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Thermal comfort increase using up cycled PET bottles shutters technology

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Abstract— ***An appropriate technology based on up-cycled PET water bottles utilization is presented. The bottles constitute the main constructive element of a shutters system. The most relevant expected application is to meliorate the interior thermal comfort on precarious residences, although many other potential applications can be considered. The designed shutters system has been exhaustively tested on real sun conditions in a medium irradiation area. For this purpose, a standard house environment has been emulated using a 1:30 scale insulated chambers endowed with a window pane. The experimental module, equipped with a monitoring system, has been duplicated in order to avoid systematic uncertainties. The effect of both empty and water-filled PET bottles shutters over the internal thermal comfort has been evaluated. This effect has been tested over the chamber interior temperature and its correlation with the ambient temperature and the irradiation level has been measured. The effects on the internal illumination are included even if further analysis is required.***
Keywords— PET, Up-cycling, Shutters, Thermal comfort, Appropriate technology

I. INTRODUCTION

A huge number of houses in underserved regions along the world, particularly in extreme climate regions, present low thermal comfort levels. Promoted by governments, cooperation for development institutions or informally built, the main reasons of this absence of comfort is linked to low investement levels, high economic costs and the lack of appropriate constructive materials availability.

House windows have been identified as a key factor in thermal house comfort regulation and deeply dependent on materials, sizes and locations [1]. Likewise, the influence of window shutters has shown an important role improving windows thermal performance and reducing the overall energy consumption in an affordable way. Night insulation and daytime temperature reduction are two of the most relevant aspects of its utilization [2].

Although there is no unanimous definition of thermal comfort [3], it is widely accepted that temperatures between 18ºC and 25ºC and relative humidity values among 40-70% represent adequate human comfort intervals [4].

Among different studies and experiences in house passive thermal control systems [5], solar water walls (also known as *transwalls*) [6] have shown close performance results to other direct gain systems, offering architectural advantages in terms of illumination [7]. Regardless, building materials are considered expensive and often unavailable in most isolated emplacements.

Residues management are the most conflictive waste components for reduce, reuse or recycle [8]. These materials are considered a major problem in most developing regions wordlwide, in particular the non-readily degradable materials as plastic and other oil derivatives.

In the context of the sustainable development initiatives, the utilization of appropriate technologies (hereafter, AT) [9] appear as a good alternative to be used on those multilevel problematic. AT are those that, requiring limited and local resources, become suitable to the social and economic conditions of the geographic area in which they will be applied, inducing low environment impacts and a strong reproducibility component.

Under the hypothesis of the upcycling of polyethylene terephthalate (hereafter, PET) bottles as constructive material, a window shutters model was designed and exhaustively tested as an AT dedicated to improve the thermal comfort levels in precarious constructions.

In order to evaluate the shutters performance, a dedicated double chamber prototype was tested at the LACEM [10] following strict scientific procedure on real sun conditions. The two identical chambers, built to a standard domestic room scale, ensure redundancy and avoid systematic uncertainties. The data acquisition period was extended along 3 months during year 2016 in which thermal comfort parameters and climatic variables were continuously monitored.

In this study case, temperature is considered as the significant thermal comfort evaluation parameter. The promising results obtained open a wide range of further research lines. In particular, the uses of other PET bottles filling fluids or explore the use of the shutters as SODIS (Solar Disinfection) vessel [11]. Effects on internal illumination must be thoroughly evaluated.

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II. EXPERIMENTAL SET-UP

A. *Prototype design*

The experimental setup is designed to avoid systematic uncertainties correlated with both constructive and climatic conditions. For this purpose, two identical chambers, working as pattern and tester respectively, were constructed (see Figure 1a). The internal volume of 0,54 m^3 each, emulates a standard house room using a 1:30 scale. In order to minimise thermal exchanges with the outside, the chambers were insulated both on the lateral and upper sides.

Each chamber is equipped with a transparent glass frontal window. Outside of the glass and embedded inside the chamber profile, a wide moveable frame was located. The frame includes two parallel wood rails on the top and the bottom ensuring bottles fastening (see Figure 1b). Main constructive characteristics are displayed in Table 1.

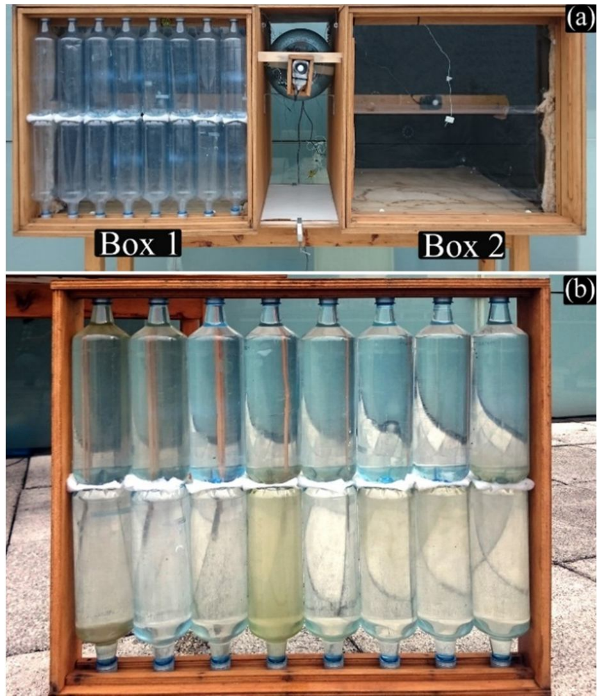

Figure 1. a) Experimental setup prototype, b) Water-filled bottles installed on the shutters frame rails

To create the shutters, 1.5-liter capacity transparent plastic PET bottles were used. The bottles were mounted in a vertical arrangement and symmetrically located (see Figure 1b). The bottles anchoring was carried out by pressure, using a low density flexible polymer as buffer pad. This configuration eases the ventilation across the interspaces created by the bottlenecks in both the upper and the lower extremes of the shutters.

Table 1. Prototype constructive characteristics

Interior volume:	0,54 m^3 (each)
Constructive material:	Marine plywood
Assembly:	Screwed
Elements size:	100x76x1.2 cm (top and bottom) 71x100x1.2 cm (sides) 73.6x71x1.2 cm (back)
Insulation:	4 cm glass wool F.V. IXXO (sides and back) 2 cm thick expanded polystyrene (EPS) (top)
Window:	4 mm thick frontal transparent glass
Window location:	15 cm far from box edge
Window fastening:	1x1 cm^2 thick wood profiles
Shutters material:	1.5-liter transparent plastic PET bottles (unlabelled)

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Mount:	Vertical arrangement by pressure with a flexible polymer buffer pad
Mounting system:	10 cm wide moveable frames with 3 cm width wood rails for bottles guide
Frames location:	5 cm far from the glass

B. Data acquisition and monitoring system

A complete set of monitoring data (internal illumination, temperatures and climatic conditions) are simultaneously collected in both chambers with a 10-minutes frequency (Figure 2). The experiment was carried out at Santiago de Compostela (Spain) (coordinates 42.8735, -8.5575).

The chambers interior illumination (L_{int}) is measured by a luxometer located in the geometrical centre of each box parallel to the glass surface (Figure 3). Two characteristic temperatures are measured in each chamber, one in the internal side of the glass (T_{glass}) and other in the geometrical center of the box (T_{int}) (see Figure 3). Moreover, the on-location vertical radiation (G_{ver}) and ambient temperature (T_{amb}) are measured. The full characteristics and physical locations of the used measurement apparatus are described on Table 2.

The complete prototype is west-faced and fastened to a fixed structure located 75 cm above the floor with a 27 cm chambers interspace.

Table 2. Data acquisition devices and characteristics

Illumination:	Iso-Tech 1332A Digital Lux Meter
	Measurement range: Up 200000 lux Resolution: 0.1 Lux Location: Chambers' geometrical center parallel to the glass surface Data acquisition: 10-min interval by direct capture from devices interfaces
Irradiation:	HT 204 Solar Power Meter pyranometer
	Measurement range: Up to 1999 W/m^2 Location: Vertical measurement between Box 1 and Box 2 Data acquisition: 10-minute interval direct photographic capture from device interface
Temperature:	Pico-Technologies TC-08 data logger (USB) with 5 TME type K thermocouples
	Diameter: 0.2 mm probe diameter Temperature range: -100ºC to +250ºC Location: Glass internal center and chambers geometrical center (each box). Ambient temperature between Box 1 and Box 2 Data acquisition: 10-minute interval via PicoLog Recorder software installed on computer

Figure 2. Sample of data capture from acquisition devices

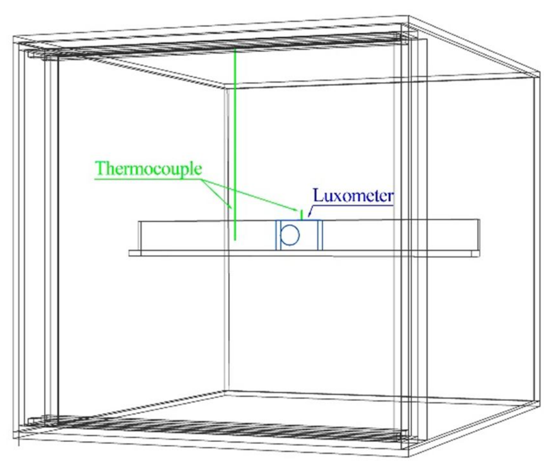

Figure 3. Measuring devices physical location

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III. METHODOLOGY

The main goal of the bottles shutters design is to increase the percentage of time in which the temperature inside a home is maintained into the comfort limits. The foreseen analysis procedure is simple: Direct comparison of both chambers' internal (T_{int}) and external (T_{glass}) temperatures. Also, their correlations with the vertical incoming radiation (G_{ver}) and the illumination level in the center of each box (L_{int}) are measured.

A. Data sample

During the data acquisition procedure, in order to individuate the possible effect of the PET bottle material and the water, two different set of samples were collected:

1) *Empty bottles shutters.* Installation of a shutters system constructed with 16 empty PET plastic bottles located in front of the glass.
2) *Water-filled bottles shutters.* Unlike the empty bottles shutters, the 16 PET plastic bottles were filled with tap water.

In both cases, pattern chamber is measured only with frontal glass. Prior to the data analysis, a system calibration was performed in order to avoid systematic errors in the measured parameters. These results were applied to all the later data. This calibration was performed with the simultaneous measurements in both chambers without shutters, it is, provided only with the frontal glass.

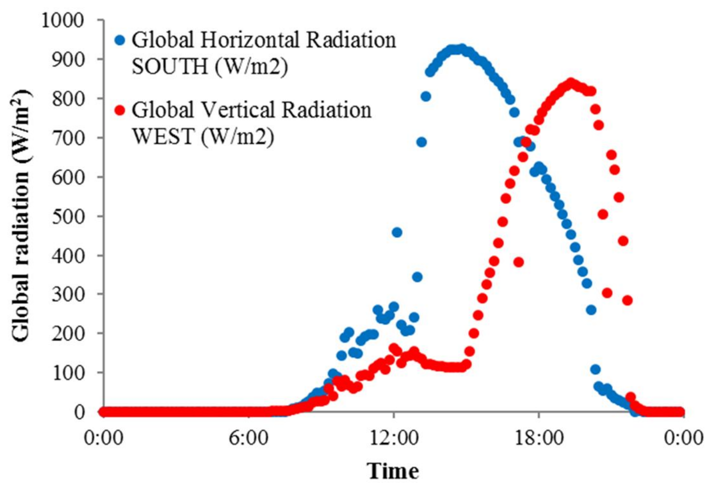

Figure 4. Global irradiation spectra sample for horizontal and vertical measures

The experimental set-up foresees a west-facing window. This orientation optimises the illumination levels during the sunset, when the human activity inside the house is higher, and restricts the high irradiation levels during middays. This window configuration is quite usual in highly irradiated regions [12]. Figure 4 shows the vertical irradiation spectrum (facing West) on the window surface, G_{ver}, and the horizontal irradiation spectrum (facing South), G_{hor}, along a full day (South radiation is shown just as reference). It can be seen the variation in time of the maximum incoming radiation depending on the orientation: While South shows its maximum at noon, West orientation has its maximum in late afternoon. Full data were measured in the experimental setup. A meteorological station located nearby [13] was used for data cross-check.

B. Variables definition

To facilitate an unbiased evaluation of the shutters-bottle effects a set of sensible variables have been defined:

1) *Variable pool* (1), used for quantitative evaluation where X will be either temperature or illumination. The upper index corresponds to the pattern (X^{pat}) chamber or to the shutters (X^{III}, with *III = EM or WF* for empty bottles or water-filled respectively).

$$\text{Pool} = \frac{X^{Pat} - X^{III}}{X^{III}} \ (\%) \tag{1}$$

2) *Unbiased temperature difference* (2), used to measure the shutters capability to avoid the external radiation warming effect (with III = PAT, EM or WF).

$$\Delta T^{III} = T^{III}_{int} - T^{III}_{glass} \tag{2}$$

3) *Absolute temperature difference* (3) defines the direct effect of the shutters once the chamber warming constructive characteristics (walls, insulation and other) are subtracted.

$$\Delta T^{absolute} = \left(T^{III}_{int} - T^{III}_{glass}\right) - \left(T^{pat}_{int} - T^{pat}_{glass}\right) \tag{3}$$

where III = PAT, EM or WF.

IV. RESULTS AND DISCUSSION

A. Data calibration

To perform an internal calibration process, a dedicated sample without any bottle-shutters was collected for a full day period in real sun conditions and west-facing location. Characteristic parameters (T_{int}, T_{glass} and L_{int}) are simultaneously monitored. The calibration constant is obtained after the experimental data correlation for both chambers. Figure 5 and Figure 6 show the observed correlation along a full sunny day as well as the temperature calibration constants obtained using a simple linear fit.

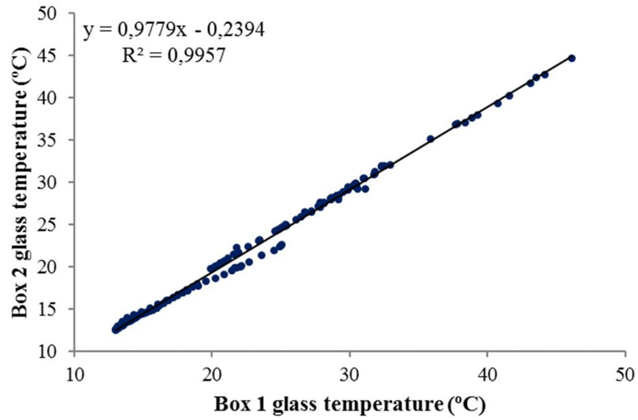

Figure 5. Correction for measured glass temperatures

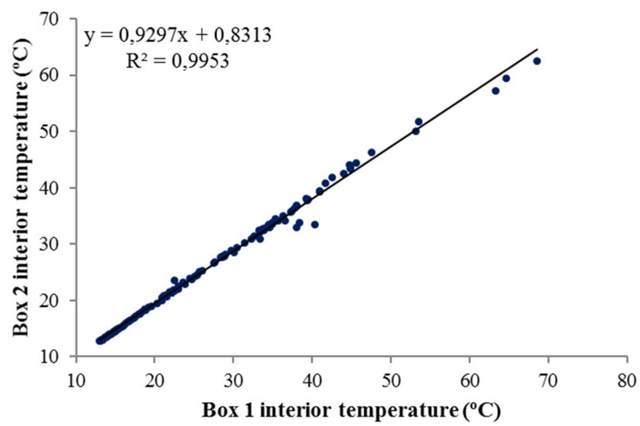

Figure 6. Correction for measured interior temperatures

B. Bottle shutters results

In order to evaluate the effect of a PET bottle shutters, a set of data samples are performed. For the first data acquisition, empty bottles are considered and the results will be presented. In the second test, the study is performed with tap water-filled bottles. For both cases, temperature will be considered for the study.

1) *Empty bottles shutters.* This dedicated data sample allows to identify the absorption and diffraction effects directly associated to the PET constructive material. Figure 7a shows the slightly T_{int} decrease due to the presence of the empty bottles shutters. This effect is associated to the PET material absorption characteristic. Otherwise, Figure 7b shows how the PET empty bottles

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shutters induce a slight increase of T_{glass}.

Figure 8 shows the shutters thermal effect correlation with the radiation measured in front of the window. For a quantitative evaluation, the temperature pool was used. As previously observed, the effect is negative over the glass on a -2% approximately. Moreover, it shows an almost constant shape in the full radiation range studied. Besides, the shutters interior effect shows a linear behaviour with a 0.02% positive slope per W/m^2 for irradiations over 400 W/m^2. Lower irradiations show no clear tendency.

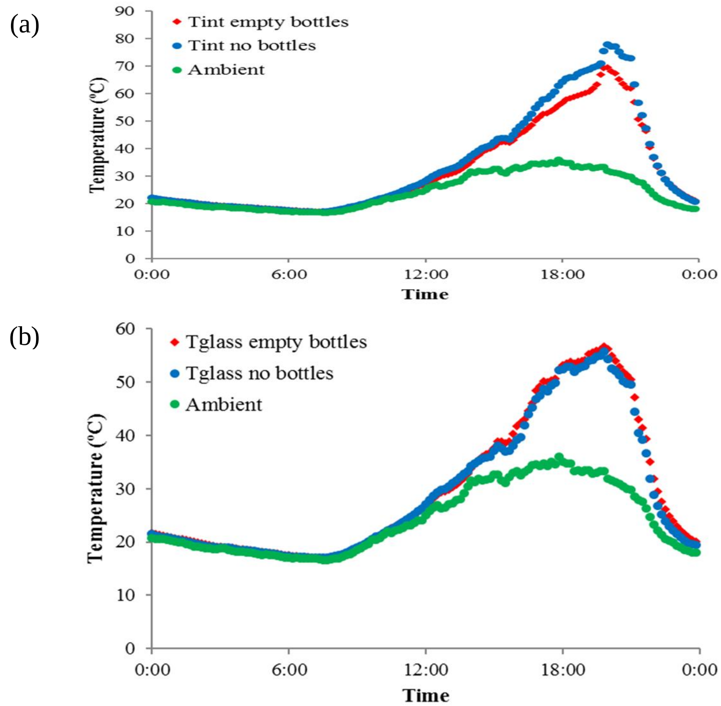

Figure 7. Temperature along a day for empty bottles data sample. a) T_{int}, b)T_{glass}. Ambient temperature is also shown for results reference.

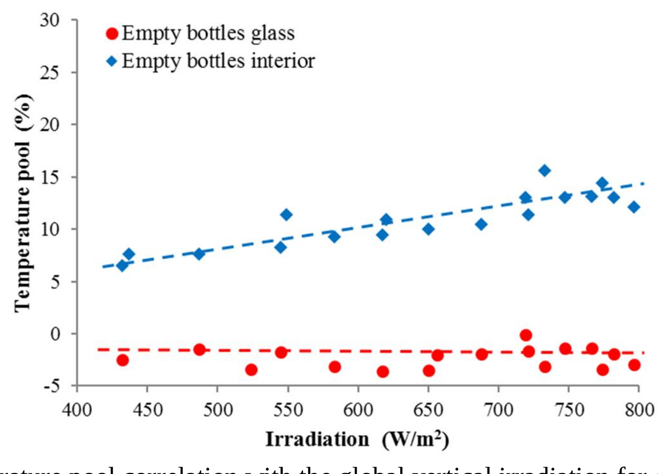

Figure 8. Temperature pool correlation with the global vertical irradiation for empty bottles test

2) *Water-filled bottles shutters.* Aiming to increase the shutters thermal mass, a second data acquisition is performed on the experimental setup by filling the bottles with tap water.

Figure 9a shows the temperature distribution in the interior of both chambers. Ambient temperature is also plotted. As expected, the temperature decreasing for water-filled bottles shutters is higher than for the previous case. Only during the night period (see red circle) temperature shapes switch. The region of interest will be examined after.

The same behaviour is observed, unlike the previous case, in the glass temperature distribution (see Figure 9b). This effect can only be awarded to the added water thermal mass.

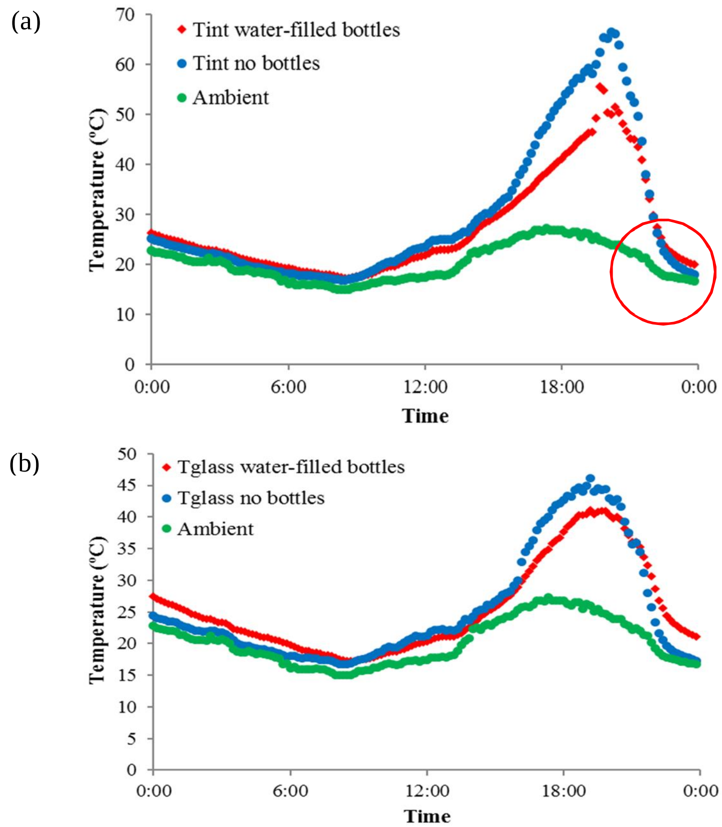

Figure 9. Temperature along a day for water-filled bottles data sample. a) T_{int}, b)T_{glass}. Ambient temperature is also shown for results reference

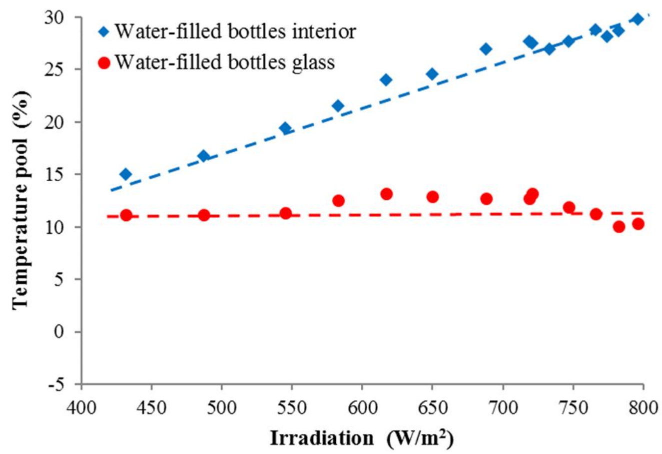

Figure 10. Temperature pool correlation with the global vertical irradiation for water-filled data sample

The temperature variable pool shows (see Figure 10) an interior temperature decrease of up to 30% in the peak sun hours with a linear dependence of 0.04% per W/m^2 for irradiations greater than 400 W/m^2. Alike, the temperature decrease effect associated to the water-filled bottles thermal resistance goes up to the 10% almost without radiation dependence.

C. Results comparison

After the gathered results, Table 3 shows the key numbers. So, while placing empty bottles increases the glass temperature in a 2%

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due to the negative PET plastic thermal resistance, the water-filled bottles decrease the glass temperature in a 10%. From these two values, an interesting result can be extracted: The water thermal mass effect on the interior temperature decrease is 12%, once the negative effect due to the plastic material is considered.

The temperature inside the chamber shows a linear dependence with the global vertical radiations over 400 W/m^2, being twice higher for the water-filled bottles tests respect to the empty ones. This result demonstrates the better performance in terms of temperature decrease for the water-filled bottles shutters.

Table 3. Main results comparison between empty and water-filled bottles tests

	T_{glass} pool	T_{int} slope (G_{ver}≥400 W/m^2)
Empty bottles	-2%	0.02% per W/m^2
Water-filled bottles	10%	0.04% per W/m^2

Until now, the bottle-shutters effects during low vertical radiation periods (below 200 W/m^2) were not evaluated. Figure 11 shows two regions of interest, above and below 50 W/m^2. Below 50 W/m^2, the water-filled bottles shutters induce a higher increase of interior temperature than the empty bottles. This thermal resistance associated to the water inside the bottles becomes a thermal battery for the night period. Regions above 50 W/m^2 show no remarkable differences between empty and water-filled bottles results.

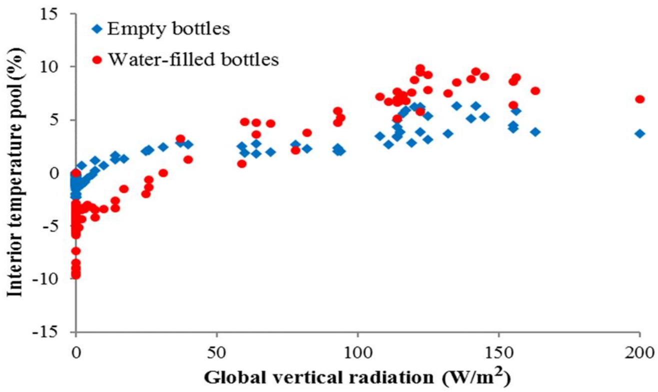

Figure 11. Internal temperature pool versus Global vertical radiation for low irradiances

The shutters blocking effect becomes crucial when considering high to very high irradiation levels periods. In fact, the desirable shutters behaviour will be an enhanced comfort inside the house (chamber). In that sense, the interior comfortability levels were measured as the shutters capability to avoid the external radiation warming effect. For this purpose, the sensible variable used is the unbiased temperature difference (ΔT^{EM}, ΔT^{WF}). Figure 12 shows the corresponding distribution. Aiming to compare with the reference situation, the pattern chamber results are also included in the plot.

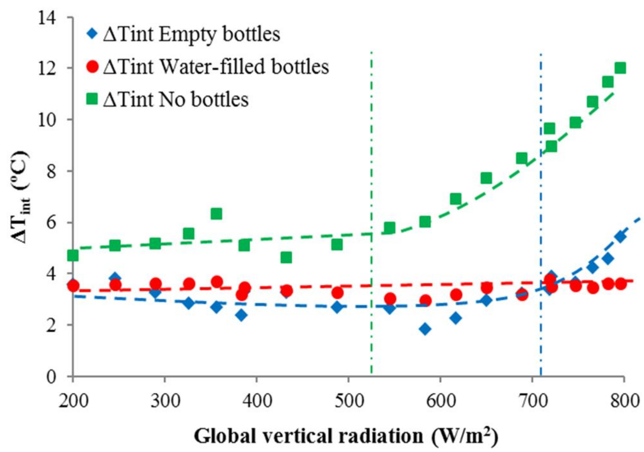

Figure 12. Unbiased temperature difference versus irradiation

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As main result, it can be seen that even at low irradiation levels, the shutters-equipped chamber shows lower warming levels. This effect looks rather constant and independent on the bottles filling fluid, fact that should be linked to the PET material. When irradiation levels increase, the unbiased temperature difference shape becomes linear with a positive slope. This inflexion point corresponds to around 500 W/m^2 for the no shutters chamber, 700 W/m^2 for empty bottles and higher than 900 W/m^2 for the water-filled shutters.

Finally, the effect of the bottles filling fluid type (air or water) can be evaluated by removing the PET component effect. For this purpose, $\Delta T^{absolute}$ is computed and shown in Figure 13. As expected, a linear correlation is observed for high irradiation levels. Moreover, the denser the filling fluid is, the higher the comfort increase will be.

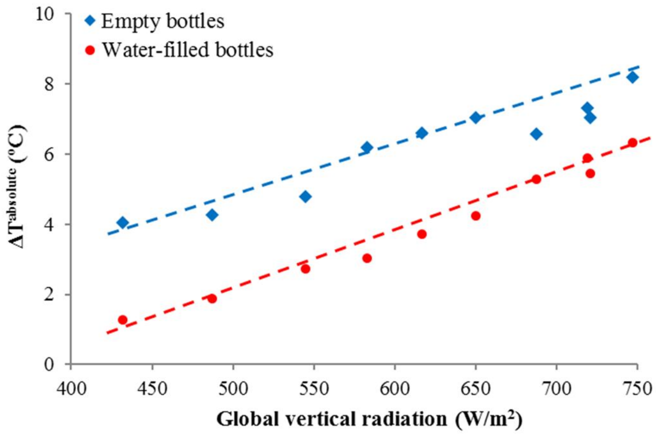

Figure 13. Absolute temperature difference versus irradiation

Under these conditions, it may be concluded the use of high-density fluids will improve the shutters thermal shield. A proper comfort study should be developed in the meantime.

D. Effect over interior illumination

Using bottle shutters improves the thermal comfort levels but decreases the interior illumination. In order to evaluate quantitatively the effects, Figure 14 shows the illumination pool for both measured tests.

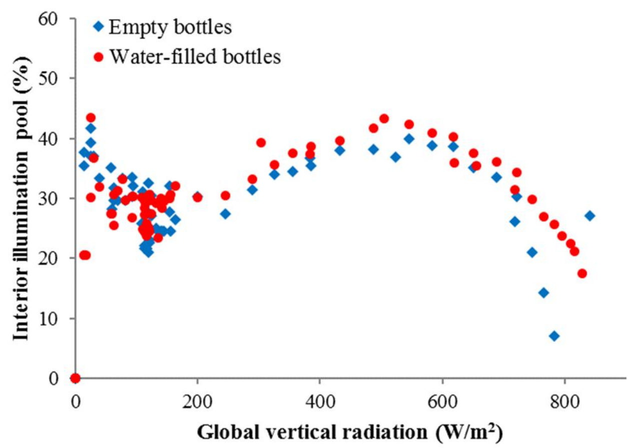

Figure 14. Illumination pool versus irradiance

As remarkable results, the shutters associated shield varies between 20 and 50% for any irradiation value. This effect is only slightly higher for the water-filled bottles test. These illumination losses are particularly negative during the lower illumination periods, specially, sunrise and sunset. The observed results are not the target of this paper and further studies are required on this topic.

V. CONCLUSIONS

A simple design shutters prototype has been constructed with upcycled materials aiming to increase the comfort level of informal households. Plastic PET bottles were used as constructive material. In order to simulate a house room conditions, an experimental setup was constructed in a 1:30 scale. The prototype, conformed by two identical chambers in order to avoid systematic uncertainties, has been tested under real sun conditions in the LACEM being the main achieved features:

During the sun peak hours, the PET bottles shutters decrease the interior chamber temperature. The decrease percentage varies from up to 30% for water-filled bottles to 10% reduction for empty bottles. In both cases, the observed temperature decrease shows a positive linear dependence with the irradiation.

The shutters installation induces an interior room temperature decrease of almost 4 ºC. Moreover, this result looks irradiation-level independent for the water-filled bottles.

The water thermal mass effect on the interior temperature decreasing is 12%, once the negative effect due to the PET material (2% around) is considered, being independent from the irradiation level. The evaluation of the bottles filling fluid effect confirms how the use of denser fluids could increase the desired thermal control.

During the night time or low irradiation level periods (under 50 W/m^2), the water-filled bottles work as a thermal mass storage stabilizing the chamber temperature.

The shutters effect over the internal illumination has been tested and a loss of 20 to 50% has been measured with almost no dependence of the bottles filling fluid (water or air), depending only on the PET material.

From the obtained results, we can conclude that the installation of bottles-shutters constitutes a reliable appropriate technology to increase the households thermal comfort. Further studies to evaluate illumination comfort level are required.

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