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The multi-azimuthal window as a passive solar system: A study of heat gain for the rational use of energy

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ABSTRACT

Multi-azimuthal windows or bay windows (MW) are projected windows and are characterized by their ability to capture more energy than flat windows (FW) while using the same opening dimension in the wall, meanwhile, the increase of surface area may increase the chances of heat loss. The evaluation and quantification of the solar heat gains for different geometric dispositions allow for the selection of the adequate MW and to predict the best passive conditioning system. Three geometric variables for defining the case studies are considered: horizontal projection, the angle of the side panels, and the area of the glass panel by orientation. This investigation calculates the thermal performance of a MW in a specific setting and climate and a comparison figure is proposed: "Multi-azimuthal/FlatSolar Gain Factor" (M/FSGF), which is defined by the solar energy transmitted through the MW relative to the FW using a window opening of the same dimension in the wall. The M/FSGF changes hour by hour in the day being greater in the early hours and in the afternoon hours. This calculation is complemented with experimental measurements in two boxes which were built at a scale of 1:1. We conclude that a MW with an angle of 45°, in the side panels, reaches an M/FSGF daily average value of 1.20, which means a 20% more solar gain than the daily average solar gain of a flat window. In addition, a window with an angle of 90° in the side panels is the best for temperate climates, with daily average solar gains of 27% greater than those of the flat window.

1. Introduction

1.1. Architectural element: the window

Taking into consideration that buildings are globally responsible for between 30% and 40% of all primary energy consumption, emissions of greenhouse gases, and waste generation [1], the window systems in a building have an important influence on the amount of energy consumed by heating, cooling and lighting. This is due to the overall heat transfer coefficient (U-value) of the windows, which is typically five times greater than those of other opaque components of the building skin (walls, roofs, etc.). However, in the last decade, there has been an increase in the percentage of transparent building envelopes when compared to opaque building envelopes in modern buildings. This trend has continued, bringing almost a complete disappearance of opaque components [2]. Therefore, the selection of a proper window system, especially in cold and temperate climates, is one of the most important and effective ways of conserving energy within building strategies [3].

The research of the characteristics and properties of window systems and their integration into the building envelope has become indispensable for many researchers. Their aim has been to create transparent façades with an optimal balance of natural lighting, interior thermal conditions and energy consumption in all seasons. Lee [4] analyzed the optimization of annual energy consumption associated with the physical properties of windows (U-value, solar heat gain coefficient SHGC, and visible transmittance) in five typical Asian climates. They presented optimized guidelines design for the properties of windows for each type of climate. These guidelines are presented along with graphics that demonstrate the properties of the window in relation to the energy performance of the building.

Maurer et al. [5] had proposed an advanced calculus for radiation transmission in transparent solar thermal collectors (TSTC). This model allows the prediction of solar gains and the solar factor (g) in the building where the system is integrated. The theoretical model presents a joint simulation between TSTC and an interior space for different façade solutions. Research findings indicate savings

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Nomenclature

α	Angle of the side panel of multi-azimuthal window [°]
P	Linear projection from the façade [m]
Cl	Length of the central panel [m]
L_1 and L_2	Length of the lateral panels[m]
ST_1	Total radiation of panel 1 (kJ/h m^2)
A_1	Surface area of the panel. usually considered of 1 m^2
I_{1b}	Beam solar radiation on panel 1 (kJ/h m^2)
i_{1d}	Diffuse solar radiation on panel 1 (kJ/h m^2)
I_{1r}	Reflected solar radiation on panel 1 (kJ/h m^2)
$\tau_{1\beta}$	Beam solar radiation transmitted by a panel with 1 glass
$\tau\delta$	Diffuse solar radiation transmitted by a panel with 1 glass
MW	Multi-azimuthal window
FW	Flat window
ET	Total radiation admitted through MW
EV	Total radiation admitted through FW
M/FSGF	Multi-azimuthal/Flat solar gain factor (dimensionless)

of primary energy of around 30% when replacing opaque envelope with TSTC, while at the same time, improving visual transparency. The developed model (Type 871) allows a precise stationary prediction of the collector gain, the heating load, and interior surface temperatures to be used in detailed thermal comfort analyses.

Saleh et al. [6] had used computer models to study advantages of the horizontal rotation of the glass in a window. They conclude that the rotation of the glass is an efficient method to increase and to reduce interior solar heat gain in a building (with cooling or heating purposes, respectively). Solar heat gains can be maximized to 63% when compared to a standard window.

It is important to consider how the window is an architectural element in itself along with the studies of these physical properties in order to achieve a better picture of the energy efficiency of the building. The window is basically an essential architectural visual device that connects interior and exterior energy flows. The window is part of the building envelope where multiple filters or barriers can be characterized as active or not, according to the momentary comfort needs of the habitants. It is understood as a three-dimensional envelope architectural element in which its own bi-dimensional constructive element glass is part of the system.

1.2. Multi-azimuthal windows (MW)

Multi-azimuthal windows (MW), from a geometric aspect, contain a central window, parallel to the façade, and side windows that can have different amplitude angles. In Fig. 1 a plan of a generic MW is presented in the Southern Hemisphere. The true North in this case corresponds to a 180° azimuth and faces the Equator. See also angle α (the angle formed between the side window and the façade, between 0° to 90°) and the linear projection, which is the distance from the plane of the facade to the edge of the center window (between 0.35 m to 1.00 m).

From the perspective of solar geometry, MWs are more likely to collect solar energy. They have a greater exposed surface to the exterior in relation to the size of a flat surface. Therefore create greater exchanges of thermal and luminous energy. These characteristics make them very interesting for use as passive solar systems where appropriate shading may be needed depending on the season [17].

These windows, formerly called Bay Windows, are not new. The first designs appeared in the fifteenth century, especially in climates with low heliophany and little direct solar radiation, and were used to increase the uptake of diffused light, for example in England. The systematic use of the Bay Window, understood as an architectural element, is associated with the Victorian and Edwardian Periods. According to Beckett [7] this type of window, employed in order to create the illusion of more voluminous interior spaces allowed a greater flow of light into the interior. These also created a wider field of view to the outside, something that cannot be achieved with a window inserted into a wall.

Formal and esthetic conditions have transcended geographical boundaries and they are used today in different climates, such as in Mendoza, Argentina (latitude −32.88S, longitude −68.81W) which is characterized as having high heliophany and abundant solar radiation. These windows result in highly variable energy behavior along with an elevated formal esthetic accepted by general society as associated with greater visual comfort and a higher standard of living. See Fig. 1 for some examples.

Currently, some of these windows have been studied in relation to the climate and how they behave as efficient integrated solar systems. One case, shown in Fig. 1 is a low cost housing building in Izola, Slovenia (latitude 45.53N, longitude 13.66E) with high heliophany and abundant available solar radiation. The project intends to increase their tridimensional space in the building envelope so it may be used in different ways throughout the day concerning aspects of thermal comfort with bioclimatic strategies in the summer (shade and natural ventilation) and in the winter with direct and indirect solar gains.

This paper provides an in depth analysis of the MW as a passive solar system in order to know its solar behavior. As there are no previous studies on MW from the heating point of view, the major research challenges of this work are:

1. To calculate and compare the solar energy transmitted by the MW compared to a flat window FW, with the same opening dimension oriented toward the Equator.
2. To establish a "gain factor" to classify the MW within the criteria of energy sensitivity in relation to its functionality as a passive solar system.
3. To analyze the thermal behavior on a box scale of 1:1 in a continental temperate climate (with high heliophany and abundant available solar radiation), in order to compare the calculated energy with thermal behavior.

It is important to emphasize that, the thermal mass plays a very important role to regulate the indoor environment stabilizing temperatures and also accumulating the energy collected by the window. As this study studies cases with the same amount and distribution of thermal mass, it has not been taken into account in the analytical calculation. However in the measurements of the prototypes all the heat transfer surfaces are taken into account. The floor has a thermal mass of brick of 3.75 m2 (0.26m3). MW perform as descript if the building has thermal mass, otherwise the enhancement of the heat transmittance of windows could play against the desired thermal gain.

2. Methodology

This methodology employs two main approaches. The first is analytical, in which equations determine the energy potential of the different geometric cases of MW. The second approach works with *ad hoc* experimental boxes built to perform *in-situ* measurements under controlled variables. The complementary analyses between the calculations and the box experimentation build a solid method-

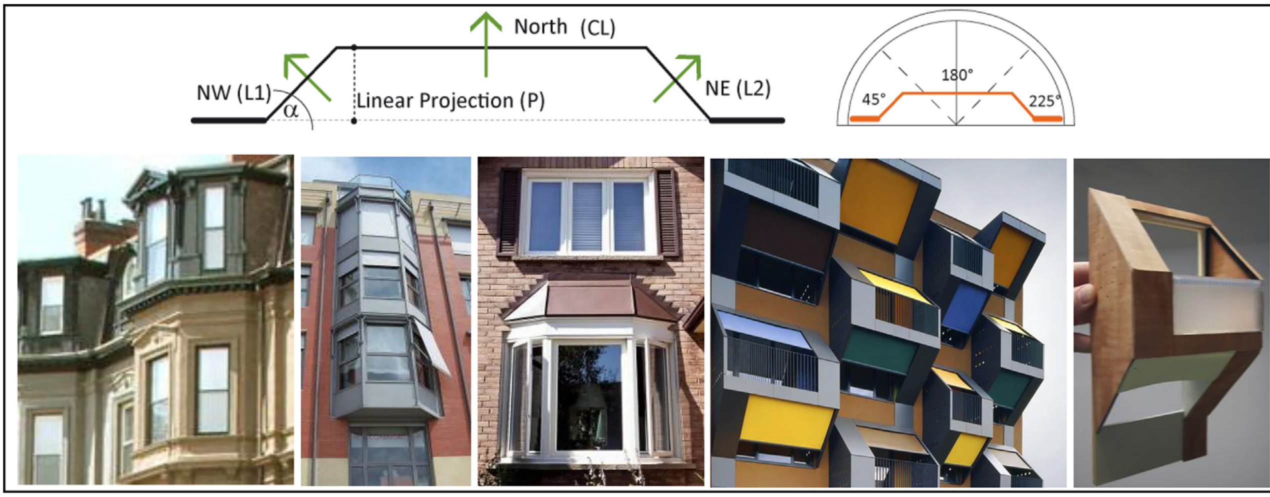

Fig. 1. Scheme for a Multi-azimuthal window orientated towards the equator and MW with azimuthal angles of each pane. Traditional buildings with projected windows in London England, in Valladolit Spain and Mendoza Argentina. Social housing in Izola, Slovenia by Ofis (lat 45.53, long 13.66).

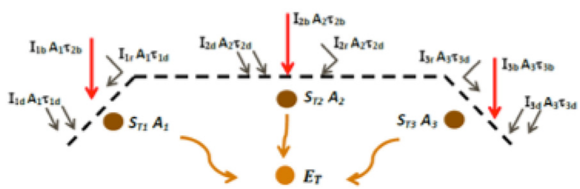

Fig. 2. Calculation of energy gain azimuthal Multi-Window (MW).

ology similar to that used by Carlos [8] and Baker [9], among others. The results obtained from this methodology allow a greater degree of knowledge to be transferred and replicated within scientific, academic and professional environments.

2.1. Energy potential

In order to analytically predict the quantity of energy a MW can contribute to a room, the total radiation [$S_T A$] (Liu and Jordan [10]) was calculatedin kJ/h using each MW pane, for every hour during a clear sky day in winter and in summer. For these calculations, an albedo of 0.3 (which corresponds to average dry concrete or grass) was assumed and the daily solar radiation data on the horizontal surface provided by Grossi [11] is incorporated. Vertical panels (slope $\beta = 90°$) and clear panes of glass, 3 mm thick, were employed. For Transmittance (τ), the calculation proposed by Duffie and Beckman [12] was used.

The expression used for each panel is shown in Eq. (1) and Fig. 2 shows a graphic of the calculation of the solar heat gain.

$$S_{T1}A_1 = I_{1b}A_1\tau_{1b} + I_{1d}A_1\tau_{1d} + I_{1r}A_1\tau_{1d} \quad (1)$$

Where: $S_{T1}A_1$ is the total radiation collected by each glass panel; I_{1b} is the beam radiation incident to the glass panel; $A_1$is the area of the panel; τ_{1b} is the beam solar radiation transmitted through the glass panel; $\tau_{1b}I_{1d}$ is the diffuse solar radiation; and τ_{1d} is the diffuse solar radiation transmitted for angle ø1 at constant 60°.

Finally, the total radiation ET in KJ/h which is transmitted by the MW will be according with Eq. (2):

$$\begin{aligned} \boldsymbol{E_T} = \boldsymbol{S_{T1}A_1} + \boldsymbol{S_{T2}A_2} + \boldsymbol{S_{T3}A_3} = A_1\left(I_{1b}\tau_{1b} + I_{1d}\tau_{1d}\right. \\ \left. + I_{1r}\tau_{1d}\right) + A_2\left(I_{2b}\tau_{2b} + I_{2d}\tau_{2d} + I_{2r}\tau_{2d}\right) \\ + A_3\left(I_{3b}\tau_{3b} + I_{3d}\tau_{3d} + I_{3r}\tau_{3d}\right) \end{aligned} \quad (2)$$

Where: $E_T$is the collected energy from the three panes of glass acting as a whole, and$S_{T1}A_1 + S_{T2}A_2 + S_{T3}A_3$ is the radiation received by each panel of glass.

It is taken for granted that the radiation transmitted by each panel of glass does not reach the other, i.e., the radiation does not crossover. This situation can occur only at low solar altitude (sunrise and sunset).

During the hours when the sun is at a higher altitude, the sunlight passing through the glass panel directly affects the floor space temperature. As $I_{1r} = I_{2r} = I_{3r}$; $I_{1d} = I_{2D} = i_{3D}$, $A_1 = A_3$. Eq. (2) is simplified in Eq. (3):

$$\boldsymbol{E_T} = A_1\left(I_{1b}\tau_{1b} + I_{3d}\tau_{3d}\right) + A_2\left(I_{2b}\tau_{2b}\right) + \left(2A_1 + A_2\right)\left(I_{3d} + I_{1r}\right)\tau_d \quad (3)$$

In order to compare the solar heat gain of the MW with the FW, total hourly radiation transmitted by a flat window (Ev), maintaining the same opening dimension, was calculated (Eq. (4)).

$$E_V = I_{2b}A_V\tau_{2b} + I_{2d}A_V\tau_d + I_{2r}A_V\tau_d \quad (4)$$

In order to compare the power gained by the MW with respect to FW it is defined the ratio between the total radiation ET entering a MW with the Ev total radiation entering through a FW, where AV is the area of the opening (see Eq. (5)).

$$\frac{\boldsymbol{E_T}}{\boldsymbol{E_V}} = \frac{A_1\left(I_{1b}\tau_{1b} + I_{3d}\tau_{3d}\right) + A_2\left(I_{2b}\tau_{2b}\right) + \left(2A_1 + A_2\right)\left(I_{3d} + I_{1r}\right)\tau_d}{I_{2b}A_V\tau_{2b} + I_{2d}A_V\tau_d + I_{2r}A_V\tau_d} \quad (5)$$

This set of equations was applied to study MW behavior with different geometric variables in the four seasons.

2.2. Experimental test box

Experimental tests are necessary to measure and evaluate windows in a controlled situation. Windows integrated in built homes are difficult to measure for evaluating its behavior due to different variables that could interfere such as different aspects of use. In experimental test boxes it is possible to control many of the variables involved in the study and this is a significant advantage. Moreover, experimental tests also allow to simultaneously measuringidentical MW and FW.

Two models were built at a scale of 1:1 in the city of Mendoza, Argentina (latitude −32.88S, longitude −68.81W). Both were built with the same materials and with the same geometry and the same orientation (fixed variables). The dimensions of the box were 1.50 m

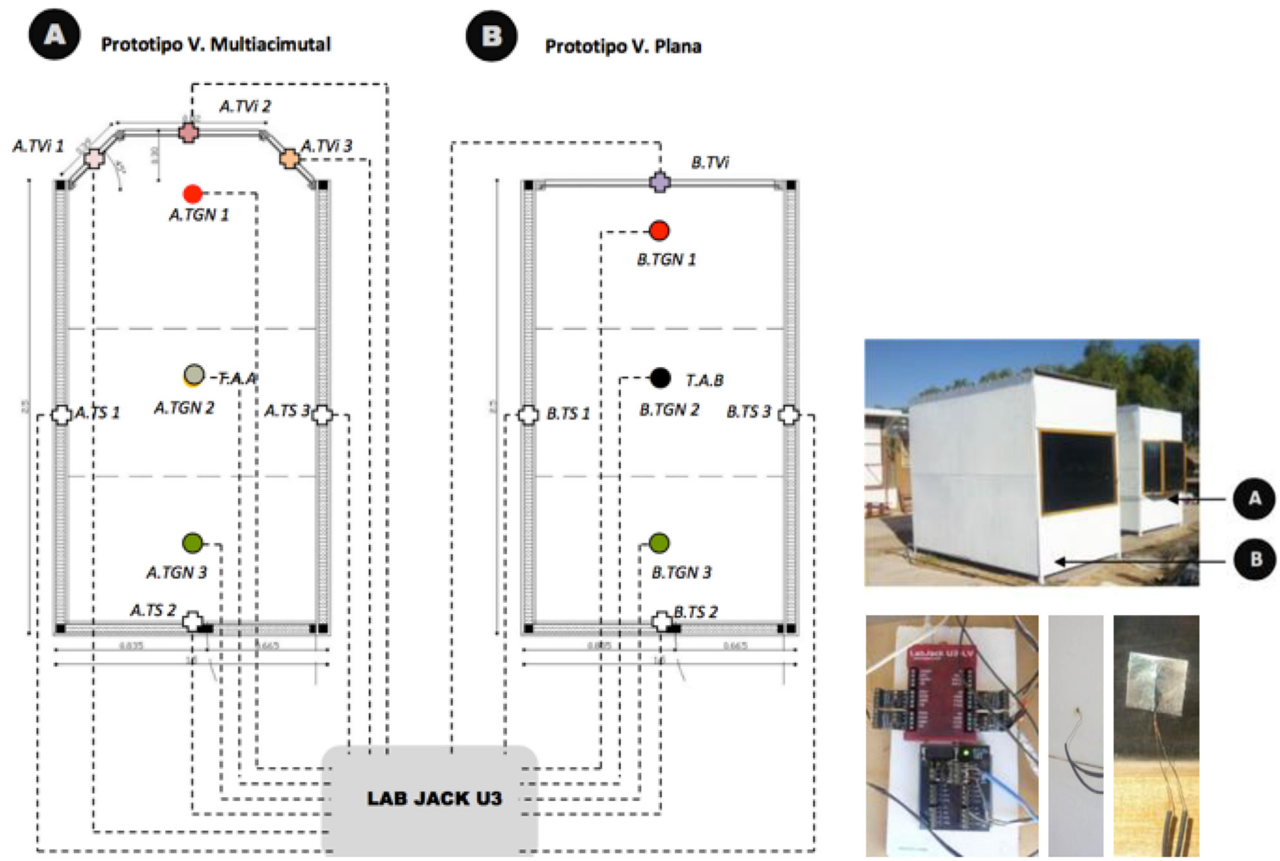

Fig. 3. Wiring plan of the sensors in the prototypes.Prototype Photos. Equator view with MW (Box A) and FW (Box B) (left). Data logger with thermocouples connected. Thermocouples in opaque wall and thermocouples in the glass of windows.

Table 1
Exposed surfaces in reference to the entire envelope and the windows.

	Transparent Elements K = 5.3 W/m2 k		Opaque Elements K = 0.803 W/m2 k			Total Exposed Envelope	Finishing Opaque Elements
	windows	*walls*	*Ceiling*	*Floor*	*Door*		*Absorption*
A **Prototype A** *Multi-azimuthal*	*7.10%* *1.85 m2*	*58.78%* *15.40 m2*	*14.31%* *3.75 m2*	*14.31%* *3.75 m2*	*5.5%* *1.45 m2*	100% 26.20 m2	*Matte white*
B **Prototype B** *Flat*	*6.30%* *1.65 m2*	*59.23%* *15.40 m2*	*14.43%* *3.75 m2*	*14.43%* *3.75 m2*	*5.7%* *1.45 m2*	100% 26.00 m2	*Matte white*

of width 2.50 m of length and 2.50 m of height. The window opening in each test box was 1.5 m of length and 1.10 m of height. In box A, the most common MW of the zone was utilized ($\alpha = 45°$ P = 0.50m) and in box B a flat window was built [13] Fig. 3 show two pictures with the Equator view and with identification Box A with MW and Box B with FW.

Table 1 shows text boxes characteristic data: exposed surfaces from each elements of the envelope and percentage, thermal conductance and the finishing of opaque elements.

Measurements of meteorological data were taken in the winter by a fixed base station, Pegasus brand EP2000, located 3 m high and without obstacles (at no less than 20 m). The station consists of a wireless console, a data recording device and sensors that detect temperature, humidity, wind speed, wind direction and solar radiation. Data was taken every 15 min.

In order to measure the interior surface temperatures of the opaque and transparent elements, as well as radiant temperature measurements, a LabJack U3-LV data recording device was used with 36 thermocouples type T. It was programmed to take data every 15 min by DaqFactory, see Fig. 3.

2.2.1. Location and climate

At the site of the experimental boxes, the climate presents high heliophany and abundant solar radiation. Based on the climate classification by Roig [15], Mendoza is identified as a continental Mediterranean province with an arid to semiarid climate located in western central Argentina. It is exposed to the action of the Atlantic anticyclone movements with foothills, depressions and plainson the Atlantic side and with high mountains and some volcanic regions to the Pacific. It is noted that in the Köppen classification [16], Mendoza belongs to both Bwh, warm desert, and Bwk, cold desert categories.

Air temperatures: both maximum and minimum temperatures demonstrate severe winter periods with temperatures below 5 °C.

Table 2
MW cases analyzed.

Cases	α	L1 [m] Cl (m) L2 [m]			P [m]	
	SIDE ANGLES	1	Central	2	Bay	Projection
Case 1	30	0.66	0.79	0.66	1.65	0.30
Case 2	45	0.47	0.99	0.47	1.65	0.30
Case 3	60	0.38	1.27	0.38	1.65	0.30
Case 4	90	0.33	1.65	0.33	1.65	0.30

Summers are rigorous, as temperatures exceed 24 °C during most of the summer cycle. The average annual temperature is 11.9 °C. The annual heating Degree Days (base temperature 18 °C) is 1384 °C day/year.

Rainfall is scarce and most intense in the summer. Precipitation reaches an annual average of 218 mm, reaffirming the semiarid characteristics of theland. Prevailing winds are from the South throughout the year. The fastest southern winds are recorded in the summer. In winter, the speeds are usually low, with 35% of the time characterized as calm.

The city of Mendoza has a significant incidence of Global Solar Radiation. In the summer, GSR ranges between 25–27 MJ/m^2 day is usually registered; while, in the winter, the lowest values are between 9–10 MJ/m^2 day on the horizontal plane.

In order to study the possibilities of the MW as a passive solar system, data was collected *in situ* in winter from June 1 to July 31.

3. Results and discussion. Analytical calculations

The case studies are defined by their geometry. They are presented in Fig. 1 and Table 2 where α is the opening angle of azimuthal planes, CL is the length of the central panel and L_1 and L_2 are the lengths of the side panels.

Next, an analysis of the study cases for the average winter day is presented.

3.1. Winter results

Fig. 4 shows the ET value (Eq. (3)) for all cases (Eq. (4)) for the same clear day (in kJ/hr for each hour). The results for winterindicate:

- Case 1 MW: the MW collects 19.5% more energy than the FW (2650 kJ/hr on average).
- Case 2 MW: the MW collects 23.0% more energy than the FW (2720 kJ/hr on average)
- Case 3 MW: the MW collects 25.0% more energy than the FW (2780 kJ/hr on average)
- Case 4: the MW collects 27.0% more energy than the FW (2829 kJ/hr on average). This is the best case.

The side panels increase differences of the MW performance compared with the FW that range from 20% (for case 1) and up to 40% (for case 4), mainly in the morning hours (8:00 a.m. to 9:00 a.m.) and in the afternoon (3:00 p.m. to 4:00 p.m.).

As the angles of the sides increase, the gain also increases, achieving peak collection 3–4 h before and after solar noon.

3.2. Summer results

Fig. 4 shows the ET value (Eq. (3)) for all cases (Eq. (4)) for the same clear day (in kJ/hr for each hour). The results for summer cases indicate:

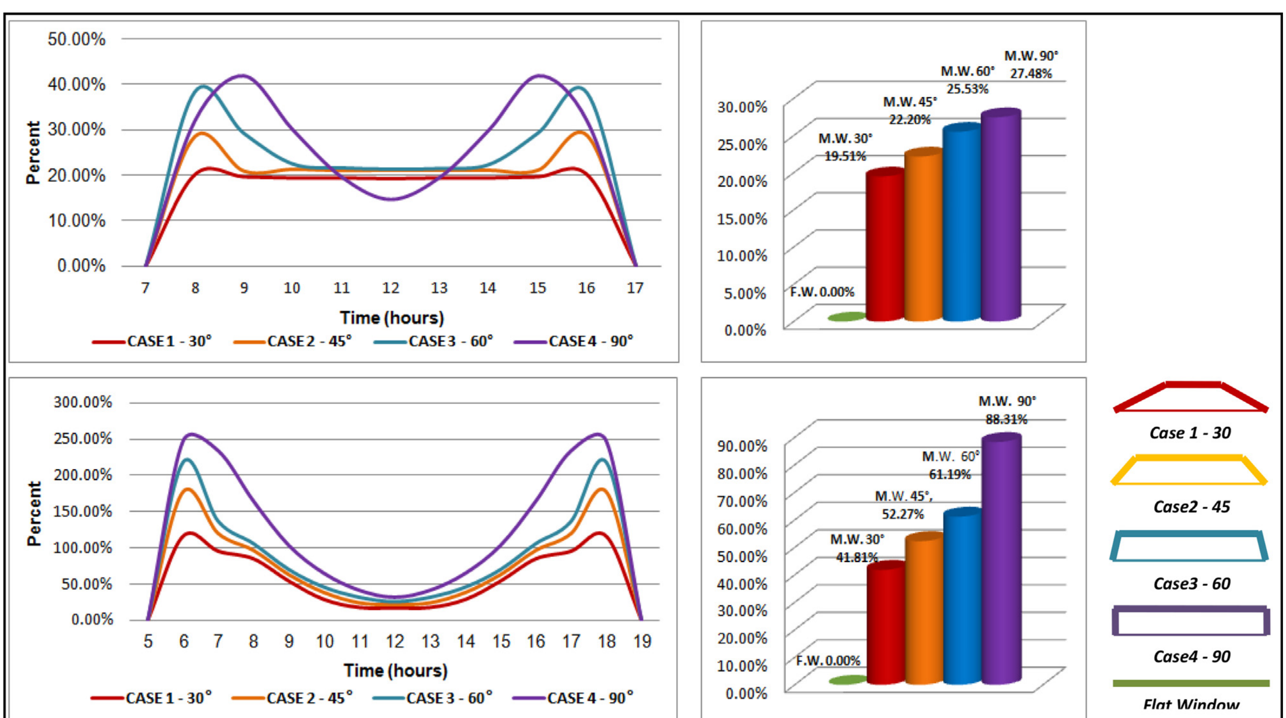

Fig. 4. Percentage of the M.W. solar gain in relation to the F.W. in the Winter and Summer.

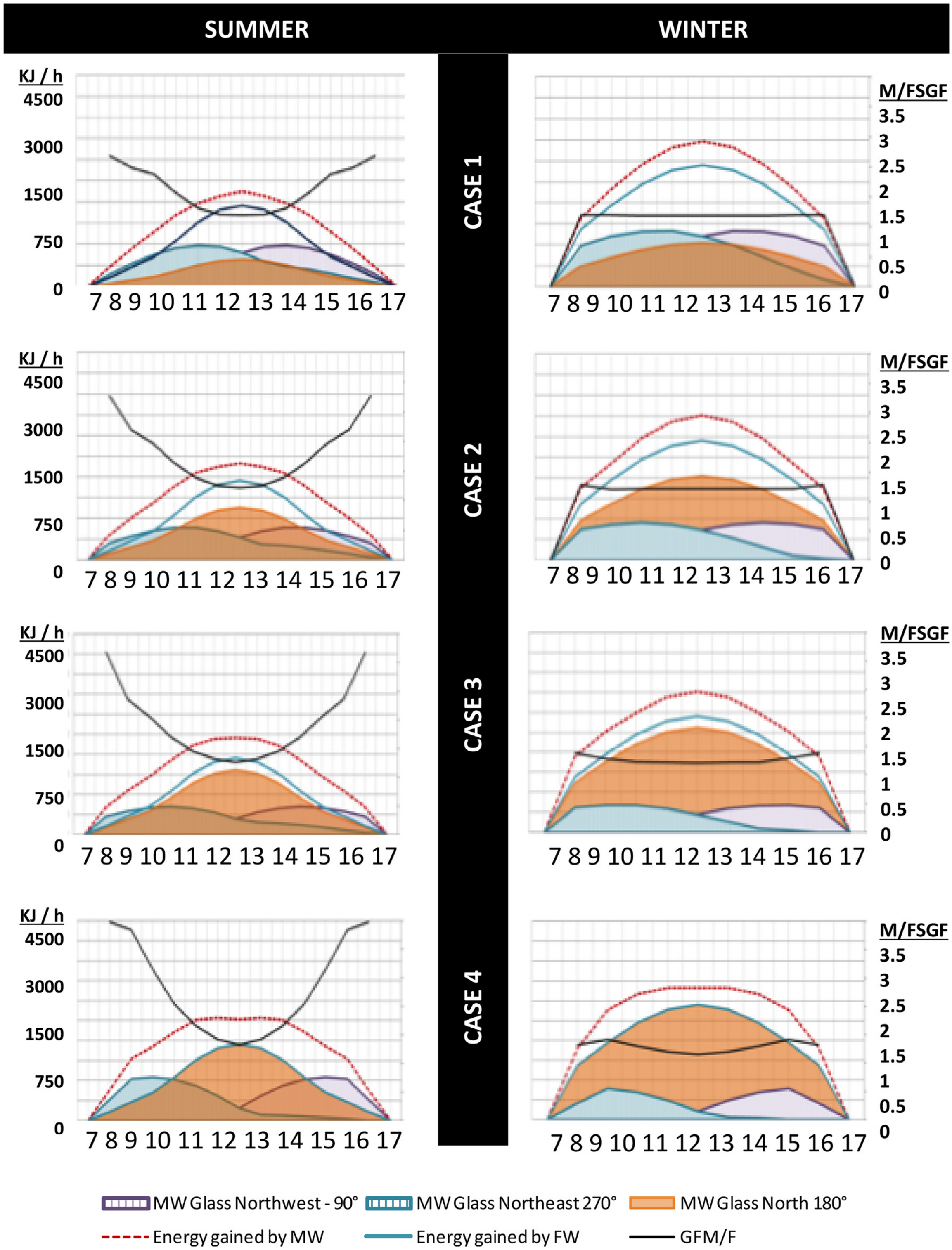

Fig. 5. Solar and M/FSGF gains of the cases studied.

- Case 1 MW: the MW collects 41.0% more energy than the FW (1473 kJ/h on average).
- Case 2 MW: the MW collects 57.0% more energy than the FW (1583 kJ/h on average)
- Case 3 MW: the MW collects 61.0% more energy than the FW (1675 kJ/h on average)
- Case 4 MW: the MW collects88.0% more energy than the FW (1960 kJ/h on average).

This is the best case due to the largest panel facing the Equator.

The sides also demonstrate differences, mainly in the morning hours (8:00 a.m.–9:00 a.m.) and afternoon (3:00 p.m.–4:00p.m.), 110% (for case 1) and 250% (for case 4).

In summer, while the side panels tend to be perpendicular to the line of the façade, the gain increase reaches peak collection 5–6 h before and after solar noon. These data confirm the need for shading in the window for protection against the incident solar radiation. These gains should be avoided in the summer and should be prevented from entering into the interior.

On the other hand, there is great potential for incorporating photovoltaic panels that take advantage of this incident energy. They can be incorporated into sunscreens.

3.3. Factors solar heat gain

In order to study the efficiency of the MW compared to the FW, acomparison figure is proposed: "Multi-azimuthal/FlatSolar Gain Factor" (M/FSGF), which is defined by the solar energy transmitted through the MW relative to the FW using a window opening of the same dimension in the wall. It indicates the difference of solar gain in relative values. Eq. (5).

$$M/FSGF = \frac{ET}{EV} \tag{5}$$

Where ET is Solar Gain Multi-Azimuthal window and EV = Solar Gain Flat window.

This equation indicates the benefits of use MW instead of FW. It is dimension less factor. When the M/FSGFis equal to unity, this implies that the same amount of solar energy can be gained by the change of windows. When FGM/FS > 1 demonstrates indicates a clear benefit to change FW by MW.

Fig. 5 shows the solar heat gained calculated hour by hour for each window, for summer and winter times in the city of Mendoza, Argentina. M/FSGF values for each hour are indicated.

For summer, the M/FSGF in the morning (7:00 a.m.–10:00 a.m.) and afternoon (2:00 p.m. to 5:00 p.m.) are higher than at the mid-day (11:00 a.m.–1:00 p.m.). In addition M/FSGF increases as the lateral glass panes are more perpendicular to the facade (30°–90° – case 1–4).

In Winter M/FSGF is almost constant in all cases. In the case of the 30°side panels, the M/FSGF is 1.5 throughout the day. In case 4 (90°) the GFM/F has a peak in the afternoon and the morning of 2 and the rest of the day varies from 1.5 to 1.9.

Even though this is a study of the collection of energy, knowing the variations of thermal behavior is essential in the analysis of the energy because it adds to the continuing investigation of the MW with *in situ* measurements in experimental boxes.

The geometric configuration of the MW provides more area for the presence of solar energy due to the projection of the window in the wall. This advantage is reflected in the percentages of solar heat gains shown by solar energy factors. These allow the comparison of MW with FW in order to know the improvement impact of replacing a FW by a MW.

It is very important to consider that:

Table 3
M/FSGF for Winter.

Angle (α)	daylight	M/FSGF	HOUR	M/FSGF DIARY
30°	8:00 to 9:00	1.20 1.20	8:00 to 18:00	**1.20**
45°	8:00 to 9:00	1.29 1.29	8:00 to 18:00	**1.21**
60°	8:00 to 9:00	1.38 1.29	8:00 to 18:00	**1.22**
90°	8:00 to 9:00	1.32 1.42	8:00 to 18:00	**1.27**

- MW with side panels angles of 90° and with a projection of 0.75 m from the façade towards the Equator gain 45.2% more than FW with the same opening and the same orientation.
- MW with side panels angles of 45° and with a projection of 0.30 m from the façade gain less energy than a FW (−1.00%) due to the smaller dimension of the northern panel of MW.
- Therefore, higher angles are recommended for situations that requires maximum collection of energy, especially 3–4 h before or after the mid-day.

Table 3 shows the values of M/FSGF in winter. The greatest value is early in the morning, when the sunlight is near perpendicular to the surface of the side panel. In the afternoon, the same values are registered as the solar radiation is symmetric.

The difference in daily energy between the MW and FW, ranges from between 1.20 M/FSGF when the α = 30° and M/FSGF of 1.278 when the α = 90°. This means earnings of 4000 kJ/day and 5760 kJ/day for the climate of Mendoza during a sunny winter day.

In summer, the difference in daily energy between the MW and FW, ranges from between 1.62 M/FSGF when the α = 30° and M/FSGF of 2.34 when the α = 90°. This means earnings of 12400 kJ/day and 46800 kJ/day for the climate of Mendoza during a sunny summer day, which involves excessive solar heat gain.

4. Results and discussion. Experimental measurements

Three experiences were examined:

Experience 1 (E1): Solar Gain through vertical planes of MW (Box A) and FW (Box B).

Experience 2 (E2): Solar Gain through upper plane of MW (Box A)

Experience 3 (E3): Solar Gain on a Metal Plate behind the glass of MW (Box A) and FW (Box B)

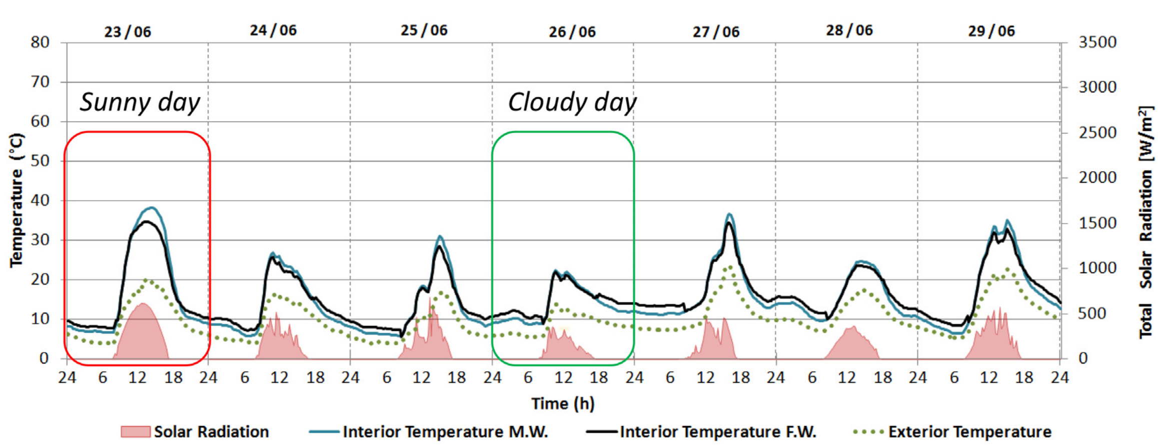

Fig. 6. Air Temperature Measurements of both Prototypes.

Table 4
Mean Minimum temperature, Mean Average and Mean Maximum Temperatures of the measured period (E1) and (E2).

	Variable	T MIN – HALF		T MEDIA – HALF		T MAX – HALF	
	Prototype	A	B	A	B	A	B
	Sensor	T.A.A	T.A.B.	T.A.A	T.A.B.	T.A.A	T.A.B.
E1	Temp °C	*4.5*	*6.1*	*12.5*	*12.3*	*38.3*	*34.6*
E2	Temp °C	*6.5*	*8.3*	*11.37*	*9.17*	*48.5*	*43.4*

4.1. Experience 1 (E1): ***Solar gain through vertical planes of MW (Box A) and FW (Box B)***

In order to measure the solar gain through glass windows, several temperatures have been measured: interior air dry bulb temperature at the center of the space, glass surface temperature and black globe temperature in three pointsat fixed height of 1.5m, equally spaced at 0.80 m from each other and 0.80 m from the window opening in a perpendicular direction.

Variable names are:

Box A: T.A.A. (dry bulb temperature),

Box B: T.A.B. (dry bulb temperature),

For the location of each sensor in the box see Fig. 3.

Measurement Period: June 23 to June 29

Selected Sunny Day: June 23

Selected Cloudy Day: June 26

In Fig. 6 is possible to observe the effect of the extra amount of solar radiation gained through the MW, which produces higher interior temperatures in Box A than the FW in Box B.

The first day, June 23rd, was a sunny winter day with a maximum solar radiation of 700 W/m^2 on the horizontal surface. The temperature (at noon) T.A.A. in Box A is 38.3 °C; near 3.7 °C higher than the temperature T.A.B. of 34.6 °C in Box B (with exterior temperatures of 19.5 °C).

At night, the box with the FW (Box B) is warmer than MW box (both boxes do not have any night protection). This is logical due to the greater exposed surface area of the MW, which directly affects the dry bulb temperature. This can also be improved with adequate night protections.

Table 4 shows the average maximum and minimum temperatures in both boxes. It is possible to see that more solar radiation is captured by the side panels of the MW in conjunction with the northern panel. In the afternoon the northwest panel of MW gains more solar radiation that the FW. It is clear that the MW has greater energy potential to be used as passive thermal conditioning system.

Temperatures on cloudy day of the boxes are very similar and to remain within the range of 20 °C at noon. At night, box A temperature falls 2 °C below box B due to the greater surface area of the MW.

Partly cloudy days offered smaller differences between Box A and Box B temperatures. Differences 1.5 °C higher was registered in Box A. On cloudy days, the curves at mid-day are similar in both boxes, having very little difference at mid-night, about 0.5 °C, which is close to the calculated error of the measurement equipment.

4.2. Experience 2 (E2): solar gain through inclined plane of MW (Box A)

This experience takes advantage of the possibility to glass the upper surface of the multi-azimuthal window to increase the solar gain. A change was made in Box A, to replace the opaque upper surface of the MW with aglass panel. The glass surface has 4 mm of thickness and is tilt 50° respect to the horizontal plane. Radiation enters at an angle of incidence that decreases the absorption and reflectance from the glass and transmits the greatest possible amount of radiation into the interior. See Fig. 7 and Table 4.

Measurement Period: August 2 to August 8

Selected Sunny Day: August 2

Selected Cloudy Day: August 3

At mid-day, maximum internal dry bulb temperatures (T.A.A. sensor) reach 49 °C in Box A, while on Box B 37 °C were recorded with T.A.B sensor, with 24 °C in the exterior and 700 W/m^2 of solar radiation. At night, Box B maintains higher interior temperatures than those recorded in Box A. The difference between the two boxes is accentuated when compared with the results obtained in Experience 1 because the glass surface is greaterin this case.

4.2.1. Behavior on sunny and cloudy days

During daylight hours, BoxA captures more solar radiation than Box B with outdoor solar radiation of 700 W/m^2 and an outside tem-

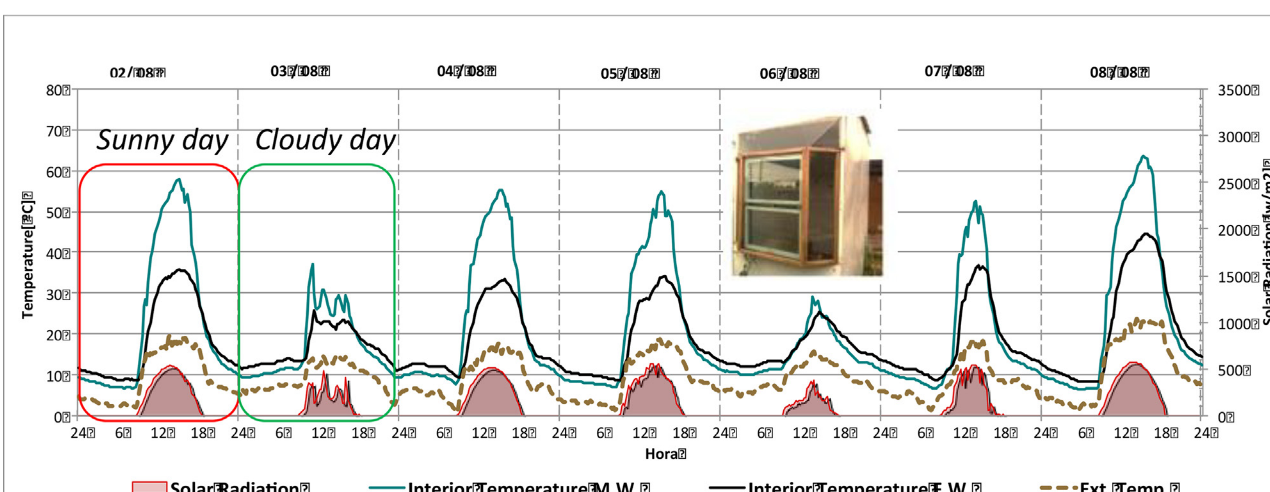

Fig. 7. Indoor temperature of both prototypes.

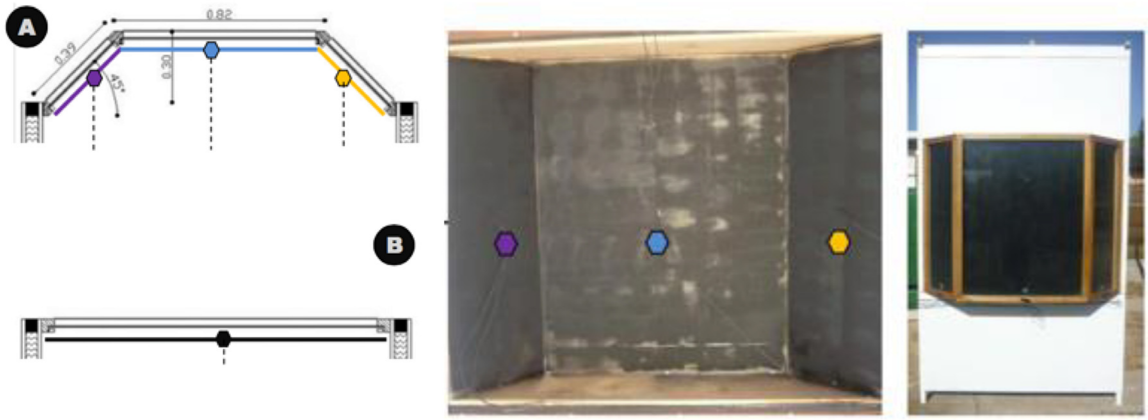

Fig. 8. Diagram of measurements of the steel panels. View of interior and exterior steel sheets.

Table 5
Surface temperatures of the Steel Panels: Mean Minimum, Mean Average and Mean Maximum Temperatures the measurement period. (E3).

Variable	T MIN – HALF				T MEDIA – HALF				T MAX – HALF			
Prototype	A		B		A		B		A		B	
sheets	NE	N	NW	PLANE	NE	N	NW	PLANE	NE	N	NW	PLANE
Temp °C	*4.8*	*7.5*	*7.1*	*0.9*	*8.1*	*11.1*	*11.8*	*4.3*	*63.2*	*68.2*	*66.8*	*65.0*

perature of 18 °C. This difference with the additional panel of glass is 19 °C, higher than the temperature obtained by Experience 1 (an outdoor solar radiation of 650 W/m^2 and an outside temperature of 19 °C).

On the chosen partly cloudy day, Fig. 7, one can see that during daylight hours, even though exterior temperatures range from between 9 °C and 19 °C, the temperature inside Box A varies between 10 °C and 30 °C and in box B the temperature varies between 12 °C and 27 °C. The addition of glass in the upper plane of MW creates a window system with a greater sensibility for the absorption and lost of heat.

4.3. Experience 3 (E3): solar gain on a metal plate behind the glass of MW (Box A) and FW (Box B)

This experience takes advantage of the change of temperature in a sheet of steel when it is exposed to solar radiation. The temperature of the sheet is directly proportional to the incidence of solar radiation and its level.

This investigation audits the energy entering through each glass panel of MW and the glass windows of FW. Steel panels with 1 mm thickness were placed in the opening of the window and at a distance of 0.04 m from the glass on the inside. They were fastened to the frame with appropriate support and painted matte black (absorbance 0.95 and emittance 0.88) behind each glass panel (Fig. 8).

A thermocouple type T was placed in the geometric center of the metal panels, in order to register the temperature of each and relate it to the solar gain from each glass window pane. The thermocouples were fixed to the metal sheets on its interior surfaces in order to avoid incident solar radiation on the sensor. Fig. 9 shows the temperatures registered for 7 consecutive days of July. See Table 5.

Measurement Period: July 14 to July 21

Selected Sunny Day: July 17

Selected Cloudy Day: July 19

The measurement period includes clear, partially cloudy as well as completely cloudy days. It can be seen that the maximum absolute temperature of the North steel panel reaches more than 70 °Cat mid-day on sunny days, see Figs. 2 and 3. This is 4 °C higher than that obtained with the FW. Concerning the side panels of the MW (NE and NW), the highest temperature peaks are offset 3 h after and before solar noon, respectively. The outside temperature is between 1 °C and 18 °C.

4.3.1. Behavior on sunny and cloudy days

Box A receives more solar radiation than Box B at the beginning of the day through the glazed NE surface; therefore, its temperature begins to increase earlier.

During daylight hours for the sunny day selected, the maximum temperatures of the azimuthal panels differ. This corresponds to the highest peak in the NW panel, which is caused bythe greater ambient air temperature in the afternoon that diminishes the heat transfer lost.

For the cloudy day, the temperatures of the steel panels in the MW remain, on average, 7.9 °C, while in the steel panels for the FW, maintain an average temperature of around 4 °C. Solar radiation level is around 750 W/m^2 in these days and with an outside temperature between 1 °C a 18 °C.

From these experiences, it is possible to quantify the potential of the MW as a passive solar system and analyze the sensitivity of the same in the audited differences.

5. Conclusions

The development of this work allowed the performance of in depth energy and thermal analysis of the multi-azimuthal window (MW) as a heating passive solar system in winter, located in continental temperate climates (Bwh and Bwk Köpper type).

The solar energy transmitted by the multi-azimuthal window (MW) and a flat window (FW), with the same opening dimension oriented toward the Equator, were calculated and compared.

Some concluding lessons can be learnt in terms of design strategies. The MWs can be applied to bioclimatic buildings, so that, in combination with other strategies, they can provide clear benefits

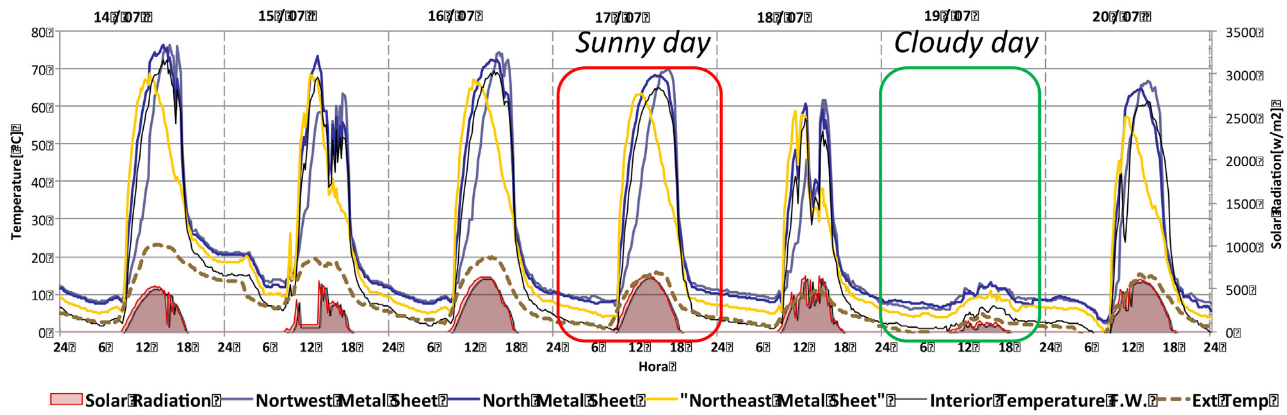

Fig. 9. Surface Temperatures of the Steel Panels.

for heating interior spaces along with generating substantial savings in power costs. These windows can create a better and more conscious environmental impact with their implementation. When the MW is used as a passive solar heating system, this investigation shows gains of between 20% and 27.8% over the use of FW and a reduction in collecting surface area of the same percentage can create an equivalent result. This could be very useful for buildings facing towards the Equator.

The Multi-azimuthal/Flat Solar Gain Factor (M/FSGF) was established with the objective to classify the MW within the criteria of energy sensitivity in relation to its functionality as a passive solar system.

For summer, the M/FSGF in the morning (7:00 a.m. to 10:00 a.m.) and afternoon (2:00 p.m. to 5:00 p.m.) are higher than at the mid-day (11:00 a.m. to 1:00 p.m.). In addition M/FSGF increases as the lateral glass panes are more perpendicular to the facade (30° to 90° – case 1–4). In Winter M/FSGF is almost constant in all cases. In the case of the 30° side panels, the M/FSGF is 1.5 throughout the day. In case 4 (90°) the GFM/F has a peak in the afternoon and the morning of 2 and the rest of the day varies from 1.5 to 1.9. Therefore, higher angles are recommended for situations that requires maximum collection of energy, especially 3–4 h before or after the mid-day.

According to the results, we consider thatthe energy and thermal behavior of the MW described in the present paper is auspicious. A MW with an angle of 45°, in the side panels, reaches an M/FSGF daily average value of 1.20, which means a 20% more solar gain than the daily average solar gain of a flat window. In addition, a window with an angle of 90° in the side panels is the best for temperate climates, with daily average solar gains of 27% greater than those of the flat window.

Thermal behavior was analyzed on a boxes scale of 1:1 in order to compare the calculated energy with thermal behavior.

Measurements of experimental boxes of the MW show an elevation of the maximum internal temperature of 3.7 °C above the FW, with a global solar radiation of 700 W/m^2. Through scatter plots, one can deduce that when the solar radiation is higher, a greater difference between the two windows (MW and FW) is evident. At night, the FW keeps a warmer temperature, which is logical, because the MW has more glass surfaces exposed to the exterior. In order to avoid this, suitable thermal protection is necessary at night for any multi-azimuthal window which is to be used as a passive system.

In order to encourage direct gain, an improvement to box A was performed by replacing the upper opaque panel of the MW with 4 mm of glass. It was installed with the correct geometry for capturing more radiation and at the appropriate angle to the sun (tilt 50° from the horizontal plane). At these latitudes, the glass panel can decrease absorptance and increase the transmittance of the glass. This modification empowers further possibilities of thermal collection of the MW. At noon, the MW reaches 49 °C, 12 °C more than the maximum of FW at a radiation level of 700 W/m^2. This represents an increase of 32.4% in the temperature of the FW, when compared to Experience 1.

When the third experience with indirect gain is analyzed, it can be concluded that the N panel of the MW reaches temperatures of 4 °C greater than the FW. This difference with the FW, happens due to the gains provided by side panels at the start and at the end of the day. As previously shown, the M/FGF in morning and afternoon is 29% (MW 45), thanks to these side panels.

Favorable results allow for a possible replication in the use of a MW as a passive system, with appropriate changes, in other regions of the country with similar climates.

The information provided in this analysis makes it possible to make more educated decisions regarding which type of MW is more convenient in each case, or to be able to rapidly quantify the energetic benefits in one type of window over another. This is very useful information not only for research and teaching but also for the professional architect who makes these types of decision while designing.

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