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Double skin glazed façades in sunny Mediterranean climates

Silvana Flores Larsen [a,*], Luis Rengifo [b], Celina Filippín [c]

[a] Instituto de Investigaciones en Energía No Convencional (INENCO) – Universidad Nacional de Salta – CONICET, Avda. Bolivia 5150, Salta, 4400, Argentina
[b] GRG Arquitectos Asociados SRL, Av. del Golf 1, Salta, 4400, Argentina
[c] CONICET – Av. Spinetto 785, Santa Rosa, La Pampa, 6300, Argentina

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ABSTRACT

Double skin glazed facades (DGF) are an actual worldwide trend in new and refurbished buildings, even in warm climates with high solar radiation levels as in the Middle East and in Mediterranean climates. In such climates, overheating of indoor spaces and therefore excessive energy consumption are the main problems to be faced. These issues are commonly addressed mostly by thermal simulation or experimental evaluations on small prototypes. However, measurements on real-scale buildings with DGFs are very unusual. This information is crucial to understand and validate the predictions of the thermal behavior of the DGF technology. In this paper, thermal measurements were carried out in an unoccupied office building with a West DGF placed in the Northwest region of Argentina during 3 months in spring/summer. The air temperature exceeded in 10 °C the outdoor air and that indoor temperatures have not exceeded the outdoor levels in the hottest hours. Two correct design decisions were the use of low-e double hermetic glazing and the addition of a screenpainting to the external DGF panel. The experimental data showed that well-designed DGFs can reduce the summer energy consumption of buildings, even using West DGFs, in sunny climates.

1. Introduction

Solar heat gain in highly glazed buildings can produce excessive energy consumption for space conditioning and a negative impact on the environment due to the associated CO_2 emissions. Among highly glazed buildings, those with double skin glazed facades (DGF) are nowadays a growing tendency propelled mostly by their modern and transparent aspect. A DGF, consisting of a normal façade, an air cavity and an additional external skin of glass, drastically modifies the surrounding environment (air temperature, solar radiation, and air velocity) of the normal façade. Thus, the DGF increases the temperature of the air cavity—usually up to 10–20 °C more than the outdoor air temperature – it reduces the solar radiation reaching the building envelope – because a portion is absorbed in the DGF glazing – and it modifies the air velocity near the façade – depending on the geometry and ventilation of the DGF. These variables together with the local climate conditions, surrounding landscape and canyon geometry, and building geometry and materials, determine the thermal behavior of the building and its energy consumption for air conditioning [1,2].

Mediterranean and hot arid climates are characterized by large solar gains and high air temperatures. In such climates, overheating and large energy consumptions of buildings are the main issues to be managed, so the inclusion of highly glazed areas in buildings is traditionally not recommended [3]. But in the last years, DGFs have been suggested as a suitable technology that could reduce the cooling load of buildings in Mediterranean and hot arid climates [4,5]. The proposal caused a controversial debate between researchers and designers which lasts until the present time. There is research showing that, even in moderate climates, the addition of a double-skin of clear glass always causes an increase in the cooling loads of a building (Gratia and De Herde [6] and Corgnati et al. [7]).

On the contrary, there is also some evidence that DGFs in hot arid areas would reduce direct solar heat gain in buildings under certain selection of glazing/shading and ventilation schemes (Hamza and Underwood [8] and Afifi [9]). The reason is that the increase of the air temperature inside the cavity can be counterbalanced by the decrease of the solar gain into internal spaces produced by an adequate selection of materials and ventilation schemes. Thus, the global effect could result in a substantial savings of cooling energy. Several authors studied different combinations of glazing in order to achieve such savings (Pérez-Grande et al. [10]). Manz [11] found that total solar energy transmittance values could be reduced by 10% with a well-designed glazing DGF. Simulations for

* Corresponding author. Tel.: +54 387 4255578.
E-mail address: seflores@unsa.edu.ar (S. Flores Larsen).

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the hot arid climate of Egypt showed that reflective double skin facade can achieve energy savings between 19 and 40% than a single skin with reflective glazing and that East or West-oriented DGFs should be avoided [8,12]. Shading devices can reduce the cooling energy around 14% [13,14]. Savings between 17 and 20% were found for buildings in the United Arab Emirates (Radhi et al. [15]). Also the cooling loads of a building with DGF can be reduced by improving the ventilation rates. Simulations for an office building in Hong Kong showed that a DGF with natural ventilation and a heat absorbing glass can reduce the building energy consumption as well as to enhance the thermal comfort (Hien et al. [16]). In Mediterranean climates, the horizontal ventilation of the air cavity was suggested as being more effective than vertical ventilation [17]. A combination of night ventilation and shading devices inside the cavity was suggested by Hashemi et al. [18]. As shown, the key point relies in the selection of the optical properties of the DGF and in the ventilation of the air cavity. This selection should be based in experimental data that support the results obtained by computer simulation.

Much of the experimental work on DGFs behavior in summer was carried out on prototypes. For example, in France, a full-scale DGF studied during a summer period, for different airflow rates in the cavity and different angles of the solar shading devices [19]. It was concluded that an effective management of the shading and ventilation of the double skin façade is needed in order to satisfy the need for summer comfort. In Italy, a south-oriented DGF with mechanical ventilation installed on a real scale test cell was monitored during one year [20]. The authors concluded that low-e coating on the inner skin showed a better performance than the module without low-e coating. Also in Italy, measurements on test cells performed by Serra et al. [21] for different air flow rates, shading devices, and internal glazing showed that during the cooling season the DGF showed in all cases a better performance than the reference test cell of traditional reflecting double-glass panel.

Field measurements on real-scale buildings with DGFs are not commonly found in the literature. Some valuable contributions were made by Pasquay [22] in Germany, Corgnati et al. (2007) in Italy [7], and Hashemi et al. (2010) [18] in Iran, for buildings under actual operating conditions. In Germany [22], the experimental study of three buildings with DGF (Siemens building, Victoria Insurance Co. and RWE Tower) showed that the temperature in the cavities was between 8 °C and 15 °C higher than the temperature of the outside air. In Turin, Italy [7], a two-year monitoring campaign of a mechanically ventilated transparent facade installed in a new office building was performed. The comparison with a traditional transparent facade indicated that the DGF provided a satisfactory performance throughout the year, but that it was still not competitive with windowed opaque facades, due to the overheating occurring during the cooling periods. During the winter, their behavior is almost comparable, even though the possibility of exploiting the ventilated facade as a solar collector to pre-heat the ventilation air proved to be effective only for a small percentage of the time. Finally, in Iran [18], the monitoring of an 11-story building with DGF indicated that, in summer, the facades oriented to West reached the higher temperatures in the cavity, of around 7.5–10.5 °C higher than outside air temperature. The measurements also showed that the cavity remained hot during the night thus increasing the cooling load requirements of the building. Thus, ventilation of the cavity and the use of shading devices were recommended to improve the DGF behavior in hot arid climates, in accordance with the suggestions of other researchers [13,19].

The previous literature review indicates that there is theoretical and experimental evidence that DGF in warm climates can reduce the cooling load of buildings with respect to a traditional glazed façade. Moreover, in accordance with Barbosa and Ip [23], there is a general consensus that further research is required for a better understanding of the processes involved in DGFs and the implication of its use in different climates. In this sense, experimental data obtained from real buildings are the main source of information but, unfortunately, it is very scarce in the literature. Only a few buildings have been measured and there is still a lack of information on this subject. Furthermore, the main studies of DGFs were carried out mostly in temperate climate conditions, and experimental reports on real-scale buildings in hot arid and in Mediterranean climates are very unusual in the literature. In this context, the present paper contributes with new experimental data of the summer thermal behavior of the first building with DGF built in Salta, a city in the Northwest region of Argentina placed at 1182 m over the sea level. It is a 5-storey office building that was extensively monitored during the cooling season and under non-occupancy condition, which ensured that user behavior and equipment management did not influence the results. Thus, indoor temperature in 10 offices, air temperature and wind velocity in the DGF cavity, and outdoor climatic conditions were monitored at a logging interval of 15 min during 3 months in spring/summer. Two analyses were performed, the first one showing the detailed hourly behavior of a week with sunny days, and the second one representing the overall summer behavior by averaged variables. The experimental results were discussed and compared with the available data in the literature. The findings obtained in this research are expected to contribute to the general knowledge about DGF behavior in arid and warm climates.

2. Climate and building description

2.1. Climate description

The city of Salta (24.8° South latitude, 65.5° West longitude, 1182 m over the sea level) is placed in the Northwest region of Argentina, near the Andes Mountains. The Köppen-Geiger climate classification for Salta is *Cwa* [24], that is, temperate climate with dry winter/hot summer pattern. The climate is classified as by the Argentinean IRAM Norm (1996) [25] as sub-tropical with dry season and daily thermal amplitudes higher than 14 °C.

Table 1 shows the climatic data for winter and summer periods, and annual averages. The winter period is dry (with a raining level of 3 mm/month in average) and the skies are cloudless, with daily solar irradiance on horizontal surface reaching 10.8 MJ/(m^2day). The average temperatures oscillates from 4 °C to 19.8 °C (mean minimum and maximum values), with absolute minimum values that fall below zero for a few days in which there are ice and frost on the ground. Because of the high solar radiation levels, the air temperature rises considerably at noon causing large daily thermal amplitudes. Moreover, even in winter, the absolute maximum values can exceed 35 °C in short periods, during special windy conditions that bring hot and dry air masses from the North.

The summer period is hot and more humid (with a raining level of 160 mm/month in average) with alternation of cloudy and sunny days. The average maximum, mean and minimum temperatures in summer are 28.3 °C, 21.3 °C, and 18.0 °C, respectively. In the last years, maximum temperatures in summer usually exceeded 30 °C, with absolute maximum values that reached 38 °C. The average daily solar irradiance on horizontal surface is around 19.2 MJ/(m^2day).

In a one-year period, the annual average temperature and humidity are around 16.3 °C and 73%, respectively. The average wind speed is around 1.39 m/s with prevailing direction from Northeast. The windiest period goes from September to November, with average values of 1.67 m/s, average maximum values of around 8.9 m/s, and prevailing direction from the Northeast.

Table 1
Meteorological data for Salta city (National Meteorological Service). Solar irradiance and relative heliophany data were obtained from Grossi-Gallegos and Righini [26].

Annual	Temperature	Mean maximum	°C	24.1
		Mean		16.3
		Mean minimum		10.0
	Relative humidity		%	73
	Mean daily solar irradiance on horizontal surface		MJ/m^{2}day	15.0
	Heating degree-days (base temperature = 18 °C)		°C day	1137
	Cooling degree-days (base temperature = 23 °C)		°C day	39
Winter (June)	Temperature	Mean maximum	°C	19.8
		Mean		10.4
		Mean minimum		4.0
	Thermal amplitude		°C	15.8
	Mean wind speed		m/s	1.30
	Relative humidity		%	77
	Relative heliophany		–	0.49
	Mean daily solar irradiance on horizontal surface		MJ/m^{2}day	10.8
Summer (December)	Temperature	Mean maximum	°C	28.3
		Mean		21.3
		Mean minimum		15.2
	Thermal amplitude		°C	13.1
	Mean wind speed		Km/h	1.58
	Relative humidity		%	71
	Relative heliophany		–	0.40
	Mean daily solar irradiance on horizontal surface		MJ/m^{2}day	19.2

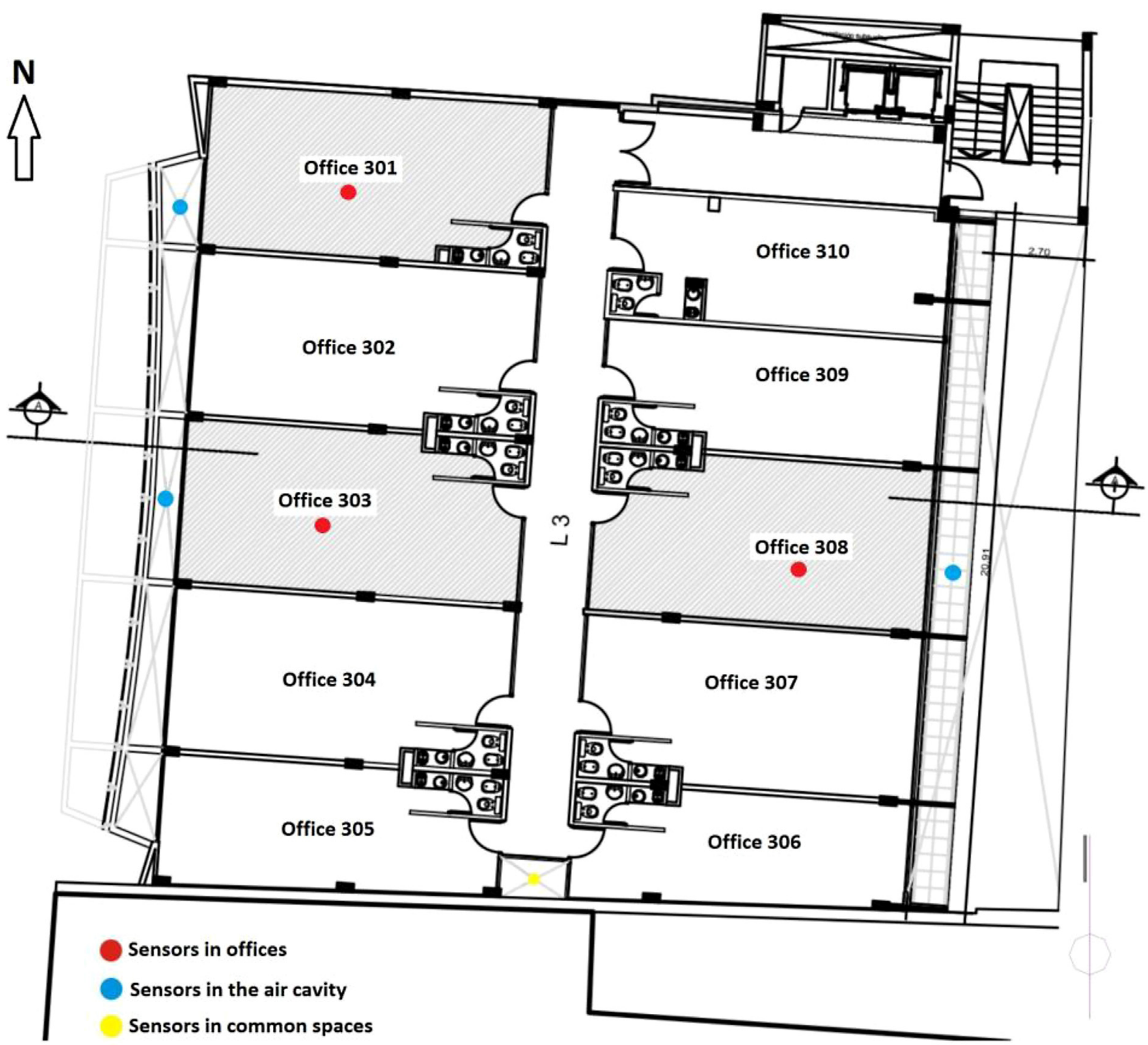

Fig. 1. Plant view of the 3rd floor. Data loggers HOBO type sensing air temperature and relative humidity were installed. Inside offices 301, 303, and 308, the data loggers (red dots) were installed at 1.5 m over the floor level. In the air cavity of the DGF and in the metallic frame of the living green wall, the data loggers (blue dots) were placed in front of the corresponding offices. At the the third floor level, an additional data logger (yellow dot) was installed in the ventilation duct coming from the underground floors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Building description

The Palermo building is a comparatively small high-rise office building built in 2012. It is situated in the historic center of Salta city, Argentina, along a North–South road (4° towards East from true North) with heavy traffic. The building has a total height from ground of around 18.2 m and a total covered surface of 5500 m^2 distributed into nine floors (three underground floors for car parking, one commercial ground floor and five floors with 50 offices), as shown in Figs. 1 and 2. The height of the building is regulated by the Province Legislation which explicitly prohibits higher buildings due to the seismic risks and to the protection of the cultural heritage of the historic city center.

North and South building envelopes are opaque walls, while East and West envelopes are glazed. The West façade is covered by a DGF which is described in the next section. In the East facade, a metallic structure was installed in order to provide, in the future, support for a living green wall. The North wall is completely exposed to wind and sun while part of the South wall, from ground to the fourth floor, is adjacent to an existing building. The offices, which are located at both sides of a central corridor, have useful areas between 30 and 70 m^2 and they are oriented either towards the East or the West. The offices are numbered from X01 (North-West corner) to X10 (North-East corner), where X symbolizes the floor level. The offices have glazing (towards East or West, depending on the side in the building) from the floor to the ceiling level, except the offices in the building corners where only 50% of the wall is glazed. Hermetic double glazing with infrared reflective properties on the external side was used (StopSol Classic Gray 6 mm + air 9/12 mm + (3 + 3) clear glass, see Table 2), with openable windows in the upper half of the glazing. Each office has an individual split air conditioning equipment, consisting of heating and cooling units with heat pump of 10467 W (9000 frig/h), installed in the building rooftop. More details can be found in [27].

In Salta city there are no building codes regarding the energy efficiency. Furthermore, in Argentina the energy prices are subsidized. Despite the situation not encourages energy efficiency, the building was designed in order to reduce its energy consumption. Thus, thermal insulation was used in the envelope and a special shading structure was applied in the exterior roof. Both of them are very unusual practices in the region. Opaque exterior walls (North and South) were built with five layers (Fig. 3), from outside to inside: outer plastering (3 cm thick, beige painting), hollow ceramic masonry (0.12 m thick), plaster with waterproofing asphaltic painting (0.03 m thick), thermal and acoustic insulation of glass wool (0.03 m thick), and gypsum board with white painting (0.0125 m thick). The overall thermal resistance of the wall is $R = 1.28\ m^2K/W$ while its thermal transmittance is $U = 0.78\ W/(m^2K)$.

The roof structure consists of a reinforced concrete slab (0.15 m thick, see Figs. 3 and 5), whose outer side is finished by a lean concrete slab (0.05 m thick). Towards the inner side there are an air space (0.25 m thick) and a gypsum board (0.0125 m thick) with thermal and acoustic insulation of glass wool (0.03 m) as ceiling finishing. Because of the high levels of solar radiation on the rooftop in summer, a novel roof shading system was used, consisting of square concrete tiles (0.03 m thick) supported in their four corners by cylindrical PVC pivots of 0.12 m height filled with concrete (see Fig. 5). Thus, the tiles provide shading to the rooftop, an air space above the roof, and a walkable surface. The roof thermal resistance is $R = 3.04\ m^2K/W$ and the thermal transmittance is $U = 0.33\ W/(m^2K)$.

2.3. Double skin glazed façade

The building has a West double skin glazed façade consisting of rectangular panels (1.24 m × 3.00 m, and 1.24 m × 3.30 m), installed 0.05 m away from each other. The panels are anchored to the concrete supporting structure through spider-type fixing

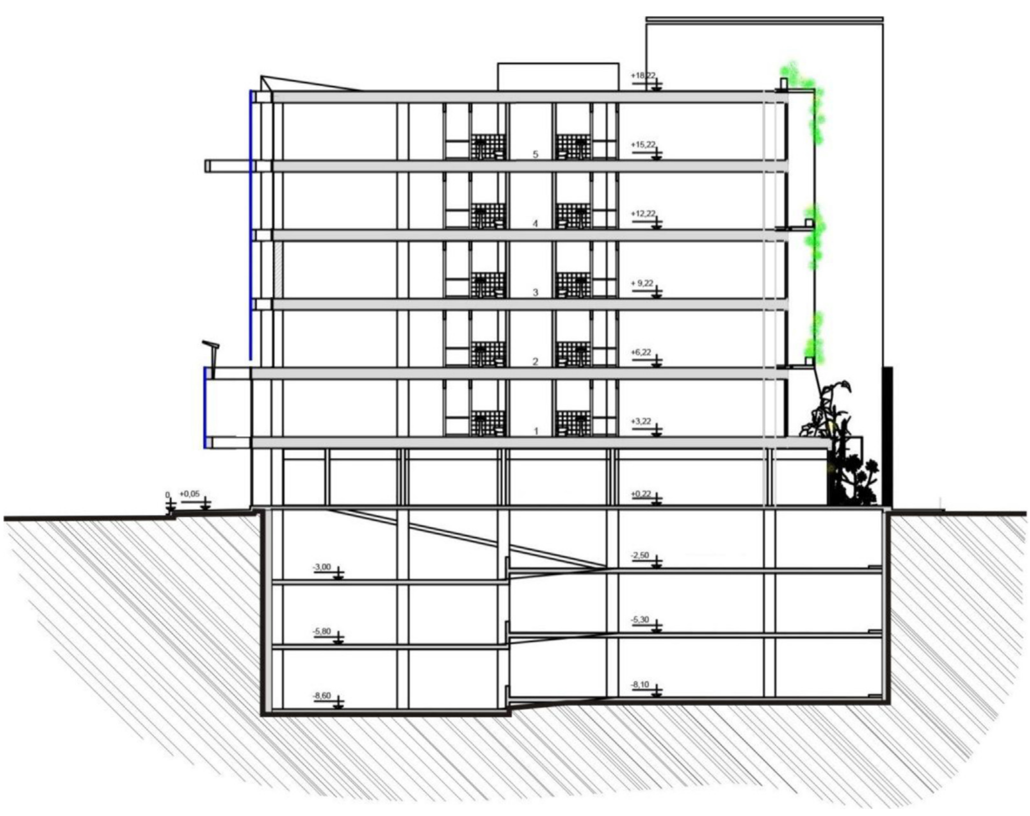

Fig. 2. Cross view of Palermo building. The DGFs are situated on the West side, one covering the first floor and the other covering floors 2nd to 5th. In the East side, a metallic structure supports a living green wall.

Table 2
Optical properties of the glass sheets used in the windows and in the DGF of Palermo building (AGC [28]; Pilkington [29]). LT: Light Transmission (%); Ext LR: Light Reflection of the exterior side (%); UV: Ultraviolet transmission (%); EA: Energy Absorption (%); SHGC: Solar Heat Gain Coefficient (%); Ug-value:Thermal Conductivity ($Wm^{-2}K^{-1}$).

Location of the glass panel		Office windows		DGF first floor
Description of the panel		Double hermetic glass (StopSol classic gray 6mm + air 9/12mm + (3 + 3) clear glass		Screen printed tempered clear glass (6 + 6)
Glass sheet commercial names		StopSol classic gray #1, 6 mm	(3 + 3) Clear glass	Eclipse advantage clear glass (without screen printing)
Thickness	**(mm)**	6	6	6
LT (%)		19	87	67
Ext LR (%)		34	–	26
UV (%)		5	–	–
Energy characteristicsEN 410 (2011)	**EA (%)**	45	–	19
	Shading coefficient	0.43	0.95	0.71
	Short wave shading	0.31	0.90	0.70
	Long wave shading	0.12	0.05	0.04
	SHGC (%)	37	83	61
Ug-value ($Wm^{-2}K^{-1}$) - EN 673		5.7	5.7	3.8

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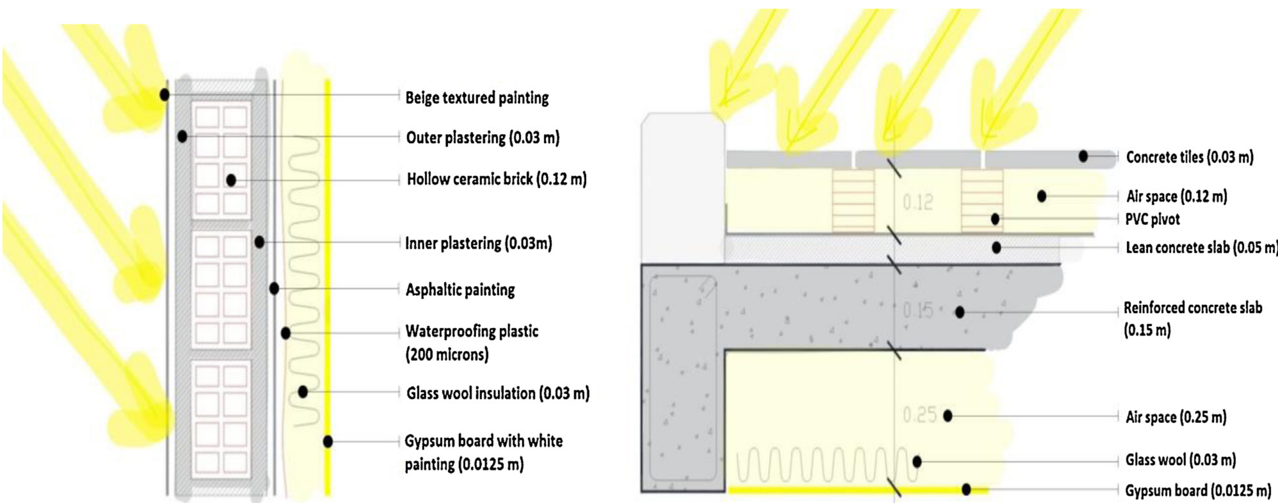

Fig. 3. Schemes of wall (left) and roof (right) layers.

Fig. 4. Building facades. (a) West DGF façades, one-storey ventilated DGF at the first floor and multi-storey DGF (2nd to 5th floor). (b) East green wall façade. (c) air cavity of the multi-storey DGF where the screen printing in the outer glass is visible.

Fig. 5. Rooftop technology (left) and individual air conditioner units (right).

system (Fig. 4). As shown in the photograph, the double skin façade is divided into two parts with different geometries: a DGF of "corridor" type and a DGF of "multistory" type, according to the classification of DGF structures given by Barbosa and Ip [23]. In a "corridor" DGF, the glass panel covers the rooms placed horizontally on the same floor while in a "multi-storey" DGF the cavity covers vertically and horizontally a number of rooms or even the entire building.

In Palermo building, the "corridor" part of the DGF covers the offices on the first floor and the glass panels are placed 2 m in front of the office windows. The rectangular air channel (2.00 m width, 23.75 m length, and 3.30 m high) is opened on top, bottom, and also on lateral sides. In the case of the "multi-storey" DGF, it is 12.00 m high and 23.75 m width, that is, the glass panels cover the offices from the second floor up to the fifth floor. The glazing shape is slightly curved (see Figs. 1 and 4) so the air channel has a variable width ranging from 1.70 m in the lateral boundaries down to 1.00 m in the façade centerline. The length and height of the air channel are 23.75 m and 12.00 m, respectively, and the bottom side is closed.

The general recommendations found in the literature in order to avoid overheating are the reduction of direct solar radiation and the use of low-e glazing instead common glazing. Guardo et al. [4] found that a reduction of external glazing transmissivity in 55% can lead to a 40% enhancement on the reduction in solar load gain. In Palermo building, glass panels were carefully selected in both, the windows in the offices and in the DGF, in order to reduce solar direct transmission and reflect the infrared wavelengths. Thus, for the glazed areas of the offices low-e hermetically sealed double glazed panels with an air chamber of 9/12 mm were used, with a gray colored low-e glazing in the side facing the DGF (StopSol Classic Gray 6 mm) and clear glass of 6 mm thick on the interior side. The low-e glazing reflects a high fraction of the heat emitted by the glass of the DGF when it is warmed by the sun. According to the data given by the manufacturer for each single glass layer (see Table 2), the light transmission of the whole panel is estimated in around 0.16 and a solar factor SHGC of around 0.31 (defined as the percentage of incident solar radiation admitted through a window, both directly transmitted and absorbed and subsequently released inward). In the case of the glass panel of the DGF, the selection resulted in a 0.012 m thick tempered clear glass panel (6 + 6 Tempered Eclipse Advantage Clear Glass). The solar transmittance of the DGF panel was reduced by using a screen printing in the back side – white in the first floor and black in the other floors – which blocks around 55–60% of the sunlight, that is, the solar radiation the reaches the window glazing is reduced. It is important to note that this screen painting also increases the energy absorption of the glass – and the glass temperature of the DGF, which is a negative collateral effect. Thus, in this case the selection of a low-e glass on exterior side of windows is mandatory in order to reduce the heat transfer along the windows.

3. Method

The building was monitored at a logging interval of 15 min from September 6th to December 6th, 2012. During this period, the building was unoccupied, windows were closed, curtains or shading devices were not installed yet, and air conditioning equipments were set off. The monitoring of a building when it is not occupied is of great importance, because all influence of user behavior and equipment management can be avoided and only the climate and building parameters influence the results. Two periods were selected for the analysis: a week of sunny days (October 12th–18th) for a detailed hourly analysis, and a period of 2 months (October 6th to December 6th) for the analysis of the average summer behavior in the two hottest months.

The exterior air temperature and humidity, and the solar irradiance on horizontal surface were registered at the rooftop of the building. Automatic 12 bits data loggers HOBO U8 and U12 were used to sense temperature (accuracy: ±0.35 °C, resolution: 0.03 °C at 25 °C) and relative humidity (accuracy: ±2.5%, resolution: 0.03%). Inside the office, a Li-200 pyranometer was used, (sensitivity: 90 μA per 1000 W/m^2, typical error: ±5%). Air velocity inside the cavity (at half the distance between glass layers) was measured every 5 min with a TSI air velocity omnidirectional transducer Model 8475 with voltage output (range: 0–5 V corresponding to air speed between 0 and 2.5 m/s, respectively; accuracy: ±3% of the reading), connected to a data acquisition system. Unfortunately, the probe was damaged by a glass cleaner during the monitoring period, so the velocity had to be taken manually. These manual readings were collected during one week, once a day (at the mid-morning or mid-afternoon), at the five floors, with a TSI VelociCalc Model 8345 air velocity meter (accuracy of 3.0% of reading or 0.015 m/s). At each level, vertical and horizontal components of the air velocity were registered. Solar irradiance on horizontal surface was sensed with a Kipp and Zonen Model CM21 pyranometer. In the offices, data loggers sensing air temperature were installed at 1.5 m over the floor level. Offices in the first (101, 103, 108), third (301, 303, 308) and fifth floors (501, 503, 505, 508) were monitored. Fig. 1 shows the location of the sensors at the third floor level. Also the temperature in the second underground garage was measured. In the DGF cavity, the air temperature and relative humidity at first (in front of office 103), third (in front of offices 301 and 303) and fifth floor levels (in front of office 503) were registered. In total, 16 data loggers were installed in the building.

4. Results

Fig. 6 shows the air temperature and the solar irradiance on horizontal surface from September 6th to December 6th. As explained before, in this period usually occur the hottest days of the cooling season, because of the predominance of clear sky days with high levels of solar irradiance and high air temperatures. The average temperature of the period was 22.2 °C. The maximum temperatures exceeded 35 °C in around 40% of the days, while the minimum temperatures reached 7 °C in the last weeks of September. As shown, the daily thermal amplitudes in sunny days oscillate between 10 °C and 15 °C. The week between October 12th and 18th was selected because it included seven sunny days with air temperatures that are typical of the cooling period.

4.1. Detailed results for one week (from October 12th to 18th)

Figs. 7–15 show the results of the hourly monitoring for the period from October 12th to 18th. This period includes days with high solar irradiances that reached 1100 W/m^2 at solar noon, as shown in Fig. 6. The first and third day presented slightly cloudy conditions in the afternoon. The mean daily solar irradiance on horizontal surface was 26 MJ/(m^{2}day), value which is 35% higher than the summer average value. Outdoor air temperature ranged from 11.0 °C to 32.3 °C, with a mean value of 21.6 °C. While the mean temperature value was near the summer average, the maximum temperatures were higher than usual. As shown, daily thermal amplitudes were higher than 10 °C, as is commonly found in dry climates. The relative humidity during the day is low, with average values between 20 and 35%. The minimum peak of relative humidity registered at noon of October 15th is not a measurement error but a meteorological effect due to a hot and dry air mass coming from the North (known as "the North wind"). Three different sensors around the building registered the same lowering of relative humidity and the value was also verified with the local airport measurements.

4.1.1. "Multi-storey" DGF behavior

Fig. 8 shows the outdoor air temperature together with the temperatures of the air inside the "multi-storey" cavity and in the Office 303 (in the center of the building). It is interesting to note that the temperature of the air in the cavity is near the outdoor temperature at the sunrise hour. During the morning, only diffuse solar radiation impinges on the DGF West façade, and the air in the cavity equals the outdoor air temperature. Since the solar noon, direct solar radiation impinges on the DGF and the temperature in the cavity starts raising, exceeding the outdoor air temperature and reaching its maximum value around the sunset. Thus, the higher differences between the outdoor air and the air in the cavity, of around 10 °C, occur between 17:30 and 18:00 in the afternoon, which is also when the office reaches its maximum temperature. During the night, the temperature in the cavity remains around 1.5–2 °C higher than outdoors because of the greenhouse effect of the DGF and the high temperature of the glass surfaces. These values are in accordance with the values reported in the literature, i.e., Pasquay [22] reported values ranging from 10 to 15 °C for three buildings with DGF that were monitored in summer in Germany, while Hashemi et al. [18] measured a difference of 8–10 °C between the cavity and outdoor temperatures, for a summer day in a Northwest DGF in Tehran, Iran.

The influence of solar radiation on the temperature of the cavity is evident in the analysis of the two consecutive days of October 15 and 16. These days presented almost similar levels of solar radiation (see Fig. 7), but the outdoor air temperature during the daytime was highly different. Despite this notorious difference in outdoor temperature, the temperature in the cavity was similar for both days, indicating that in cloudless days solar radiation has a stronger influence on the temperature of the cavity than the outdoor air temperature.

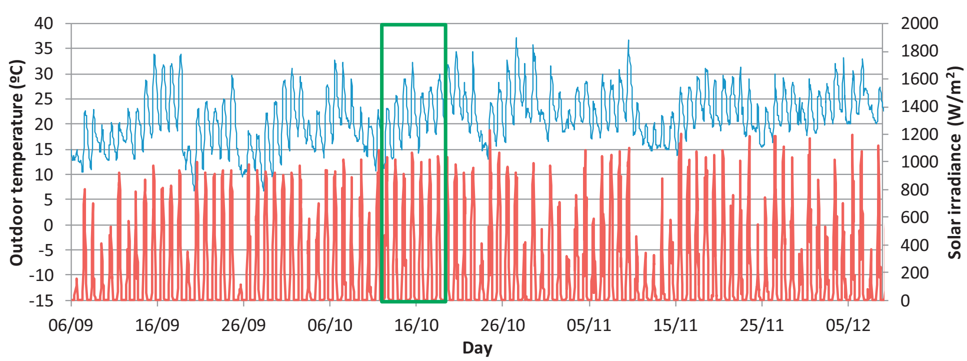

Fig. 6. air temperature and solar irradiance on horizontal surface for the period from September 6th to December 6th, 2012, measured in Salta city. The rectangle indicates the week selected for the detailed analysis.

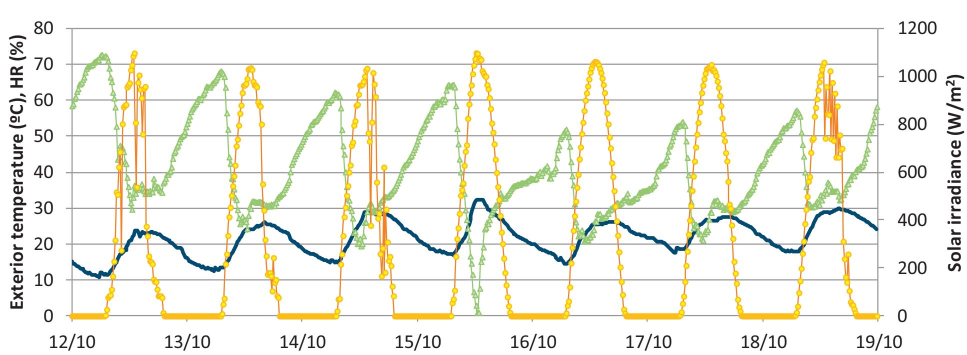

Fig. 7. Outdoor air temperature, relative humidity and solar irradiance on horizontal surface for the period between October 12nd and 18th, 2012.

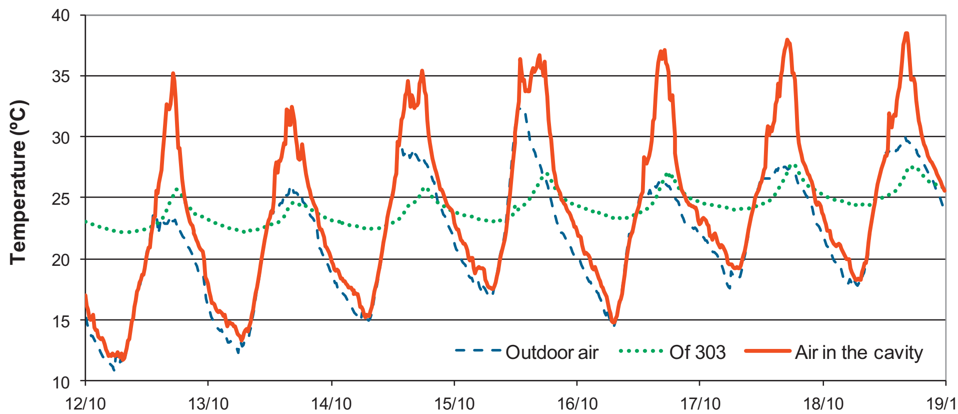

Fig. 8. Temperature of the air in the cavity, inside the Office 303, and outdoors.

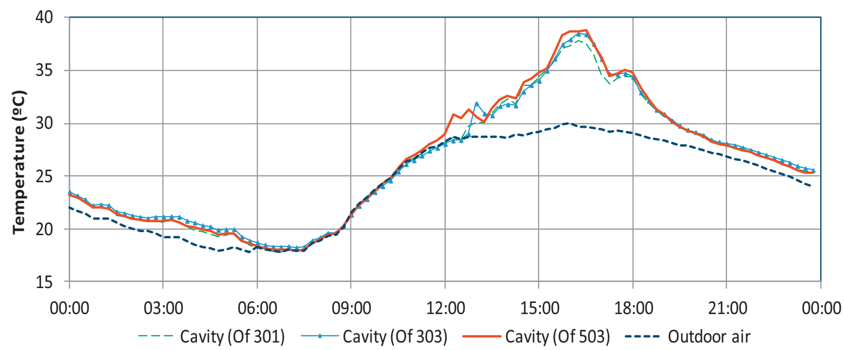

Fig. 9. Temperature of the air inside the double façade on October 18th, 2012.

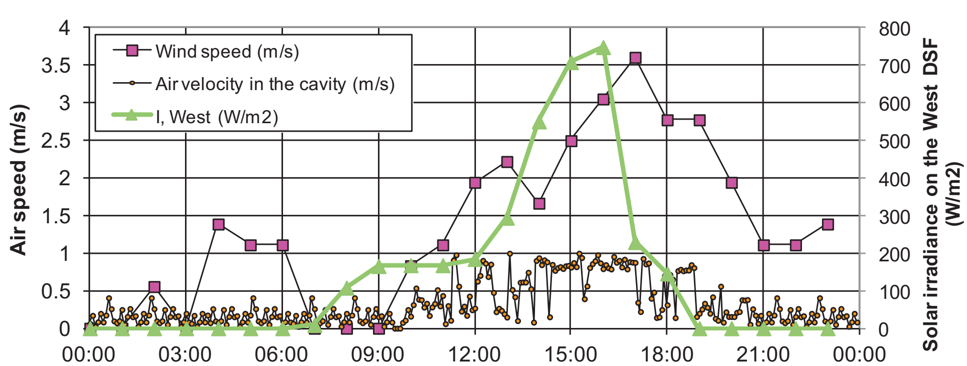

Fig. 10. exterior wind speed (m/s), air velocity in the cavity (m/s), and solar irradiance impinging on the West DGF façade (W/m^2) on October 18th.

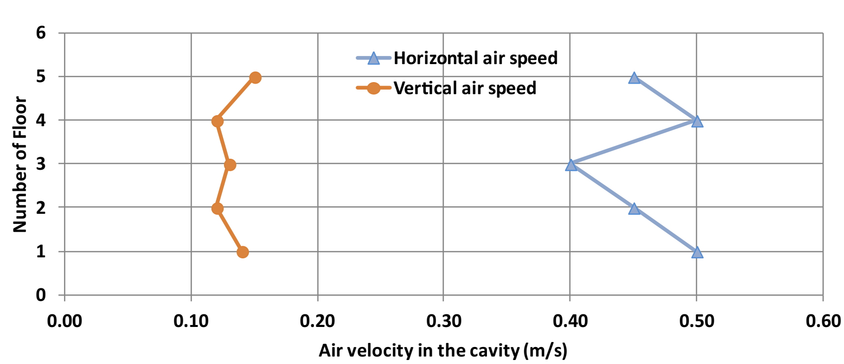

Fig. 11. manual records of horizontal and vertical air velocity in the multi-storey DGF façade, at different floor heights (floors 2 to 5), on October 18th at 10:00AM. Measured data for the first floor, of the "corridor" DGF is included for comparison.

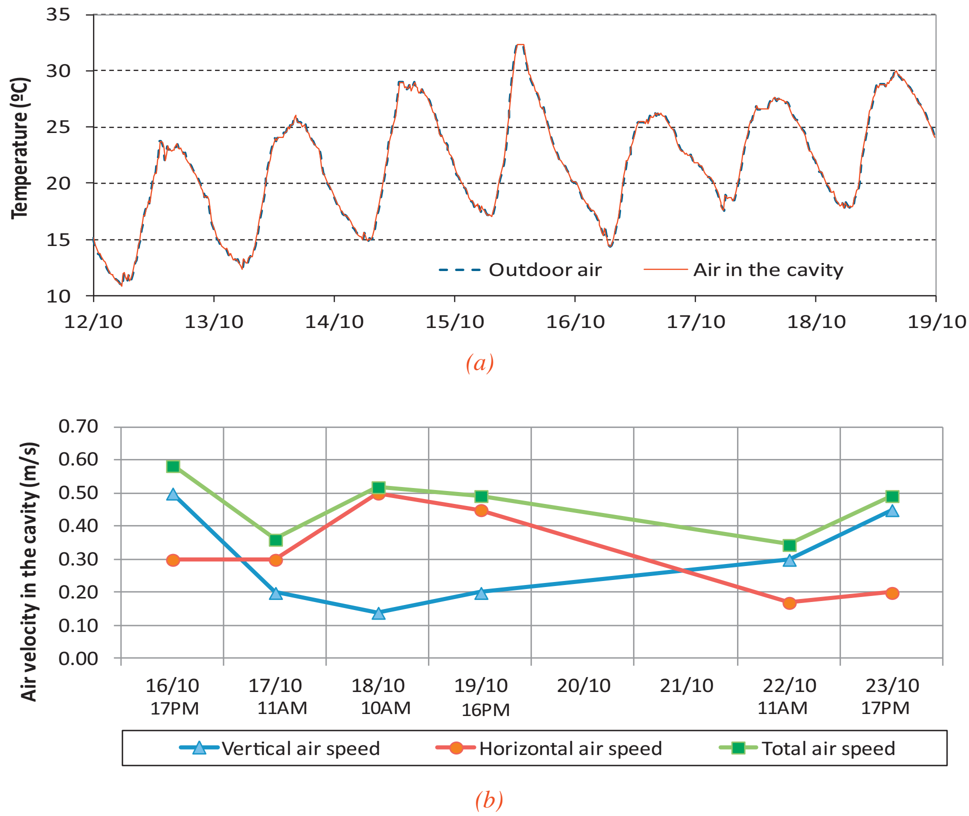

Fig. 12. (a) Air temperature in the cavity, at the first floor level in front of office 103. (b) Air velocity in the cavity, at the first floor level in front of office 103. The instantaneous air speed components on the vertical and horizontal directions are shown, together with the total air speed.

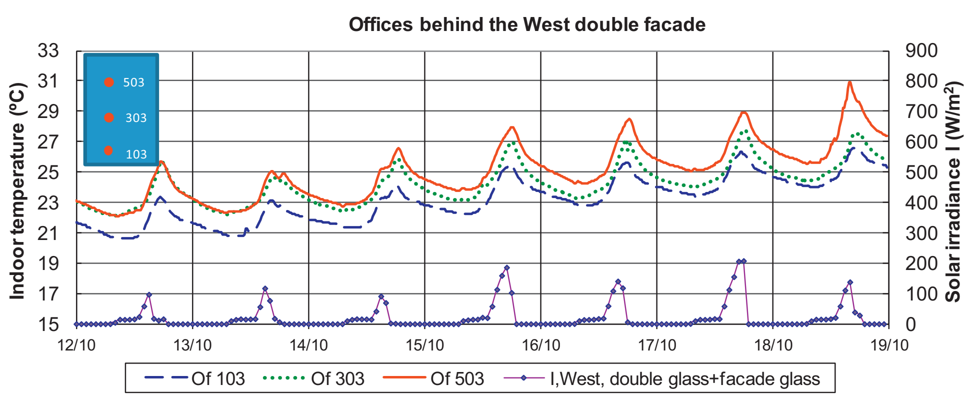

Fig. 13. Temperature (◦C) of three offices behind the West double façade and solar irradiance transmitted by the glazing (double hermetic glazing of office window + DGF glass panel) into Office 503 of the top floor (W/m^2), for the period between October 12nd and 18th, 2012.

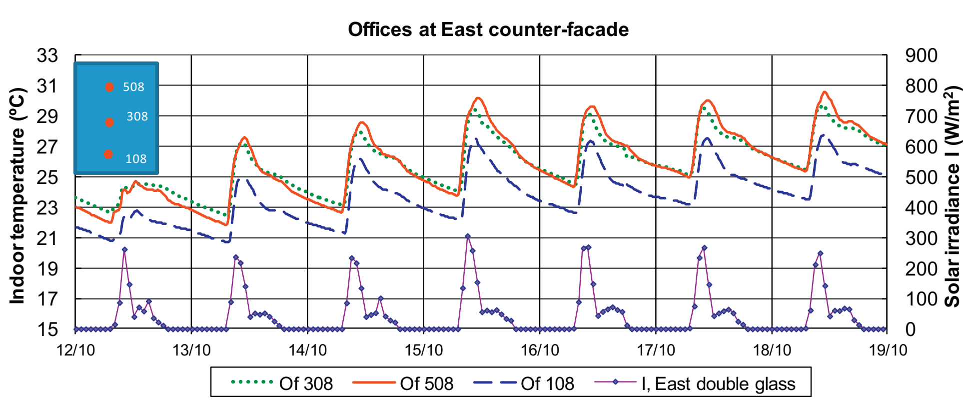

Fig. 14. Temperature (◦C) of three offices behind the East counter-façade and solar irradiance transmitted by the hermetic double glazing into Office 508 of the top floor (W/m^2), for the period between October 12nd and 18th, 2012.

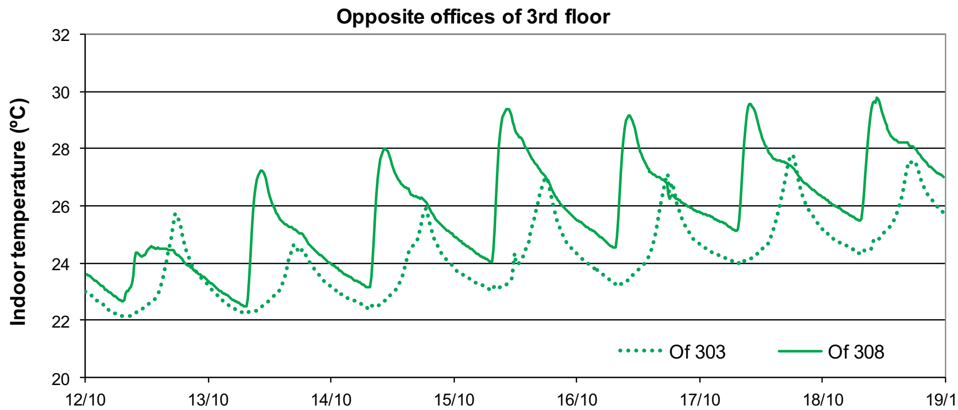

Fig. 15. indoor air temperature (°C) in opposite offices of the 3rd floor, for the period between October 12nd and 18th, 2012. Office 303 (West) faces the DGF while Office 308 (East) does not have DGF.

Fig. 9 shows the variation of the cavity temperature with the position inside the DGF. For clarity, only one day is presented (October 18th.), but this situation is similar for all the monitored period. An increasing temperature profile with height (characteristic of the buoyancy effect) is not found. Instead, Fig. 9 shows that the air temperature in the cavity at the 3rd and 5th floors were very similar, indicating that the wind-driven effect was higher than the buoyancy effect. Also there are not notorious differences at points in the same horizontal level, that is, between the temperature of the cavity at the center (Of 303) and at the lateral side (Of 301) on the 3rd floor. Because the temperature in the cavity is always higher than the outdoor temperature, it can be concluded that the ventilation rate is not sufficient to completely drain out the heat accumulation. But even in this situation, the reduction of the direct solar heat gain overpasses the effect of the higher air temperature and the global result is a reduction of the cooling loads of the building.

Fig. 10 shows the behavior of the air velocity inside the DGF together with the outdoor wind speed on October 18th. Measurements were made in the center point of the DGF, that is, in the 3rd floor, in front of the Office 303. The results show that both, the exterior wind speed and the air velocity in the cavity, are lower during the night, with average values of 0.42 m/s and 0.15 m/s, respectively. Thus, it seems to be a strong correlation between the wind speed and the air velocity inside the cavity. During the day, the air velocity in the cavity rises up to a roughly constant value of around v_{air} = 0.82 m/s in coincidence with the rise of the wind speed (average outdoor wind speed: 2.64 m/s). That is, the air velocity in the cavity is 3.2 times lower than the wind speed. This figure is lower than the proposed by Stec and Paasen [30], who found through CFD simulation that the air velocity in the cavity is around four times lower than the wind speed. The average air changes *ACH* in the DGF calculated for the sunny hours is around 120 air changes per hour. This value was estimated for the cavity geometry (flow area A = 15.6 m^2, volume of cavity V = 385 m^3) with an air velocity v_{air} = 0.82 m/s (ACH = 3600 v_{air} A/V).

Additionaly, Pasquay [22] developed a correlation between the opening area and the air flow, which is a straight line (airflow per m^2 of façade area, in m^3/(m^2 h) = 5.8 × percentage of opening per m^2 of façade area). In the case of Palermo building, the lateral opening area is 7% of the DGF façade area, so the correlation gives a value of 41 m^3/(m^2 h), which corresponds to 30 air changes per hour and to an average daily air velocity of around 0.20 m/s. In Palermo building, the measured daily average air velocity in the cavity is 0.32 m/s (around 48 air changes per hour), that is, the value predicted by Pasquays's correlation is lower to the value we have found in the measurements.

Fig. 11 shows the information about the air velocity provided by the manual measurements. On October 18th, air velocity in the cavity was registered at 10:00 for vertical and horizontal positions of the sensor at each floor along the DGF centerline (Offices 103,203, 303, 403, and 503). For Office 303, the vertical and horizontal air velocities were 0.13 m/s and 0.40 m/s, respectively. Thus, it is inferred that the angle between the air velocity and the horizontal is around 18°, that is, the air movement in the horizontal direction is stronger than in the vertical direction. This situation is similar at all heights. The inspection of manual data collected for other days and hours confirmed the observation that the predominant air flow in the DGF comes from the lateral openings. In general, in the DGF described in the literature, the ventilation occurs in the vertical so published work related to DGF with lateral ventilation is scarce. In this case the air movement inside the cavity is quite complex, with eddies and recirculation that produce the mixing of the air in the cavity [5,11]. In the case of horizontal flow, these authors predict the formation of rising columns of fluid near the walls of the double facade that are recirculated down to the center of the flow channel, promoting the flow mixing. Also the presence of the concrete structures supporting the DGF glazing increases even more the turbulence in the cavity. This air mixing can explain why the temperatures of the air measured at the 3rd and 5th floors were similar and it confirms the fact that the wind driven effect overpassed the buoyancy driven effect.

4.1.2. "Corridor" DGF

Fig. 12 shows the outdoor air temperature and the air temperature inside the "corridor" cavity placed in front of the first floor. This floor do not receives solar radiation because of the shading produced by the surrounding buildings. Both temperatures are similar, situation which is caused by the high ventilation level of the cavity (it is opened on the four sides) and because the surrounding buildings completely shade the DGF at this floor level. Only diffuse solar radiation reaches the DGF glass panel.

Fig. 12(b) shows the manual measurements of the air velocity in the cavity in two directions (vertical and horizontal) and the module of the total air speed. The total air velocity, obtained from the two components, oscillates between 0.36 and 0.58 m/s, with an average value of around 0.47 m/s. It is noted that the air comes from different directions, thus, sometimes the vertical air speed is higher than the horizontal one, and sometimes the opposite is true. Thus, in this case there is not a predominant direction for the air flow. Instead, it is variable due to the turbulence effects occurring inside the cavity. It is concluded that the "corridor" DGF slightly influences the indoor temperature of the offices behind it. Its effect is an additional reduction of the low values of diffuse solar radiation that impinges on the glazing panels of the offices. So, the DGF function is mainly related to aesthetics and other reasons (acoustic performance, continuity of the façade, etc.).

4.1.3. Thermal behavior of the offices

Fig. 13 shows the temperature of the indoor air for three offices at different levels facing the West double glazed façade. Also the solar irradiance behind the glazing (hermetic double glass panel + single glass of the DGF) is shown. The peak air temperatures inside the offices did not exceed the outdoor air temperatures, even without air conditioning or night ventilation. The lowest temperatures were registered in the office of the first floor, with a mean value of 23.1 °C for the period and a maximum value of 26.6 °C. Office in the top floor presents the highest air temperatures: a mean value of 25.0 °C in the period and a maximum value of 31.0 °C. Offices in the top floor are not shadowed by neighboring buildings so the solar radiation levels are higher than in offices of the lower floors. It is worth to note that the hour at which the air reaches the maximum temperature, between 17:30 and 18:30, is the hour at which the air in the DGF cavity reaches its maximum value. Thus, the air cavity and the offices are strongly governed by the solar radiation level.

Fig. 13 also shows the global solar irradiance reaching the floor of the Office 503. The maximum values occurred in the afternoon, as expected for the West orientation of the office, and it oscillated between 100 and 200 W/m^2. The shading effect of the glazing is clear when Figs. 8 and 10 are compared: the solar irradiance reaching the DGF is around 750 W/m^2 (at the peak hour) and it is reduced down to around 140 W/m^2 inside the office. Thus, the total reduction (DGF + hermetic double glazing panel) is of around 5.4 times the incident radiation figure.

Fig. 14 shows the indoor air temperature in the offices of the East counter-façade. As expected, the first floor presents the lower temperatures because the direct solar radiation is blocked by the neighboring walls. In the upper floors the temperature is around 2 °C higher than in the first floor; mean temperatures for the period are 23.7 °C (Office 108) and 25.8 °C (Offices 308 and 508). Maximum temperatures in the offices occur between 10:00 and 11:30 AM, due to the East orientation of the glazed areas. The highest temperature is reached by the office in the top of the building: on October 15th, the highest temperature was registered at Office 508 at 11:00 AM, with a value of 30.2 °C (outdoor air temperature at this moment was 26.8 °C). Offices in this façade were in thermal discomfort 67% of the hours in the period (42% in Office 108, 82% in Office 308, and 78% in Office 508). Temperatures of offices facing East are higher than those facing West because the double glazed façade in the West lowers the direct solar radiation that enters into the offices. The solar irradiance reaching the floor of the Office 508 oscillated between 250 and 310 W/m^2 and it occurred in the morning, due to the East orientation of the office.

Finally, Fig. 15 includes two opposite offices of the third floor, one facing the West DGF (Office 303) and the other facing East (Office 308). The office behind the DGF reached a mean indoor temperature 1.6 °C lower than the office facing East without the DGF. Also the average thermal swing in the office behind the DGF is lower than the opposite office. It is evident the effect of lowering the direct solar heat gain of the DGF. A green vertical façade was proposed as a feasible passive solution for the East façade. Plants are expected to grow in the next summer period.

4.1.4. Thermal comfort evaluation

The thermal evaluation was made following the ANSI/ASHRAE Standard 55-2010 [31] through the calculation *Predicted Mean Vote index (PMV) and the Predicted Percentage of Dissatisfied* (PPD). The PMV index predicts the mean value of the votes of a large group of persons on a 7-points thermal sensation scale (+3: hot, +2: warm; +1: slightly warm; 0: neutral; −1: slightly cool, −2: cool; −3: cold). The PPD index predicts quantitatively the percentage of thermally dissatisfied people who feel too cool or too warm. The ANSI/ASHRAE Standard 55 recommends a range of −0.5 < PMV < +0.5 and PPD < 15%. The equations for PMV/PPD are calculated as:

$$PMV = 0.303[\exp(-0.036M) + 0.028]L \quad (1)$$

$$PPD = 100 - 95\exp[-(0.03353\ \ PMV^4 + 0.2179\ \ PMV^2)] \quad (2)$$

where, M is the metabolic rated (W/m^2) and L is the thermal load on the body (W/m^2) calculated from the Standard. L depends on the clothing level, the metabolic rate, the indoor air velocity, the dry bulb air temperature, the relative humidity, and the mean radiant temperature.

In Palermo building, PMV and PPD were calculated for offices 103, 303 and 503 for the week between October 12th and 18th. The calculations were made for a metabolic rate of 93 W/m^2 (standing and light activity, corresponding to 1.6 met), clothing level of 0.5 clo (typical summer indoor clothing) (variables were: clo = 0.55 (0.078 m^2 K/W), and indoor air velocity of 0.1 m/s. The air temperature and relative humidity data were obtained from the monitored values. Because in highly glazed buildings the mean radiant temperature can depart from air temperature, in Palermo the indoor mean radiant temperature was estimated from thermal simulation of the building with EnergyPlus a validated software for transient thermal simulation of buildings developed by the U.S. Department of Energy [32].

The results for PVM and PPD are shown in Fig. 16. PMV values are inside the recommended range during the first hours of the period, with a constantly growing tendency in the next days. The last day (October 18th) is the most uncomfortable, with PMV peak values between 1.5 and 2 for in Office 503 ("slighlty warm" to "warm" perception), around one for Office 303 ("slightly warm"). Office 103 is the most comfortable, with PMV values that do not reach +1. PPD behavior is very similar to PMV ones, with a percentage of dissatisfied people that grows significantly in the last days. On October 18th, at the peak hour, around 22% of people feels "slightly warm" in Office 103, 32% in Office 303 and 68% in Office 503. In the whole period, offices' indoor environment is comfortable around 82% of the week in Office 103, 62% in Office 303 and 42% in Office 503. It is important to note that these values correspond to the building under no-occupancy conditions. When the building is occupied, the people will make use of the individual air conditioning units to achieve the thermal comfort. So the analysis of PMV and PPD values allows detecting when people will feel uncomfortable and thus the percentage of time when it is probable that the air conditioning units will be functioning.

4.2. Average behavior in summer

As explained, the measured temperatures were averaged for each office and for outdoor air on the period from October 6th to December 6th. The average temperature in the DGF cavity was obtained by averaging the data of all sensors placed inside this cavity in the same period. For every measured series, the mean maximum value was obtained by extracting the maximum value in each day of the period and averaging these values. The same procedure was used to obtain the mean minimum values.

Fig. 17 shows the absolute maximum, mean maximum, mean, mean minimum, and absolute minimum air temperatures in different offices of the building. For simplicity, only the offices in the building centerline are presented (offices 103, 303, and 503 towards West; offices 108, 308, and 508 towards East). The outdoor air temperature ranged from minimum values around 11.0 °C up to

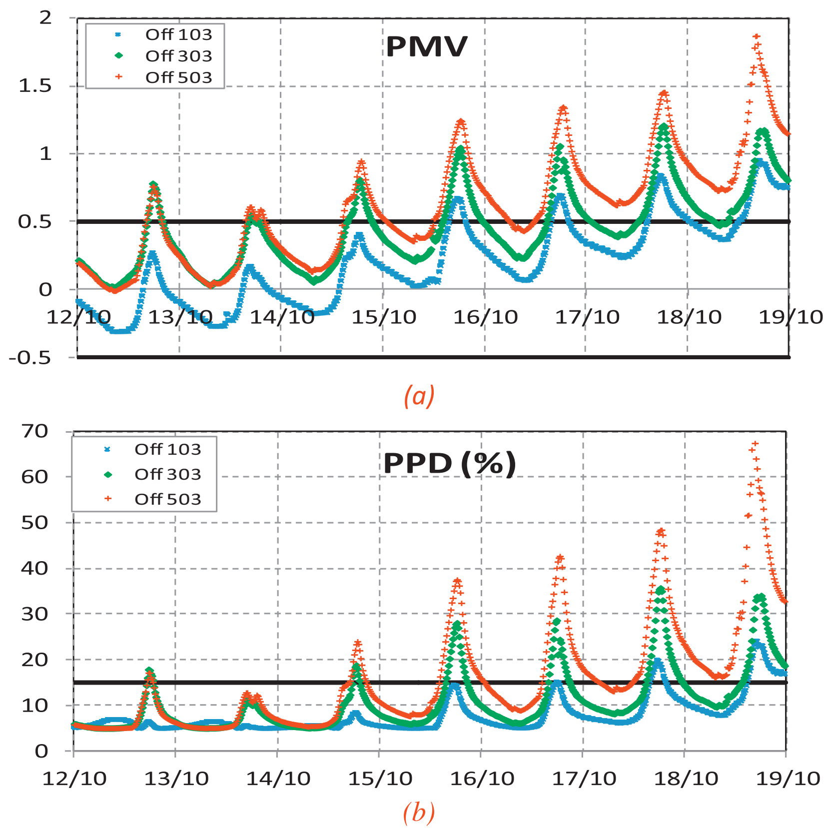

Fig. 16. (a) PMV and (b) PPD calculated for the offices 103, 303, and 503, for the period between October 12nd and 18th, 2012. The black lines show the suggested values of ASHRAE 55 Standard for hygrothermal comfort.

34.5 °C for the hottest days. The mean outdoor air temperature in the period was 23.3 °C with average maximum and minimum values of 26.8 °C and 18.3 °C, respectively. The mean temperature of the period was 2.0 °C higher than the typical 30-year average summer values provided by the Meteorological Service, situation that gave us the opportunity to analyze the behavior of this building under rigorous summer conditions.

It is interesting to note that, whereas the mean temperature of the air in the multi-storey cavity (2nd to 5th floor) was only 1 °C higher than outdoors, the maximum peak values in the cavity were 10 °C higher than outdoors, reaching 45 °C.

Fig. 17 shows that the average temperatures in the offices were around 2.2 °C higher than outdoor mean temperature. The lowest mean temperatures were registered in offices at the first floor, with mean values around 25.0 °C and indoor amplitudes of 2.5 °C. In particular, Office 103 presents the lowest values of all offices. The reason is that this office is situated in front of the ventilated one-storey DGF, whose temperature was identical to the outdoor air temperature because of the high level of ventilation of the cavity. On the contrary, in the offices situated in front of the multi-storey DGF from 2nd to 5th floor, the mean air temperatures were 1 °C higher (around 26 °C) than in the first floor. The offices in the top floor registered the highest values (with a mean value of 26.7 °C and thermal amplitudes of around 3 °C). The peak air temperatures in the period (red dots) were around 30.4 °C (for the West offices) and 31.7 °C (for the East Offices), indicating that even in

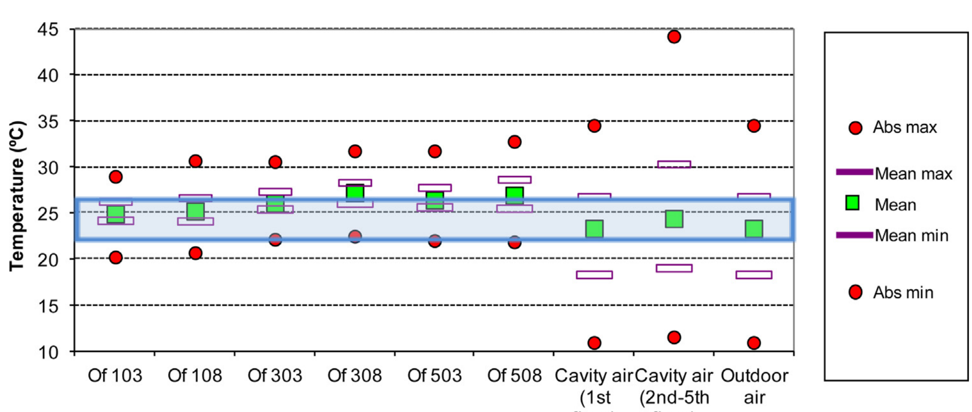

Fig. 17. Absolute maximum, mean maximum, mean, mean minimum, and absolute minimum air temperatures in the different offices, for the period of October 6th to December 6th. Comfort zone is marked in a blue rectangle.

the hottest days without air conditioning or night ventilation, the indoor air temperature never exceeded the outdoor air temperature. In highly glazed buildings, it is usual that indoor temperatures exceed the outdoor ones in several degrees, so the results found in Palermo building are promissory. Moreover, the good results obtained in the top floor evidences the adequacy of the roof technology, with a ventilated air chamber and thermal insulation for climates with high solar radiation levels.

5. Conclusions

Field measurements under no-occupancy conditions were carried out in an office building with a West DGF, for a cooling period in the arid climate of Salta city, Argentina. It is concluded that the overheating caused by DGFs in Mediterranean or warm climatic conditions can be avoided by an appropriate selection of glazing and ventilation. Furthermore, a well-designed DGF can reduce the energy consumption of the building in the cooling periods, even when it faces towards West.

The main results and recommendations are summarized below:

- The temperature of the air in the cavity is higher than outdoors during the whole day. The difference with the outdoor air oscillates between 2 °C (night) and 10 °C (day). This figure is in line with the results found in other DGF with different authors X.
- The addition of the screenpainting layer to the external DGF panel strongly reduces the direct solar gain in the offices. This strategy is more economic than using a special filtering glass (such as low-e or heat mirror glazing) for the DGF. This solution was not found in the literature so it is proposed as a new cost-effective possibility for hot sunny climates. In moderate climates the winter situation should be checked.
- It is recommended to use glazing with high insulation properties and, if possible, low-e coatings, for the glazed areas of the offices facing the DGF cavity. The insulation of the double glazing minimizes heat transfer from the warmer air in the cavity, while the low-e minimizes the radiative heat transfer from the DGF glass. The suggestion of using this type of glazing is in accordance with other authors [10–12].
- The lateral (natural) ventilation is effective to partially remove the heat accumulation of the DGF. The air velocity in the cavity (0.82 m/s) is 3.2 times lower than the wind speed, providing a ventilation rate of around 120 air changes per hour. The results of this paper provide experimental evidence that this ventilation mode could be an effective alternative to vertical ventilation.
- The addition of mechanical ventilation is also a suitable option. It is related to the insulating level of the office glazing (high *U*-values will be more benefited by high ventilation rates that low *U*-values).
- Finally, when thermal simulations of buildings with DGF laterally ventilated are made, it seems reasonable to use an average value for the air changes inside the cavity instead of a calculation of the ventilation rate due to the stack effect, in accordance with Pasquay [22]. This is because, in DGF with lateral ventilation, the air velocity in the cavity depends more on wind speed and direction than on the temperature driven ventilation. The geometry of the neighboring buildings should also be considered as they modify the wind profile.

The paper has contributed with valuable experimental information about the thermal behavior of DGF in warm Mediterranean climates. These façades can be applied both, in new buildings or in the refurbishment of old buildings. Because the use of this type of façade in arid and sunny climates is expected to grow exponentially in time, as occurred in other regions of the world, the results obtained in this research are expected to be of high interest.

6. Aknowledgements

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