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Retrofitting of ETFE roofs

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Abstract

ETFE is one of the most stable chemical compounds and its films are largely employed in the building industry due to the very good long-term stability, resistance to soiling and high light transmittance. The mechanical strength is relatively good, especially considering that the material is not reinforced by a woven support, and make ETFE foils suitable for load bearing envelopes characterised by small spans or supported by cables [1].

ETFE foils are traditionally used for multilayer pneumatic cushions, however, in recent projects the application of single skin ETFE foils has been successfully investigated. This innovative application opens new areas of interest in the area of the building envelope, such as a protective secondary facade. In addition, the growing demand for reducing the heating\cooling costs has recently increased the demand for ETFE foils with pigments or surface treatments able to improve the environmental performance of lightweight envelopes based on ETFE foils [2].

This research paper describes the thermal performance of an existing ETFE roof in Verona and the subsequent retrofitting of the structure in order to meet the targets of solar shading specified by the client. The paper includes the data obtained through the monitoring of the structure before and after the installation of a new set of cushions manufactured with a bespoke silver ETFE designed in order to reduce the solar gains and improve the overall level of comfort during the warm season.

Keywords: ETFE, retrofitting, roof, optimization, comfort, thermal performance, shading.

1. Introduction

The development a new generations of lightweight envelopes based on ETFE foils opened several new applications in the building sector. Like the majority of lightweight structures, ETFE roofs and facades have been proven to be a safe and reliable building system with several technical advantages when compared with traditional solutions [3] such as glazed structures.

Thanks to the intrinsic structural efficiency of ETFE structures and the reduced overall weight per square meter, the manufactured membrane can be easily packed, stored and shipped. Due to the relatively low transportation costs, the packed façade can be delivered all over the world virtually with no limits in terms of logistics. Once on site, the assembly process is relatively fast and efficient due to the high level of accuracy of manufacture, the adjustable boundary details and the reduced weights and volumes to be handled, which require less (and smaller) lifting equipment. In addition, there are no limitations in terms of combination with others building materials such as steel, aluminum, wood, reinforced concrete, composites etc.

The manufacturing techniques carried out on site are reduce to the mere assembly of the of the components that, thanks to the reduced weight and volumes, is characterized by a reduced number of risks and dangerous activities. The advantages in terms of safety are not solely restricted to the building phase. Like in the wok of Kawaguchi [4], ETFE foils provide severla safety benefits in case of earthquakes when used as a replacement for (brittle) glass in overhead situations, such as atria. In addition coated fabrics and foils have a good fire behavior and have been successfully approved in several projects.

However, one of the main challenges of ETFE envelopes is related to the current global environmental targets which aims to reduce the running costs and the environmental impacts without compromising the levels of comfort. Due to the due to intrinsic low thermal inertia of ETFE structures and their complex building physic driven by radiation input and losses, this aspects is often a critical aspects which, in some specific project, lead to poor level of comforts below the level of performance estimated during the design phase (or expected by the client).

The ETFE roof designed and fabricated in 2011 fort the Winter Garden of the Crown Plaza Hotel in Verona is an examples of projects based on ETFE foils that required the retrofitting of the original envelope and the replacement of some of the ETFE cushions in order to achieve the level of comfort specified by the client.

2. The ETFE Winter Garden designed for the Crown Plaza Hotel in Verona

In 2011 Canobbio S.p.A. completed the installation of the pneumatic enveloped designed by Mario Bellini Associati for the Winter Garden included in the Crown Plaza Hotel in Verona, Italy [4]. The structure is part of a multipurpose complex designed adopting several cutting-edge solutions in terms of energy efficiency, building automation and overall management of the building.

It is the first example of a building enclosed by an ETFE envelope realized in Italy and it serves the nearly Crowne Plaza Hotel for meetings and events. It is characterised by a charming timber structure based on a 3D double curved envelope obtained through 7 transversal arches hinge connected to the concrete foundations. At south, the ellipsoidal volume is interrupted and partially shaded by the cubic concrete structure for the main services (mechanical ventilation, under floor heating/cooling etc.). In the orthogonal direction, the arches are connected by 11 curved longitudinal steel profiles which maintain the distance between the timber arches and provide support for the ETFE cushions.

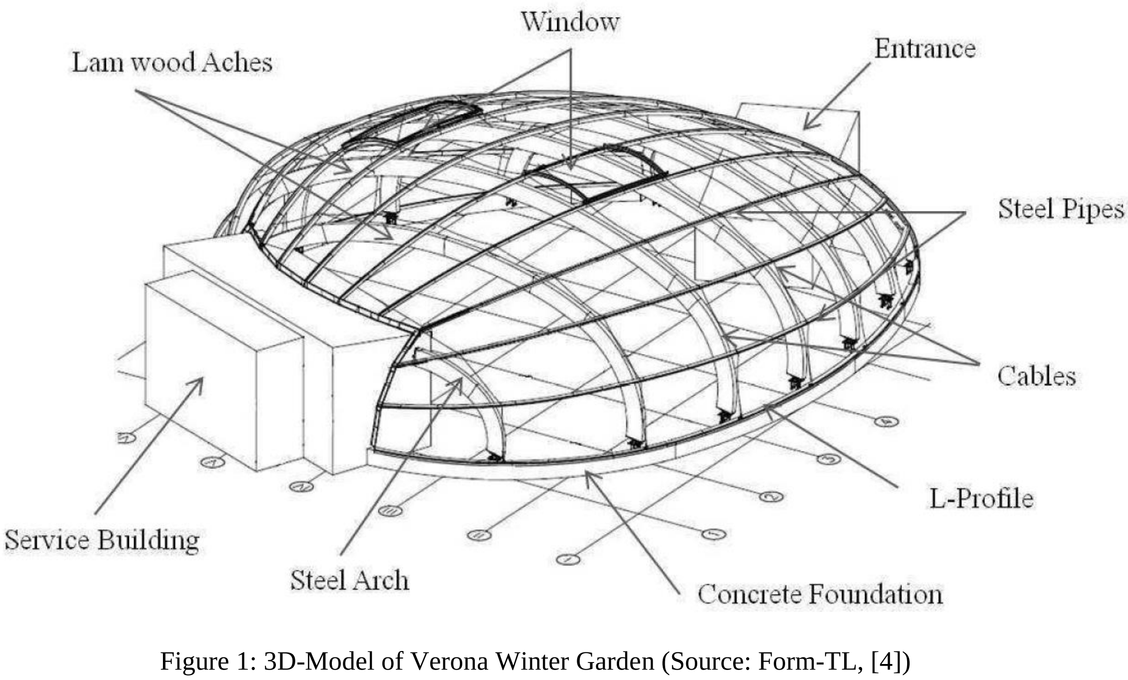

Figure 1: 3D-Model of Verona Winter Garden (Source: Form-TL, [4])

The envelope is based on 12 rectangular ETFE cushions with four layers characterised by a different level of shading achieved thought a variable density of the printed pattern. The cushions are inflated by two fans with dehumidification function, to pre-dry the outside air and prevent the formation within the cushion of condensation or algae. The two external chambers are connected and inflated at 300 Pa, the intermediate chamber is inflated at 330Pa. The pattern, based on silver reflective dots, is obtained through roll-to-roll printing according to the targeted visual impact given by the architect and the shading requirements.

Despite the progressive optimisation of the geometry and level of shading of the external envelope described by Monticelli et al. [4], the use of the Winter Garden in the warm season highlighted several critical aspects related to the amount of solar radiation inside the structure which generated excessive solar gains, glare and high level of discomfort due to the direct solar radiation on the users.

3. Monitoring of the existing status

The actual performance of the building before the intervention has been monitored recording and comparing the solar radiation measured by two pyrometers placed externally on top of the ETFE roof and internally in correspondence of the different cushions and patterns. An example of the measuring layout and of the data recorded is presented in Figure 2.

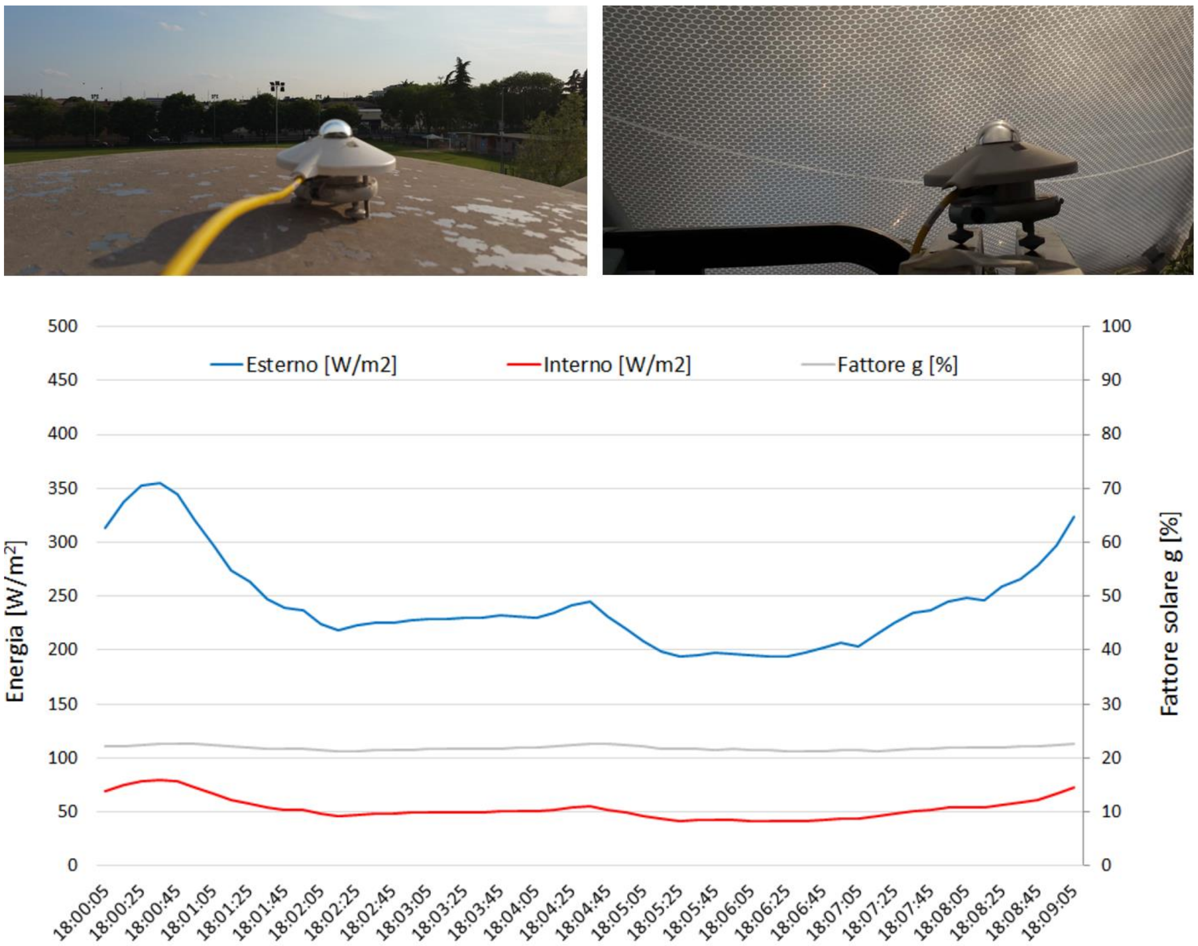

Figure 2: Solar radiation and solar factor measured in correspondence of the pattern “70% Dark” with a solar factor equal to 0.22 (Source: Maco Technology)

4. Estimation of the level of shading required

As highlighted by the data obtained during the monitoring of the current performance of the structure, the solar radiation, even if partially filtered by the ETFE envelope, represents the main source of discomfort for the user of the structure. The level of discomfort can be compensated through other parameters as the room temperature, the air speed etc., which is, in fact, what the owner of the Winter Garden did during recent years. However, the running costs and the overall level of dissatisfaction of the user suggested that the best strategy to address the problem is to modify the overall level of shading of the external ETFE envelope.

The procedure here described assumed the highest values of temperature and air speed achievable by the services currently installed on the basis of the comfort of the users and a reasonable economic sustainability of the building. Starting from this values, it has been determined the level of shading required in order to achieve the targeted level of comfort. The procedure adopted follows the research carried out by Arens et a. [5] and on the model of comfort described by Zhang et al. in the paper "Thermal sensation and comfort models for non-uniform and transient environments".

The targets of comfort adopted are specified by the norm ASHRAE 55-2013 "Thermal environmental conditions for human occupancy" [7].

4.1. Definition of the main thermal parameters

List of the parameters adopted.

ERF (effective radiant field): it describes the additional (positive or negative) longwave radiation energy at the body surface when surrounding surface temperatures are different from the air temperature. It is in W/m^2, where area refers to body surface area.

MRT (mean radiant temperature): it describes the surrounding surface temperature of a space.

ERF and MRT are related by the formula:

$$ERF = f_{eff} \cdot h_r \cdot (MRT - T_a) \tag{1}$$

Where:

$\mathbf{f_{eff}}$ is the fraction of the body surface exposed to radiation from the environment (equal to 0.696 for a seated person and 0.725 for a standing person).

$\mathbf{h_r}$ is the radiation heat transfer coefficient (W/m^2).

$\mathbf{T_a}$ is the air temperature (°C)

According to Arens et al [5] the The energy flux actually absorbed by the body is ERF times the long-wave emissivity/absorptivity a_{LW} and can be assumed equal to 0.95. Through the following formula it is possible to extimate the Solar radiation absorbed on the body's surface related to an additional amount of longwave flux, $\mathbf{ERF_{solar}}$:

$$\alpha_{Lw} ERF_{solar} = \alpha_{Sw} E_{solar} \tag{2}$$

Where:

$\mathbf{E_{solar}}$ is the shortwave solar radiant flux on the body surface (W/m^2)

$\boldsymbol{\alpha_{Sw}}$ is short-wave absorptivity,(assumed equal to 0.67 for (white) skin and average clothing).

$\mathbf{E_{solar}}$ is the sum of three fluxes that have been filtered by fenestration properties and geometry, and are distributed on the occupant body surface: direct beam solar energy coming directly from the sun (E_{dir}), diffuse solar energy coming from the sky vault (E_{diff}), and solar energy reflected upward from the floor (E_{refl}). Like in Arens et al. [5], it has been assumed that the diffuse radiation from the sky is distributed on the upper half of the radiatively-exposed portion of the body as in the formula:

$$E_{diff} = 0.5 f_{eff} f_{svv} T_{sol} I_{diff} \tag{3}$$

Where:

$\mathbf{f_{svv}}$ is the fraction of sky vault in occupant's view

$\mathbf{I_{diff}}$ is diffuse sky irradiance received on an upward-facing horizontal surface (expressed in W/m^2 and obtained from the meteorologic data)

$\mathbf{T_{sol}}$ is the total solar transmittance, the ratio of incident shortwave radiation to the total shortwave radiation passing through the glass and shades of a window system.

Similarly to the procedure followed by Arens et al [5], in this work the total outdoor solar radiation on the horizontal (I_{TH}) is assumed filtered by both T_{sol} and f_{svv} and multiplied by the reflectance (albedo) of the floor and lower furnishings (R_{floor}). The short-wave reflected to the lower half of the body is then combined with the increased long-wave radiation from floor surfaces warmed by the non-reflected portion of the solar.

$$E_{refl} = 0.5 f_{eff} f_{SVV} T_{sol} I_{TH} R_{floor} \tag{4}$$

Where:

$\mathbf{I_{TH}}$ is the total horizontal direct and diffuse irradiance outdoors (W/m^2)

$\mathbf{R_{floor}}$ is the floor reflectance (assumed equal to 0.2 + 0.3 for short-wave plus long-wave combined).

The direct radiation is given by the following formula where it clear to see that it has effects only on the projected area Ap of the body and is reduced by any shading of the body provided by the indoor surroundings:

$$E_{dir} = \left(A_p/A_D\right) f_{bes} T_{sol} I_{dir} \tag{5}$$

Where

$\mathbf{A_p}$ is the projected area of a standard person exposed to direct beam sunlight;

$\mathbf{A_D}$ is the DuBois surface area of the assumed person (around 1.8 m^2);

$\mathbf{f_{bes}}$ is the fraction of body exposed to sunlight (without considering the self-shading);

$\mathbf{I_{TH}}$ is the direct solar beam (normal) solar radiation.

The parameters about the radiation, obtained by the meteorological data, are correlated by the formula:

$$ERF_{solar} = \left(0.5 f_{eff} f_{SW}\left(I_{diff} + I_{TH} R_{floor}\right) + A_p f_{bes} I_{dir}/A_D\right) T_{sol} (\alpha_{SW}/\alpha_{LW}) \tag{6}$$

Where, with the projected area factor f_p empirically determined by Fanger, the projected area of a standard person exposed to direct beam sunlight is given by the formula:

$$A_p = f_{eff} f_p A_D \tag{7}$$

4.2. ERF e (MRT-Tair) of the most representative date dates

Table 1 reports the values of the several parameters adopted in order to determine the most critical days of the year and hours of the day.

Table 1: Values of the different parameters assumed for the calculations

f_{eff} = 0,73	A_d = 1,80m^2	A_p/A_D = 0,13	T_{sol} = 0,20	α_{SW} = 0,67
f_{svv} = 0,70	A_p = 0,23m^2	f_{bes} = 0,75	R_{floor} = 0,50	α_{LW} = 0,95

The most significant days investigated for the calculation of the Effective Radiant Field and the Mean Radiant Temperature are the 21st of June and the 21st of September. The 21st of June is considered the most critical day for the risk of overheating of the structure. The 21st of September has been considered for a typical day with average values of temperature and solar radiation.

Table 2: ERF e (MRT-T_{air}) of the most representative date dates and times

Time		8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jun.	ERF [w/m^2]	10.1	15.7	21.6	27.5	31.6	32.4	30.8	27.0	20.8	14.4	9.0
	MRT-T_{air} [°C]	2.3	3.6	**5.0**	**6.3**	**7.3**	**7.4**	**7.1**	**6.2**	**4.8**	3.3	2.1
21 Sept.	ERF [w/m^2]	2.5	6.5	11.9	17.1	20.6	21.5	22.1	17.2	11.3	5.6	1.6
	MRT-T_{air} [°C]	0.6	1.5	2.7	3.9	**4.7**	**4.9**	**5.1**	4.0	2.6	1.3	0.4

According to the value MRT-T_{air} it has been possible to calculate the level of comfort reached in the warm hours of the 21st of June and the 21st of September. The results are described in figure 3 according to the CBE Thermal Comfort Tool developed by the Center for the Built Environment at the University of California Berkeley [8]. The tool is a web-based graphical user interface for thermal comfort prediction according to ASHRAE Standard 55. It Includes models for conventional building systems (predicted mean vote) and also for comfort using the adaptive comfort model, and with increased air speeds (for example, when using fans for cooling).

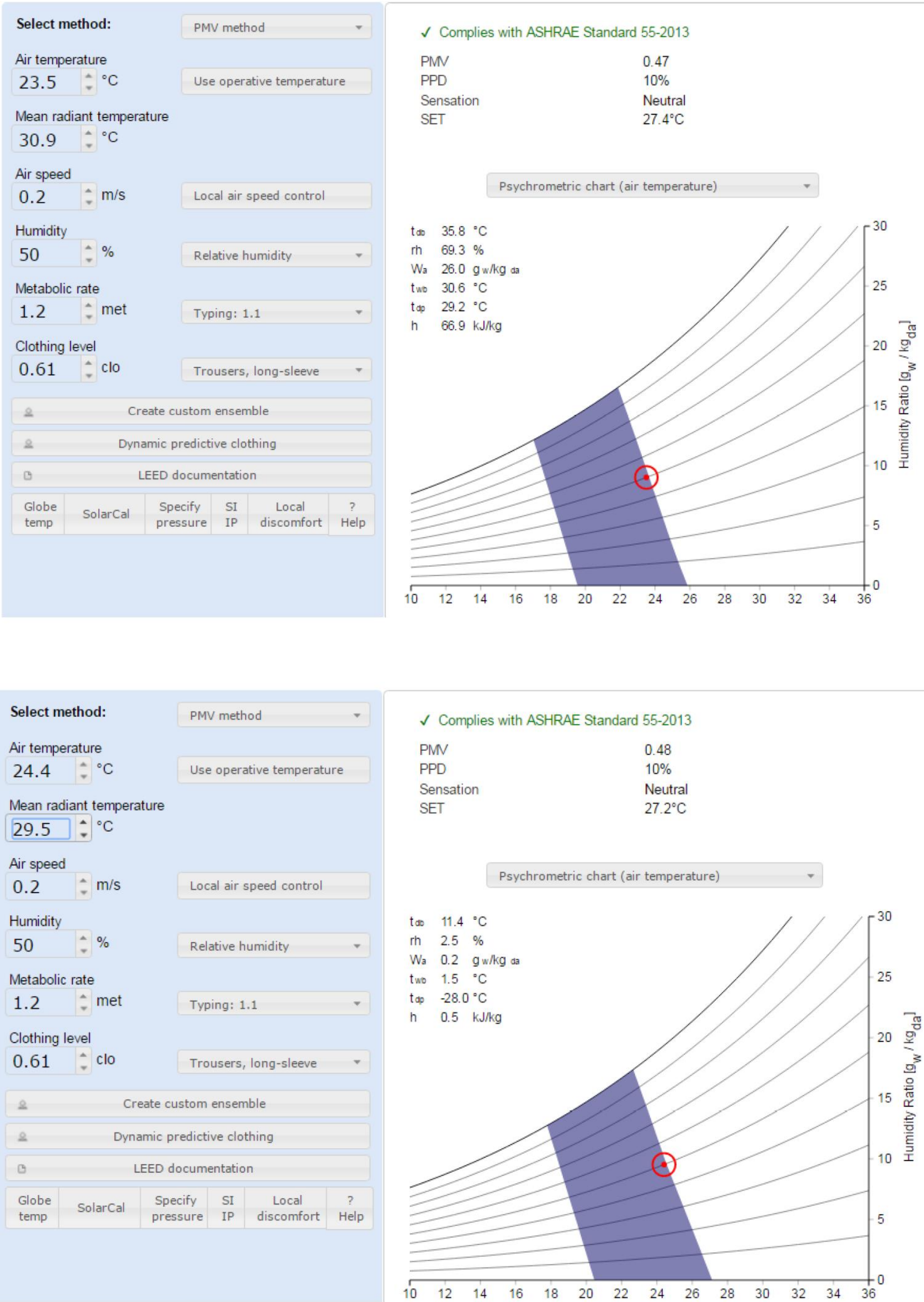

Figure 3: CBE Thermal Comfort Tool, [8]. The expected level of comfort can be achieve with an internal temperature equal to 23.5°C on the 21st of June and to 24.4 °C on the 21st of September.

5. Intervention and preliminary results

According to the results of the simulations it has been possible to plan the replacement of 7 of the 12 ETFE cushions with a new silver ETFE cladding designed to provide the required level of shelter.

The intervention is currently under monitoring, however, the preliminary data provided by the pyrometers installed confirm an overall g-value of 0.27, a remarkable improvement of the level of confront and a significant reduction of the amount of electricity absorbed during the warm season.

Figure 4: Winter Garden, Crown Plaza Hotel - Verona, after the replacement of 7 of the 12 ETFE cushions (Source: Maco Technology)

6. Conclusion

The paper presents the successful retrofitting of The ETFE Winter Garden designed for the Crown Plaza Hotel in Verona in order to achieve the expected level of comforts. The research is based on the data of solar radiation collected before and after the intervention and uses the model of comfort described by Zhang et al. in the paper “Thermal sensation and comfort models for non-uniform and transient environments” and the CBE Thermal Comfort Tool developed by the Center for the Built Environment at the University of California Berkeley.

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