conditioning respectively, reducing energy consumption during summer by 16% (Pan & Chu, 2016). Also in Hong Kong, research determined that on sunny and cloudy days the orientation had an important effect on the performance of the GSF, reaching a reduction of 6.1°C within the cavity and of 3.6°C in the interior space (Pan, Wei, & Chu, 2018).

In Chile, the integration of vegetation on façades has been carried out intuitively by some architects, with no studies that support its effectiveness. Currently, there are only studies related to the phenomenon of urban heat islands associated with environmental pollution, showing that vegetation improves the city temperatures (Romero, Irarrázaval, Opazo, Salgado, & Smith, 2010). This work aims at evaluating the potential of the hygrothermal performance of the GSF, to determine if and how evapotranspiration works in the climate of Santiago that, according to the Köppen climate classification, is located in a "warm-dry summer Mediterranean" climate zone (33°27′ S-70°41′ W), characterised by dry and warm summers (38.5% average daily relative humidity)(Peel, Finlayson, & McMahon, 2007), a wide thermal oscillation (15°C daily and 13°C in annual maximum ranges) and high levels of sun irradiation (above 1000 W/m^2 in summer).

Our goal is to establish a baseline that allows future experimental studies to be opened, depending on whether or not GSF have potential for application in dry and warm climates. The study was made through the measurement of four case studies with different orientations and different plant species, both in their type and in their state of maturity, applied in different architectural configurations of the façade.

2 EXPERIMENT

2.1 PRESENTATION OF CASE STUDIES

This study was conducted in the city of Santiago de Chile (33.46° lat. South, 70.65 ° long. West, 580 m.a.s.l.) in order to comparatively evaluate the performance of GSF in four case studies. Temperature and relative humidity outside and inside the cavity were measured at three different heights to assess the performance in each case.

2.1.1 Case 1

Case 1 is a three-storey office building, where the GSF has a north-west orientation that covers its entire height. The support consists of pillars and an expanded metal mesh spaced 70 cm from the building enclosure (Fig. 1). The plant species used is called *Parthenocissus quinquefolia*, commonly known as "Virginia creeper", and was planted directly into the ground. It is a climbing species native to North America and is often used for ornamental purposes. It is characterised for being a woody plant with climbing habits and deciduous leaves, of fast and intense growth, able to reach 20 meters of height in its mature state. It adheres firmly to the support structure due to the presence of tendrils with suction cups at the tip of their leaves, that facilitate their vertical growth. Its leaves range from 3 to 20 cm long and 10 cm wide, divided into five elongated leaflets with serrated edges. It changes colours that vary from a dark green in summer to an intense red colour in autumn, until they fall off the branches as the cold season progresses. It can be placed in semi-shaded areas or those exposed directly to sun, without distinction. Although it grows in any type of soil, the foliage will be denser if planted deep in a humid ground.

FIG. 1 Schematic section and north-west façade of Case 1

The pictures in Fig. 1 show that at the time of taking the measurements, the foliage of the plants was dense, and the leaves had regular sizes, constituting multiple layers that reached a thickness of at least 30 cm. Among those analysed, this is the case in which vegetation is most dense and the only one in which the plant grows from the natural soil.

2.1.2 Case 2

Case 2 is a four-storey building in a university campus, with a north-facing GSF. It grows in planters located on the second and fourth floors, along the entire façade. The support consists of vertical elements and horizontal wiring 82 cm apart from the glazing (Fig. 2). The plant species used is a climber called *Wisteria sinensis* or "Chinese wisteria". It is native to China and belongs to the legume family. It is characterised by high density deciduous foliage that is lost when autumn arrives. The leaves reach up to 25 cm long, divided into between 7 to 13 leaflets of 2 to 6 cm length each. Being a plant of powerful growth and thick trunks, it needs firm structures capable of supporting its weight, able to reach heights of up to 30 meters. It stands out for its fragrant flowering in early spring, before its leaves sprout, lasting for several months. It is considered shade tolerant, but it only blossoms when exposed to the sun. Presenting an important root system, it requires deep soils, ideally directly into the ground.

FIG. 2 Schematic section and north façade of Case 2

The photographs in Fig. 2 show that, in this case, the foliage of the vegetation varies in height without covering the entire façade because its planting has been recent, and the expected growth at the time of taking the measurements has not yet been achieved. However, in some areas, the leaves´ density is high, reaching a thickness of 15 to 20 cm. The measuring instruments were installed in this area of the second floor.

2.1.3 Case 3

Case 3 is a seventeen-storey office building, located in a financial district (Fig. 3). The GSF is oriented to the south-west and has been planted every three floors at the top of the façade. The support consists of horizontal and vertical profiles that follow the curved shape of the façade, at a distance of 120 cm from the face. The plant species used, as in Case 1, is the *Parthenocissus quinquefolia* or "Virginia creeper", with characteristics that have already been explained. Unlike the previous case, these are planted in large planters to provide them with sufficient substrate to their roots.

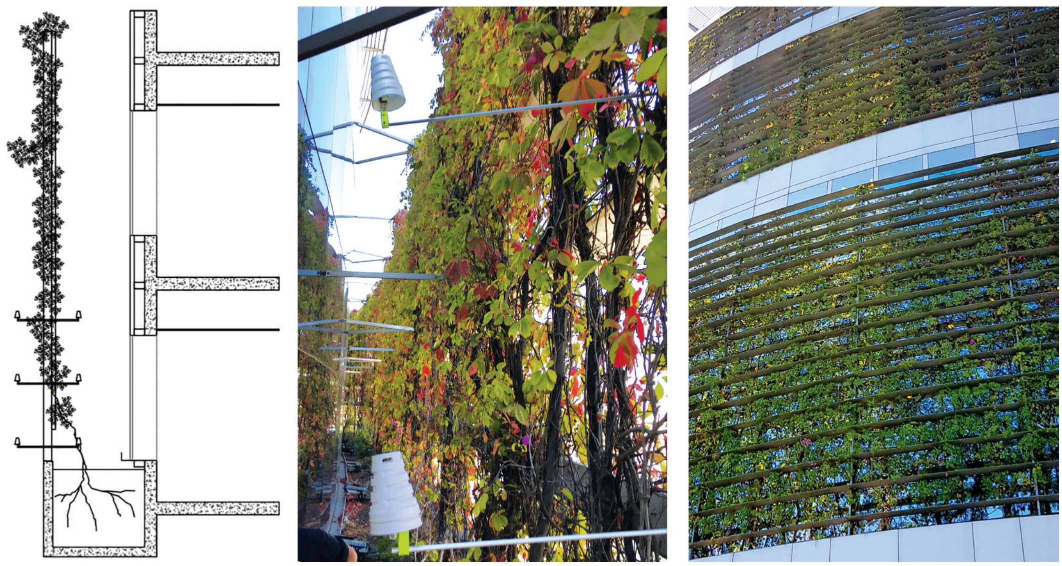

FIG. 3 Schematic section and south-west façade of Case 3

The photographs in Fig. 3 show that the foliage of the vegetation is variable. As it is a species in an adult state, the vegetation near the substrate presents a greater amount of woody branches which were predominant at the time of measurement, so its density can be considered average in relation to the set of cases.

2.1.4 Case 4

Case 4 is a twelve-storey high-rise university building. The GSF is located on the north-east façade and has been planted in planters on each floor. The support consists of vertical profiling and horizontal wiring separated 105 cm from the building's façade (Fig. 4). The species used was a perennial climber named *Jasminum grandiflorum*, known as "Spanish jasmine", native to the Himalayas and Southern Asia. It is characterised by irregular growth, with branches that wrap around each other, forming a wide set that are difficult to keep orderly. However, in the presence of a support, it can climb up to 6 or 7 m in height, forming a hanging semi-dense crown, depending on the support, since it does not reach it spontaneously. Its leaves are green and compound, divided into 5 to 7 leaflets of 2 cm in length. Its flowering is continuous, from the end of spring until the beginning of autumn, and may continue even in winter. This species is only adapted to warm-temperate climates as it does not resist cold very well and it is recommended that it be planted in sunny soil and protected from the wind.

FIG. 4 Schematic section and north-east façade of Case 4

The photographs in Fig. 4 show that the density of the foliage is low, related to the set of case studies, practically comprising a layer of leaves as protection. In addition, the growth is not uniform on the façade since its maintenance is the responsibility of the building managers. The location of the instruments was defined at the point where the highest growth maturity and foliage uniformity were found.

Table 1 summarises the characteristics of the four cases studied, reflecting their diversity, an issue that will allow us to have a comparative analysis of different conditions and characteristics of application of GSF in Santiago de Chile.

TABLE 1 Characteristics of the case studies synthesis

	CASE 1	CASE 2	CASE 3	CASE 4
Species Sc. Name	Parthenocissus quinquefolia	Wisteria sinensis	Parthenocissus quinquefolia	Jasminum grandiflorum
Foliage type	Deciduous	Deciduous	Deciduous	Perennial
Foliage density	Very high	High	Medium	Low
Building use	Offices	Educational	Offices	Educational
Green façade orientation	North-West	North	South-West	North-East

2.2 MEASUREMENTS

The goal of the measurements was to establish the hygrothermal performance of the GSF of the case studies to detect the effect of evapotranspiration within the different conditions in which they are located. As for the measurement, Voltcraft DL-121TH Data Logger Thermohygrometers were used. Measurements were carried out over five days in March 2019. Temperature and humidity records were made in intervals of one minute. Fig. 5 schematically shows that the measuring instruments were installed at three different heights (0.5, 1.5, and 2.5m from the monitoring floor) to work within the average. Temperature and relative humidity, inside and outside the cavity, were measured to compare the differences. The sensors were protected from direct solar radiation.

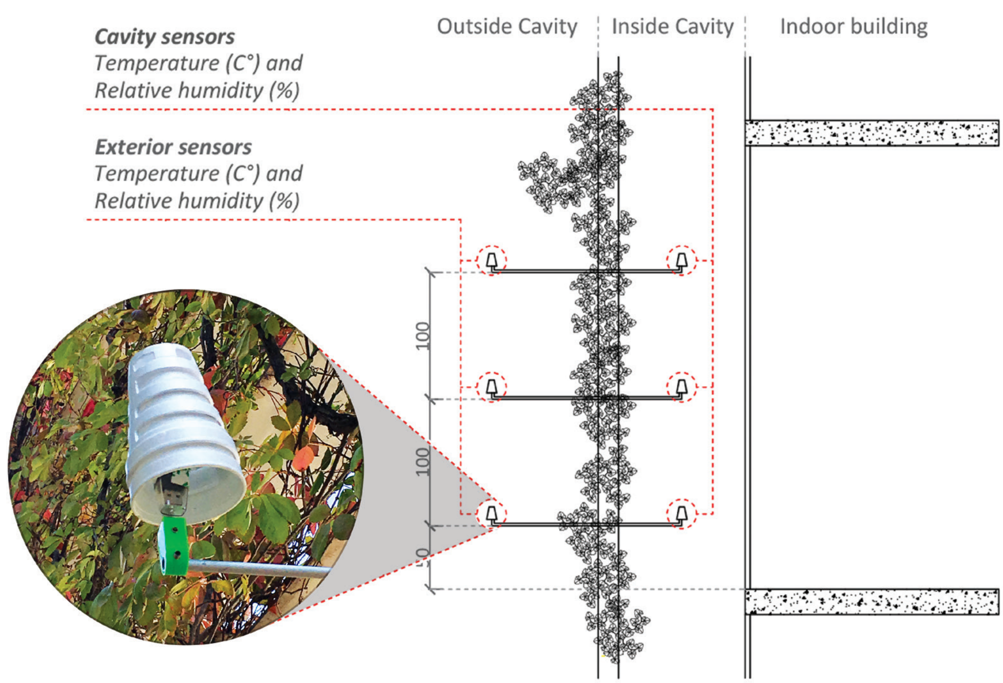

FIG. 5 Sensors location

Fig. 6 shows the climatic conditions during the days measured, with different cloud conditions, as shown by the icons above. Day 2 was completely sunny and day 4 was completely cloudy. The other days were partially clouded and sunny throughout the day. Temperatures ranged from 10° to 27° C, and the maximum daily relative humidity was close to 90% at noon and around 30 to 40% in the afternoon. Sun radiation measured in the horizontal plane was correlative to cloud cover, reaching between 800 and 900 W/m^2 as a daily maximum.

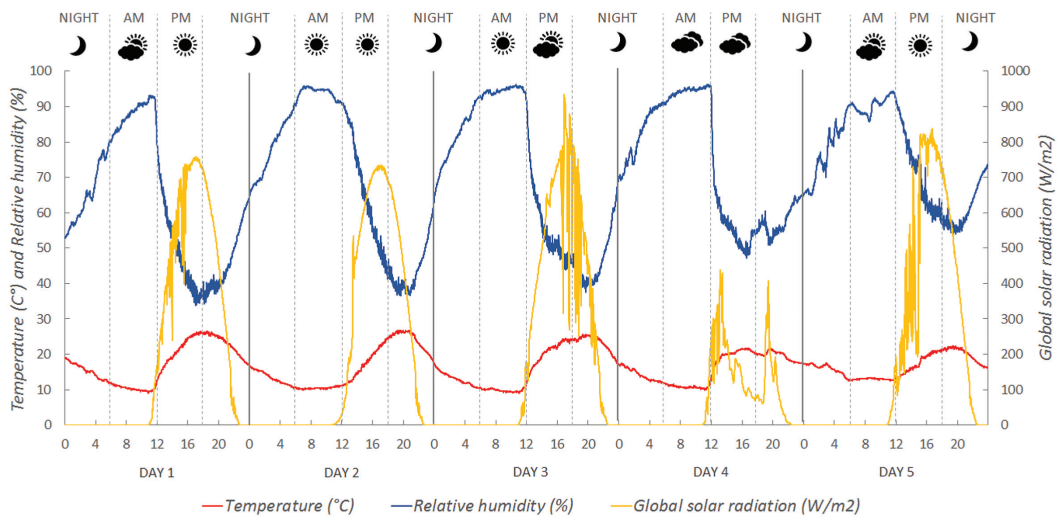

FIG. 6 Weather conditions March 27-31, 2019 in Santiago de Chile

3 RESULTS

In general, it was observed in all cases, that inside the cavities of the GSF, in the afternoon and at night, the relative humidity outside was higher and the temperature was lower. However, during the day this behaviour was reversed, with a temperature decrease and a relative humidity increase with respect to the outside. This performance accounts for the existence of two different daily periods: passive cooling by evapotranspiration in the presence of sun radiation and passive heating in its absence.

Table 2 summarises the global statistics of temperature and humidity differentials for each case in the periods of passive cooling due to evapotranspiration, which is the one of interest for the climate of Santiago. The differential is obtained by calculating the difference between the data recorded outside and inside the cavity, meaning when result is zero, inside and outside data are equivalent. Otherwise, the minimums differential normally corresponds to cloudy days and the maximums to sunny days.

TABLE 2 Global statistics of temperature and humidity differentials

	CASE 1		CASE 2		CASE 3		CASE 4	
	Temp. (°C)	R. Hum. (%)	Temp. (°C)	R. Hum. (%)	Temp. (°C)	R. Hum. (%)	Temp. (°C)	R. Hum. (%)
Maximum	8,0	30,4	4,2	14,4	2,5	6,4	4,3	6,9
Minimum	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Average	2,8	8,8	1,4	4,6	0,6	1,5	0,9	1,6
Std. Dev.	2,2	6,5	1,1	3,0	0,6	1,2	0,8	1,4

The results of each case study are presented in the following.

3.1 CASE 1

Fig. 7 shows that the passive cooling effect due to evapotranspiration occurred between approximately 8:00 a.m. and 5:00 p.m., with an observed average temperature reduction of 2.8°C, a maximum of 8°C, and an increase in relative humidity average of 8.8%, with a maximum of 30.4%. The standard deviations of temperature and relative humidity were of 2.2° C and a 6.5%, respectively, which accounts for constant cooling, with moderate oscillating relative humidity. On cloudy days, the hydrothermal effect of the cavity decreased, and the relative humidity worked less intensively. On sunny days, the effect of evapotranspiration was regular from morning until the hours of greatest global radiation, due to its north-west orientation.

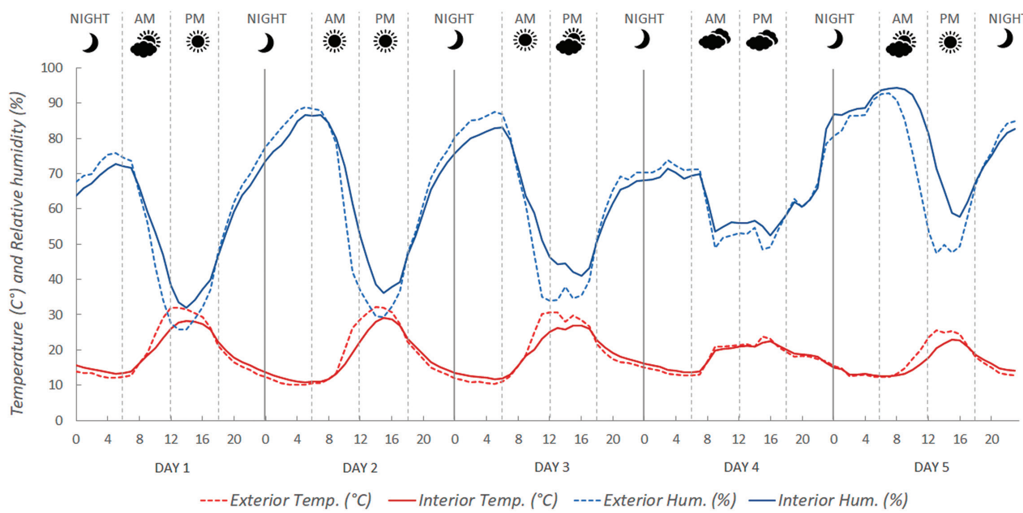

FIG. 7 Daily interior/exterior cavity temperature and relative humidity recorded for Case 1

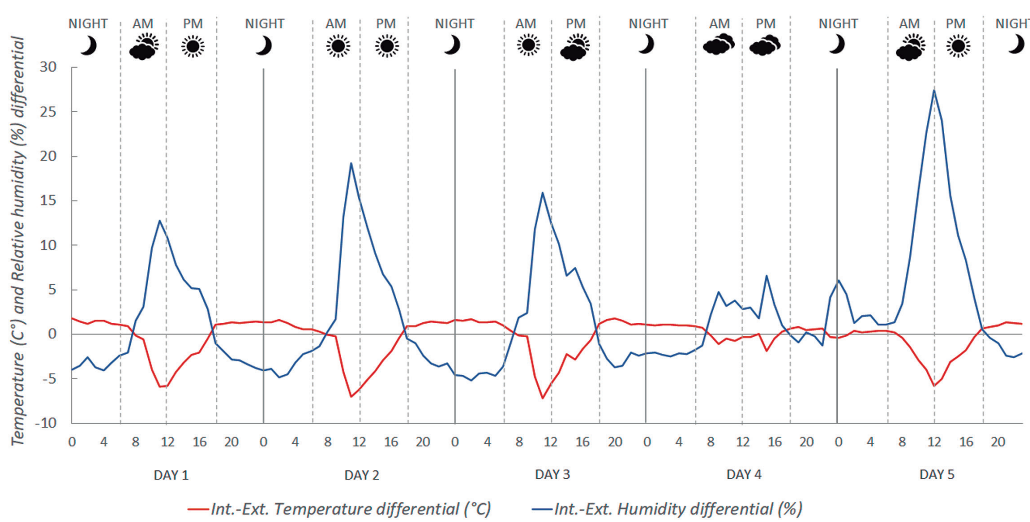

FIG. 8 Daily interior/exterior cavity temperature and relative humidity recorded for Case 1

Fig. 8 shows that, inside the cavity, there were temperature reductions every day during the passive cooling period (day) and temperature increases in the passive heating periods (afternoon-night). The hygrothermal inversion occurred at 8:00 and 17:00. The decrease in passive cooling was also observed on day 4, which was cloudy, compared to sunny or partial days, although the hygrothermal inversion schedule was persistent.

3.2 CASE 2

Fig. 9 shows that the passive cooling effect due to evapotranspiration worked between approximately 9:00 a.m. and 6:00 p.m., reaching an average reduction of 1.4°C and a maximum of 4.2°C, with an average increase in the relative humidity of 4.7% and a maximum of 14.4%. The standard deviations of temperature and relative humidity were of 1.1°C and a 3.0%, respectively, which accounts for persistent but moderate passive cooling. On the other hand, the difference between cloudy and sunny days is less relevant, especially in the temperature differences of the cavity with respect to the outside. Passive cooling was more relevant throughout the morning, decreasing the temperature at midday, even though the increase in relative humidity was more persistent. The regularity of the performance of this GSF can be associated with its north orientation, which ensures sun exposure for most of the day.

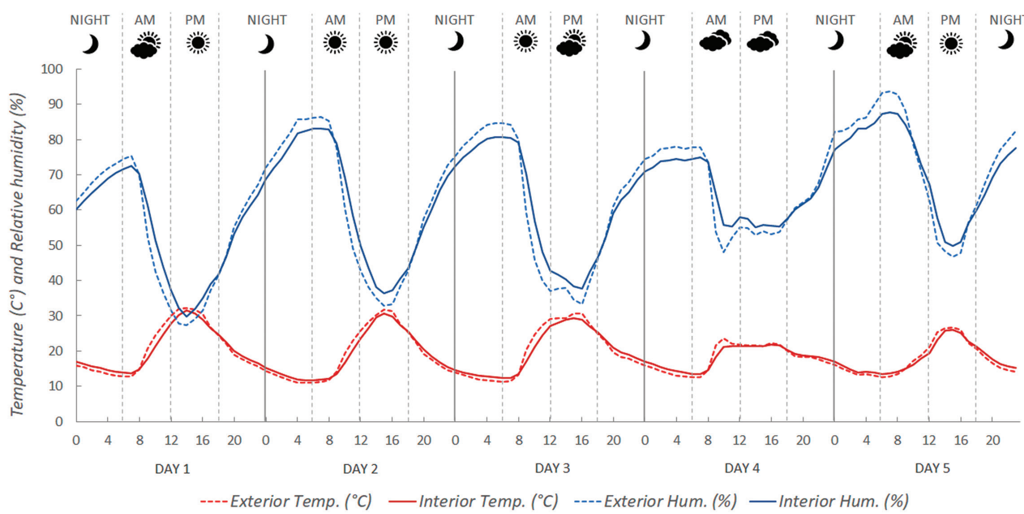

FIG. 9 Daily interior/exterior cavity temperature and relative humidity recorded for Case 2

Fig. 10 shows how, inside the cavity, the phenomenon of hygrothermal inversion was also observed at 9:00 and 18:00 and passive cooling was similar on both cloudy and sunny days, with more significant increases in relative humidity in the cooling periods, that is, when the foliage received solar radiation.

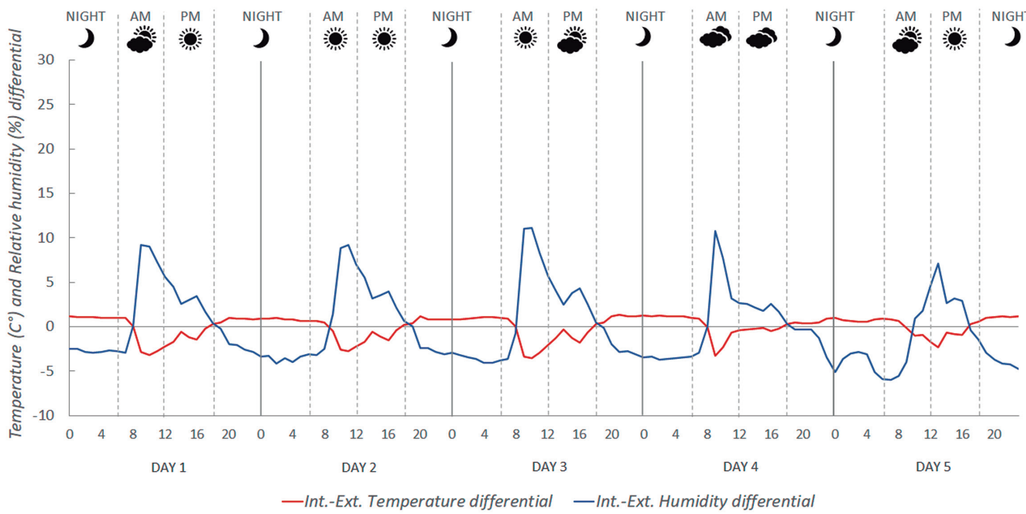

FIG. 10 Daily interior/exterior cavity temperature and relative humidity differential recorded in Case 2

3.3 CASE 3

Fig. 11 shows that the passive cooling effect due to evapotranspiration was active between approximately 9:00 a.m. and 7:00 p.m., reaching an average reduction of 0.6°C, a maximum of 2.5°C, and an average increase in relative humidity of 1.5%, with a maximum of 6.4%. The standard deviations of temperature and relative humidity were of 0.6°C and 1.5%, respectively, which shows persistent passive cooling, although of low overall intensity. The performance of this particular GSF is relatively low and almost irrelevant on cloudy days; however, on sunny days it is possible to appreciate that it reached its peak between approximately 15:00 and 18:00.

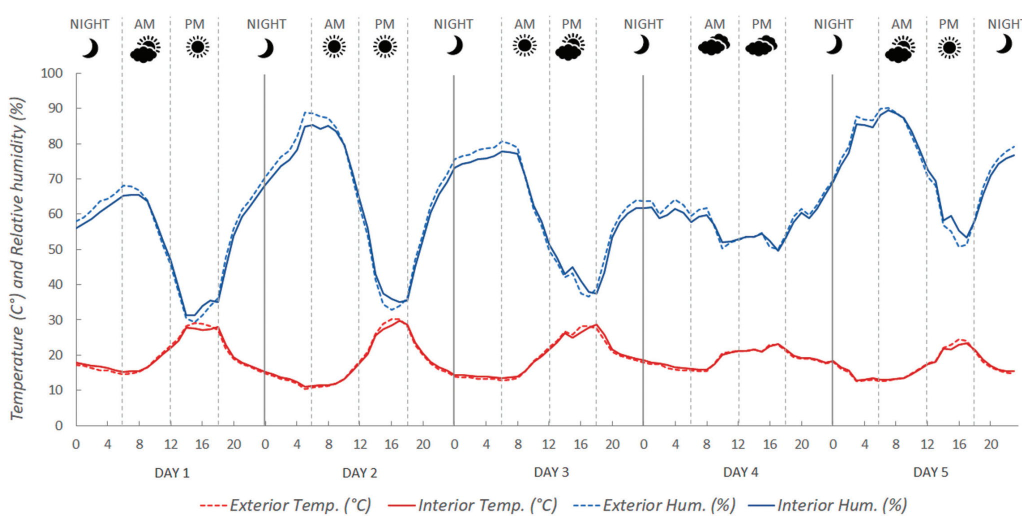

FIG. 11 Daily interior/exterior cavity temperature and relative humidity recorded for Case 3

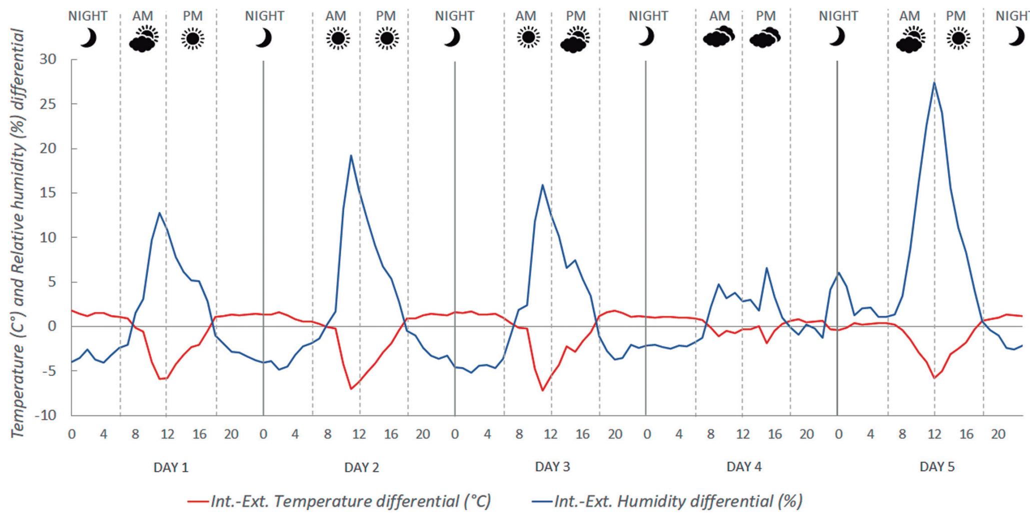

FIG. 12 Daily interior/exterior cavity temperature and relative humidity differential recorded in Case 1

Fig. 12 shows that, within the cavity, the same phenomenon of thermal hygrothermal inversion occurred between day and evening, at 9:00 and 18:00 respectively. In this case, the general operation was less efficient than the previous ones, with few differences in temperature and humidity on sunny days and was practically non-functioning on cloudy days. This can be associated to the low sun exposure received due to its south-west orientation and its foliage, which was of medium density at the time of taking the measurements.

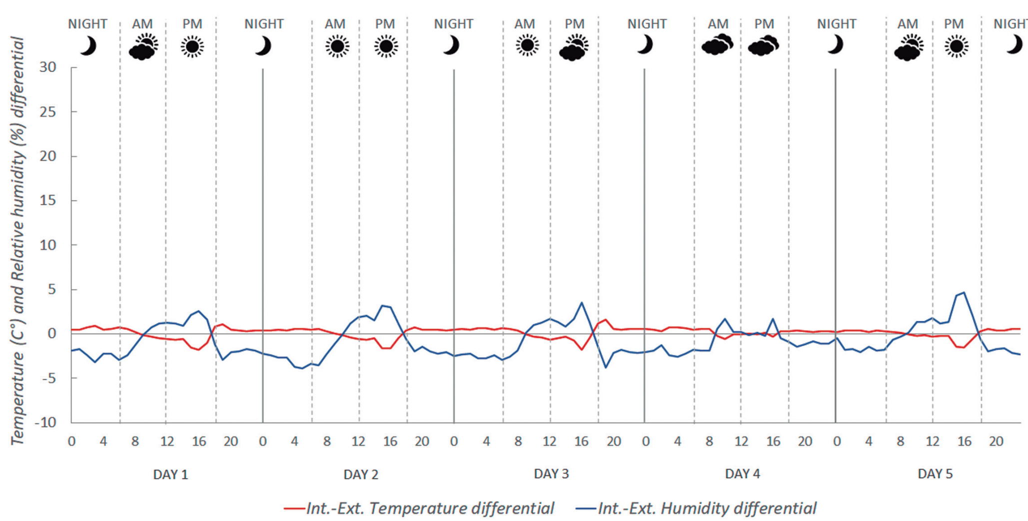

FIG. 13 Daily interior/exterior cavity temperature and relative humidity differential recorded in Case 3

3.4 CASE 4

Fig. 13 shows that the passive cooling effect due to evapotranspiration occurred between approximately 9:00 a.m. and 7:00 p.m. During this period, there was an average reduction of 0.9°C, with a maximum of 4.3°C and an increase in average relative humidity of 1.6% with a maximum of 6.9%. The standard deviations of temperature and relative humidity were of 0.8°C and 1.4%, respectively, which shows persistent passive cooling and very low overall intensity. The performance of this GSF reached its peak between 12:00 and 16:00 on sunny days.

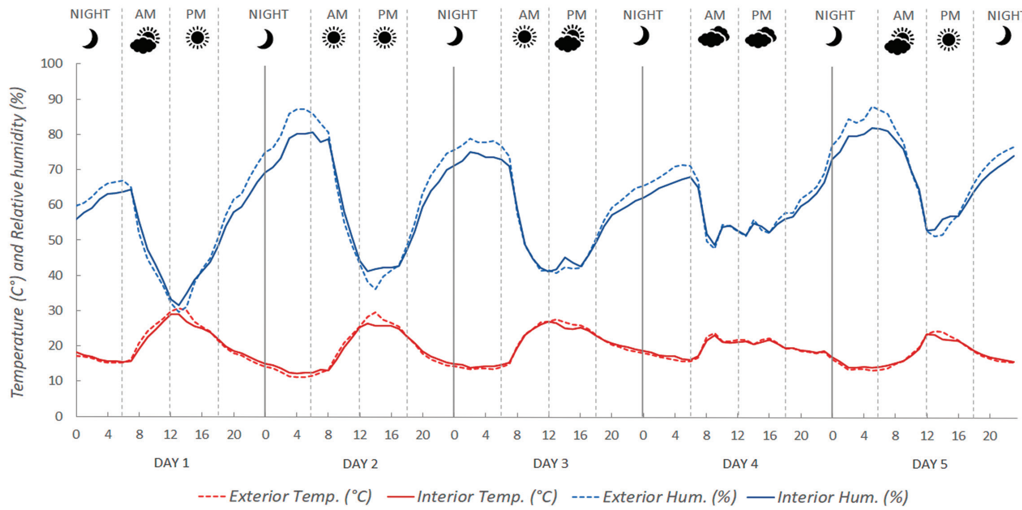

FIG. 14 Daily interior/exterior cavity temperature and relative humidity recorded for Case 4

Fig. 14 shows that, inside the cavity, the hygrothermal inversion occurred regularly at 9:00 and 19:00, and passive cooling was similar on cloudy and sunny days, with a greater decrease in relative humidity on cloudy days. Despite being well exposed to the sun due to its northeast orientation, the low density of the foliage did not allow the potential of this GSF to be reached.

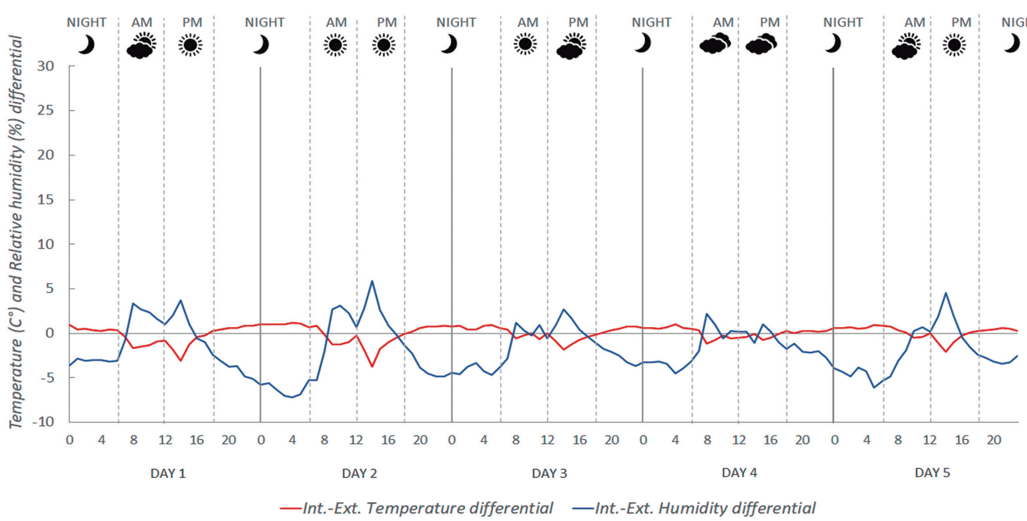

FIG. 15 Daily interior/exterior cavity temperature and relative humidity differential recorded in Case 4

4 DISCUSSION

Fig. 15 shows the temperature differential measured in the complete sample. Regularly, the temperature drops during the day and rises in the late evening, with minimal differences in the times when the hygrothermal inversion occurs inside the cavity. Case 1 is the one that reaches the best thermal performances, which is associated with the highest density of its foliage; it is followed by Case 2, where foliage follows in density. The differences in the temperature peaks show that the hours of highest cooling are different in each case, a matter that may be associated with their different orientations. Cases 1 and 2, which have a northern component, tend to reach their peaks around noon, whereas the rest, which have a western component, tend to do it in the afternoon.

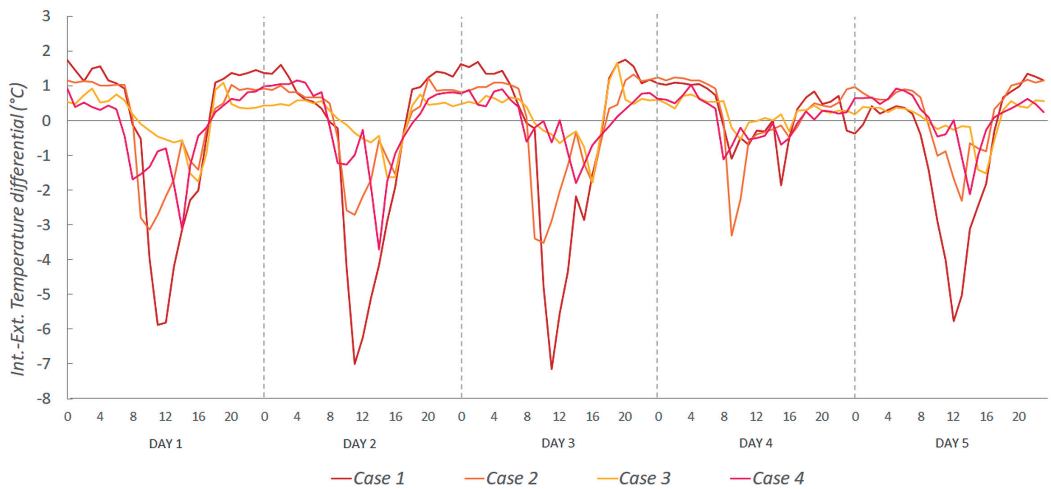

FIG. 16 Daily interior/exterior cavity temperature differential recorded in Case Studies 1 to 4

Fig. 16 shows the humidity differential in the cavities and accounts for phenomena similar to the previous one. Cases 1 and 2, which have denser foliage and a north-facing component in their orientation, are more effective in lowering the relative humidity of the cavity. The effect produced by the decrease in radiation is evident, since on day 4, which was cloudy, the time logic is lost in all cases.

From the above, it can be deduced that passive cooling is effective; however, it is dependent on two main factors: the foliage of the vegetation, which determines the intensity of the passive cooling by evapotranspiration, and the orientation, which is responsible for the hours in which it occurs by action of sun radiation.

The graphs in Fig. 17 synthetically show the differences in temperature and humidity observed in the sample. Case 1 is the one that has the best performance of the four, reaching an 8°C temperature reduction and a 30% increase in relative humidity, which represents an ideal of GSF, since it can become an effective support for cooling systems of the building. Case 2 follows in their overall performance and both have the highest foliage densities, a parameter that appears as a condition for the effectiveness of a GSF. The greater leaf thickness generates a greater evaporation surface, which results in higher passive cooling within the cavity.

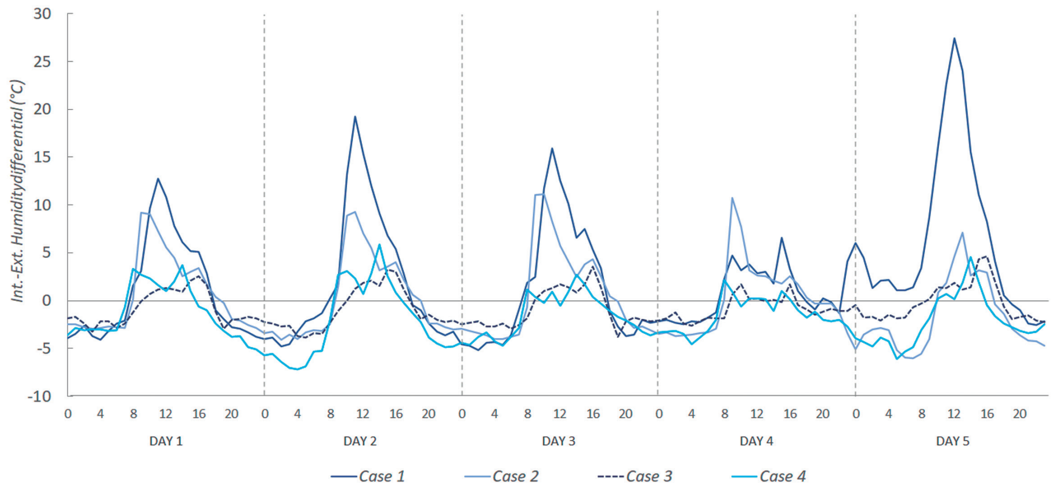

FIG. 17 Daily interior/exterior cavity relative humidity differential recorded in Case Studies 1 to 4

Cases 3 and 4 are those with the lowest foliage density and worst performances; however, Case 3, with a south-west orientation and average density foliage, reaches lower temperature and relative humidity differentials in the cavity than Case 4, whose orientation is north-east and is provided with a lower amount of foliage. Between them, the best result is determined by the sun exposure they are subjected to, which highly depends on the orientation of the GSF. The comparison of these cases shows that the density of the foliage is not a sufficient parameter if the façade does not have an orientation that allows adequate sun exposure.

Fig. 18 shows the orientation of the different case studies, allowing the possibility to observe that the peak performance time in all four cases occurs at times when the angles of solar incidence are not perpendicular to the façade, but lateral, according to the predominant orientation. This suggests that orientation plays a fundamental role in the application of double vegetable skins and that their hygrothermal behaviour is associated with the radiation conditions to which they are exposed. On the other hand, passive cooling persists over many hours, therefore, its correct application would allow its contribution to the overall energy balance of buildings to be incorporated.

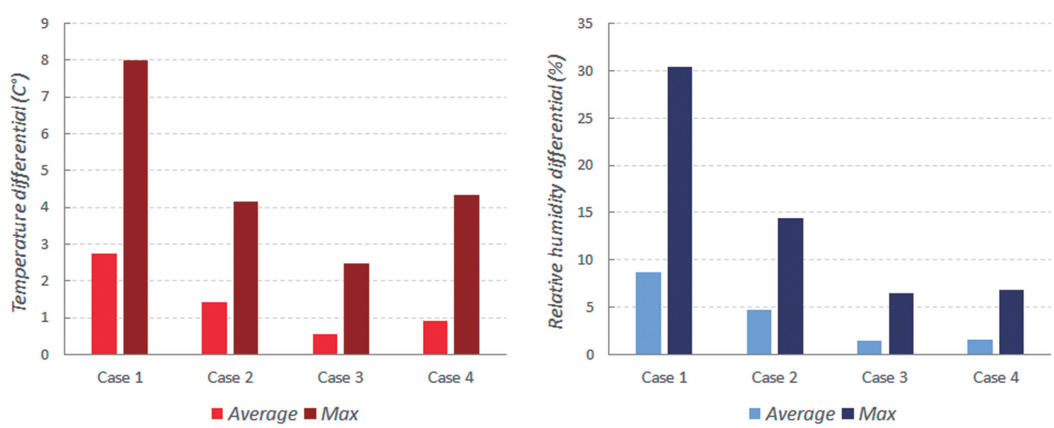

FIG. 18 Interior/exterior cavity temperature (°C) and relative humidity (%) differentials

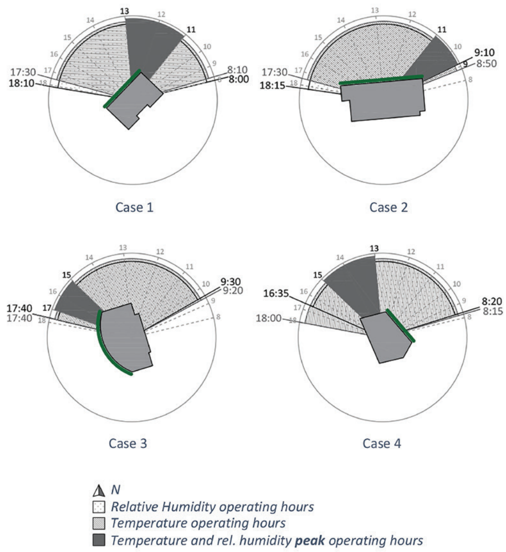

FIG. 19 GSF operating hours for Case Studies 1 to 4

The graphs in Fig. 19 show the correlation between the temperature and relative humidity differentials for each case and their R^2 values, which, in all cases, are greater than 0.8. It can also be observed that hygrothermal behaviour occurs inside the cavities. The points found in the first quadrant correspond to the moments when passive cooling takes place inside the cavities and the opposite situation appears in the fourth quadrant, that is, when heating occurs within the cavity.

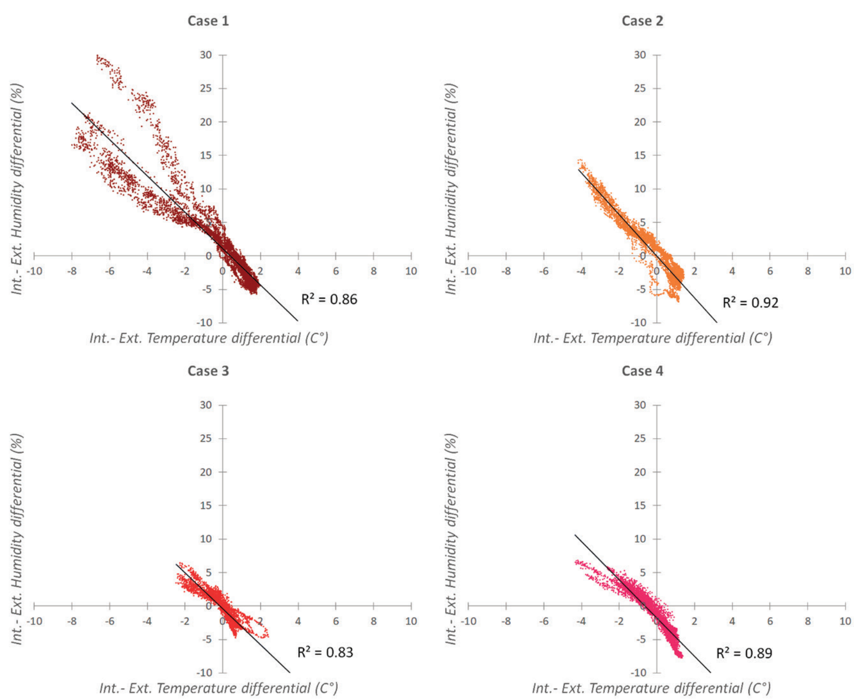

FIG. 20 Correlation between temperature and relative humidity differentials for each case and their R2 values

Cases 1 and 2 are the ones that show a greater development in the first quadrant and cases 3 and 4 tend to develop symmetrically in the first and fourth.

Case 1 shows its high efficiency in obtaining passive cooling, showing two different series in the first quadrant: one where the slope is greater, representing the passive cooling peak moments; and another with a lower slope, that represents the regular operation during the day. On the other hand, the fourth quadrant shows little development, which accounts for the fact that warming is marginal compared to cooling.

Case 2 shows a regular slope in the first quadrant, although it reaches lower values of temperature and relative humidity compared to the previous case. In the fourth quadrant, its trend is similar to the previous one, raising the temperature by almost 2°C and lowering the humidity by around 7%.

Case 3 shows a symmetrical development in quadrants 1 and 4, exceeding 2°C at times when the cavity warms up. The cooling observed in quadrant 1 is scarce compared to the previous cases.

Case 4 shows a performance similar to the previous; however, cooling is more efficient, reaching up to a difference of 4°C and similar humidity differentials. Its performance in the fourth quadrant is the one that achieves the highest relative humidity losses of all cases.

This comparison confirms the aforementioned: cases 1 and 2, which are those with greater foliage and better orientation, perform better, proving the relevance of their foliage; and with respect to cases 3 and 4, which have less foliage, worse orientation, and performance, orientation prevails as the most relevant aspect, since despite the fact of having less foliage and better orientation, Case 3 gives a better performance.

5 CONCLUSIONS

By contrasting the results of these four case studies, we can conclude that the decisive parameters in the performance of a GSF in a temperate-warm climate, such as that of Santiago de Chile, are the orientation of the façade and the density of foliage of the selected plant species.

Regarding orientation, we found that sun exposure is directly proportional to the behaviour of a GSF. When the angle of solar incidence is between 0° and 50° with respect to the façade, the performance peaks are reached. On the other hand, the intensity of solar radiation determines the hygrothermal variations inside the cavity, promoting evapotranspiration that produces passive cooling.

The second determining factor is the foliage density of the selected plant species. The more plant tissue the double plant skin develops, the greater the moisture retention and release capacity in the inner cavity, thus increasing its passive cooling properties during the day.

In this way, we can claim that GSF are a solution that has great potential to be developed in the city of Santiago. However, it is necessary to carry out further research to find the ideal species and the application conditions that allow their operation as a passive cooling system that collaborates with the building's own cooling devices to be optimised.

This study shows the need to carry out experimental studies in order to establish the parameters for a correct design of the double vegetable skins in Santiago de Chile, so that they become part of the building's cooling system and are not only considered as ornamental solutions.

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