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An innovative solar shading device for outdoor thermal comfort

Adriana ANGELOTTI*[,b], Alara KUTLU[a,b], Salvatore VISCUSO[a,b], Andrea ALONGI*[,b], Alessandra ZANELLI[a,b]

*Politecnico di Milano, Energy Department
v. Lambruschini 4A, 20156 Milano, Italy
adriana.angelotti@polimi.it

[a] Politecnico di Milano, Department of Architecture, Built environment and Construction engineering, v. Ponzio 31, 20133 Milano, Italy

[b] Politecnico di Milano, Interdepartmental Laboratory for Textiles and Polymers (TetxilesHub), v. Ponzio 31, 20133 Milano, Italy

Abstract

This study illustrates the design, the development and the testing of an innovative solar shading device to be installed in outdoor urban spaces, with the aim to provide better thermal comfort during summer. The device consists in either a single or a double membrane tensioned through a flying mast and hung to existing poles and trees. Adjustable corner joints facilitate the installation and dismantling by the users and guarantee adaptation to most urban spaces. The double membrane configuration is proposed in order to reach a very low solar transmissivity, while an adequate air gap between the two layers allows cooling by ventilation. Two 25 m^2 prototypes were created and installed side by side in an outdoor space in the Politecnico campus in Milan, Italy: a single layer device (based on a standard white membrane) and a double layer one (adopting a standard white membrane on the top and a low emissivity membrane on the bottom). The experimental campaign showed that the latter can provide better thermal comfort, since the mean radiant temperature under the double layer device was found to be lower (about 3°C on average and about 5°C at maximum) than under the single membrane.

Keywords: lightweight structures, membrane, thermal emissivity, solar reflectivity, solar shading, thermal comfort, mean radiant temperature, urban space.

1. Introduction

Outdoor thermal comfort is a relatively new and emerging field of research and design (Johansson et al. 2014). Providing urban spaces with adequate thermal comfort conditions, especially during summer, enhances the use of the public space by the citizens, promoting urban sociability. At the same time, the more the citizens spend their free time outdoor, the less energy is potentially consumed to provide mechanical air conditioning indoor.

However, achieving adequate comfort conditions outdoor during summer is becoming more and more challenging due to the climate change. Heat waves phenomena are becoming more frequent and intense. Thus, there is an increasing demand for strategies and solutions impacting on the urban microclimate in different phases, ranging from the early design of the public space to its renovation and adaptation.

Sun shading is key to mitigate heat stress during summer, as it helps to maintain a low Mean Radiant Temperature. The latter is defined as the "uniform temperature of an imaginary enclosure made of black surfaces in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure" (ASHRAE 2001). Therefore, it summarizes into a single index the effect of the many radiative heat transfers between a body and its surrounding environment. While indoor the Mean Radiant Temperature is mainly related to infrared radiation from the building surfaces, in outdoor environments it is largely influenced by solar radiation.

Solar control in outdoor environments can be achieved through either trees or artificial devices made up of textiles or membranes. When comparing thermal comfort conditions for pedestrians under trees and under sun sails shading an entire urban canyon, Kantor (Kantor et al. 2018) found that the first were more effective, either because the tree canopies have a lower solar transmissivity than fabric sails or because the evapotranspiration provides an additional cooling effect. However, the greening strategy is more easily adopted in the design phase of a new urban area, while using textiles or membranes to shade sunny open areas is a simple, reversible and flexible intervention that can renovate an existing urban space, turning it into a comfortable niche. Artificial shading devices are often canopies installed in urban canyons at the rooftop level (Paolini et al. 2014), as in traditional urban design in Mediterranean countries, or lightweight structures at the ground level, such as the Palenque pavilion developed for the Expo international exhibition held in Sevilla, Spain, in 1992.

This study focuses on the design, the development and the testing of an innovative solar shading device based on membranes, to be installed in outdoor streets and squares to improve thermal comfort during summer. The research has manyfold objectives: on the one side to widen the possibilities of application of sun shading to different urban spaces by developing adaptable devices, on the other side to improve the microclimatic mitigation performance of artificial shading devices. To the latter purpose, non-conventional membrane materials, featuring a low thermal emissivity, and double layers configuration are investigated.

After describing the concept of the shading device, the development of two prototypes is reported. Finally, the results of an experimental campaign comparing their performance are illustrated and discussed.

2. The urban solar shading device concept

The basis for the urban solar shading device is the membrane kit. Each membrane kit consists of a membrane layer, a supporting element or flying mast and two belts forming a cross. By using only one membrane kit, a single layer shading device is obtained: the flying mast is connected in a reversible way on one side to the membrane and on the other side to the belts, so that a pre-tensioned lightweight structure is created (Figure 1, top). The structure can then be hung to four existing poles or trees by means of additional cables, suitably tensioned. The design challenge is the development of adjustable corners joints, able to facilitate the installation and dismantling by the users and guaranteeing adaptability to most urban spaces. If properly tensioned, the shape of the device allows to prevent the rain accumulation on the membrane.

A good solution to improve the performance of extremely thin and flexible membrane materials - which in many cases cannot themselves offer adequate thermal performances - is to use a multi-layer design approach (Knippers et al., 2011). Multi-layer systems combine a variable number of layers made of materials with specific functions (e.g., permeability to water, light and noise, thermal insulation, radiation reflection and fire resistance) to provide better thermal and optical performance such as reduced U-values compared to a single material (Göppert & Paech, 2015).

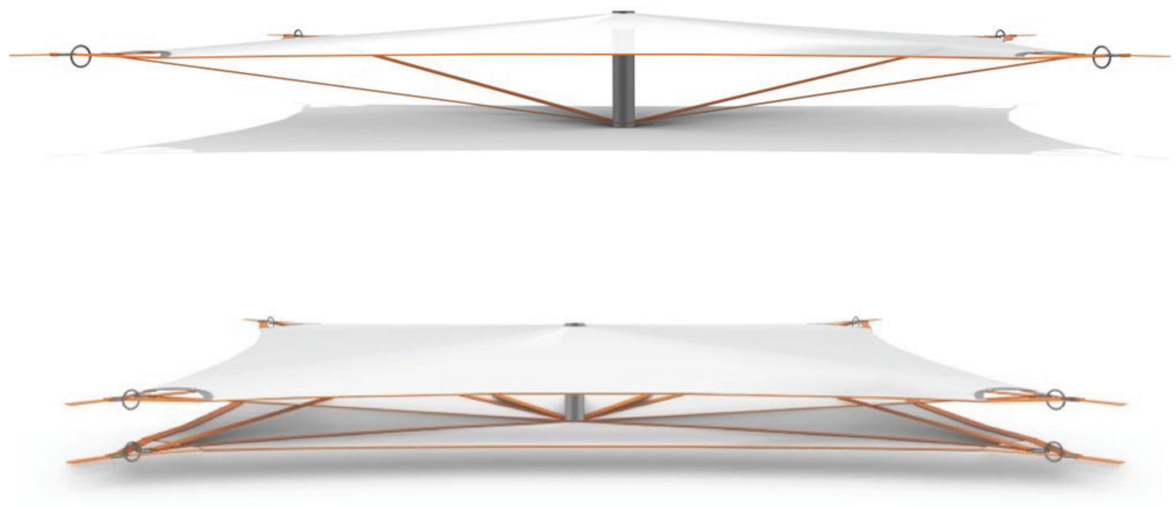

Figure 1: Single layer (top) and double layer (bottom) shading devices

Based on these premises, the concept focused on a modular approach for the ongoing developing shading system: in fact, two membrane kits can be used to create a double layer shading device, which appears as a modular implementation of the single membrane device achieved by adding a bottom membrane (Figure 1, bottom). To use lightweight flexible materials correctly, it is first necessary to accurately determine the physical properties of the individual materials in order to evaluate the contribution of each layer that composes the multi-layer envelope system. Nevertheless, even if the contributions of individual components are known, also the order and assembly method in which the layers are placed affects the overall performance of the system. Since the double layer device is symmetrical, it is possible to switch the top and bottom membranes, investigating the impact of materials with different solar and thermal properties and the influence of their position.

The double membrane configuration is characterized by a lower solar transmissivity with respect to the single layer one; at the same time, an adequate air gap between the two layers helps to keep cool the bottom membrane, which is the one exchanging heat with the persons below. The height of the flying mast determines the maximum width of the air gap (Figure 1, bottom).

3. Development of the prototypes

Two prototypes with membrane area of about 25 m^2 were designed by the research group and realized by Canobbio Textiles Engineering srl (Figure 2): a single layer and a double layer one, based on membrane materials produced by Ferrari Textiles. The fabric form of both layers is computer generated using specific software for the industry. This 'form' is then converted into flat panel which can then be cut out to create paper patterns, or the information can be used by a plotter/cutter.

Figure 2: The manufacturing of the prototypes at the Canobbio Textile Engineering factory

The single layer device is based on a standard white membrane. The double layer one adopts the same standard white membrane for the top layer and a low emissivity membrane for the bottom one, with the low emissivity side facing the ground. The solar and thermal properties of the membrane materials derived from the technical data sheet are reported in Table 1, where it has to be mentioned that the two sides of the standard white membrane are the same, while the low emissivity membrane features a special aluminium coating on one side, leading to different thermal emissivities on the two sides. The low emissivity membrane material is usually adopted for solar control inside buildings, so that the use proposed in this work can be considered non-conventional.

Because of the nature of the technical fabrics used, the presence of the double curve and the process of manufacturing, tension is always required in order to induce the correct shape and take out any minor creases in the fabric. This tensioning can take many forms: from simply hand pulling a canopy into place and Velcro fixing, to tensioning a corner of a canopy with a rigging screw or turn buckle, depending on the size of the structure and the use. In this case, two plastic hollow pipes 80 cm long with a diameter of 10 cm serve as flying masts; tubes are then fastened to the corners of the canopies by means of adjustable belts and Velcro fixings. Although the flat fabric is not specifically stretchy, it will stretch a very small amount particularly across the bias of the fabric (Knippers et al., 2011). For that reason, the stretch amount must be compensated and thus the additional length has to be deducted from the panel size. In the tested prototypes, the manufacturer adopted a compensation of 1%.

Membrane	τ_{sol}	ρ_{sol}	ε
Standard white (Precontraint 502-8102 white)	10%	76%	0.9
Low emissivity (Soltis low-e 99-2061E)	6%	68%	0.9 (A side) /0.35 (B side)

Table 1: Solar transmissivity, solar reflectivity and thermal emissivity of the membrane materials adopted in the prototypes

4. Experimental campaign

4.1 Experimental methods

The two prototypes were installed side by side in an outdoor space in the Politecnico campus in Milan, Italy (Figure 3). The campaign lasted for two weeks in September 2021. The experimental site is a green area with an almost regular array of trees, so that the shading devices were hung to 6 trees overall. During the day, the trees could partially shade the devices, yet the orientation of the trees and of the devices was such that shading by the trees happened almost in the same way contemporarily on the two devices.

It was not possible to install the two devices on the same ground surface, so that one was placed over grass and the other over a cement pavement covered with clear gravel. In order to avoid any influence of the different ground cover on the comparison, in the first part of the campaign the single membrane device was placed over grass, while in the second part it was placed over the cement pavement. The opposite happened to the double membrane device.

The measurement set up consisted of a mobile data acquisition system and two small dataloggers, equipped with several sensors. Below each prototype a standard black globe thermometer was installed at the conventional height of the center of a standing person, namely 1.1 m from the ground. A third globe thermometer was placed in the sun close to the prototypes. On the bottom side of the single layer device and on the bottom side of the lower membrane of the double layer device a thermocouple was placed, in order to measure the surface temperature of the membrane directly radiating towards the ground and towards any person below the devices. The temperature of the ground surface shaded by each prototype was measured by means of two thermocouples. Further, the main microclimatic parameters were measured, namely air temperature and humidity by means of a thermo-hygrometer, wind velocity at 1.1 m height through an ultrasonic anemometer and global solar irradiance on the horizontal in open field by means of a solar radiometer. Data were acquired every 30 s in the central hours of the day.

The Mean Radiant Temperature (MRT) below each shading device and in open field was then calculated from the globes temperature, the air temperature and the wind speed data, averaged every 5 minutes. Air temperature and humidity as well as wind speed can reasonably considered equal below the two sun shading devices, while the Mean Radiant Temperature was expected to be different for two reasons: the solar radiation transmitted is different and the thermal radiation emitted towards an underlying person by the bottom surfaces is different. Therefore, the measurements were aimed at verifying the existence of a difference in the MRT produced by the two prototypes, resulting in a different thermal comfort perceived by a person standing alternatively under them.

Figure 3: The two prototypes installed side-by-side in the Politecnico campus

4.2 Experimental results

4.2.1 Installation test

Installing the prototypes allowed to identify some key aspects able to ease and speed up the installation and dismantling phases. First of all, it might occur that existing supports (poles, trees) for hanging the shading devices are not arranged symmetrically with respect to the membrane geometry. Therefore, the membrane corners should be equipped with multiple or redundant connections that can be steered at least in two directions per side, allowing to properly tension the kit in any condition.

Furthermore, Velcro was chosen as the most important element for regulating the length of the crossed tapes stabilizing the kit. Even if this device made the prototyping easier to be managed, it proved to be very uncomfortable during the installation stage, as it requires the operator is able to maintain the tension through the force exerted by his/her own arms, thus losing a clear reference of the length reached by the entire system of tension. This problem can be easily remedied with the integration of turnbuckles at the end of the crossed belts, close to the corresponding flying mast.

The requirement of interchangeability for both membrane layers – the above and the below ones – is guaranteed only if the kits are completely independent from each other, i.e., each membrane is stabilized by its flying mast and by its system of crossed ribbons. To speed up the prototyping and installation stages, this was only partially done during the experimentation in the campus site, in which the surrounding trees only permit to set up an irregular hanging system for the membrane kits. The single-layer and double-layer shading devices - installed side by side (Figure 3) - do not appear perfectly tensioned as the lower membrane was not installed independently, but simply hung from the upper one. If this has not invalidated the thermal comfort test, it is certainly to be considered an ineffective fallback, but potentially dangerous for the stability of the entire structure over time. In fact, the lower membrane hanging from the upper one does not work properly as it is not able to resist the wind load and can potentially accumulate rainwater until it collapses. Therefore, to install the double layer device using an irregular hanging points layout, the two membrane kits must be firstly pre-coupled and tensioned in mid-air and then raised to the desired distance (based on the optimal air gap for ventilation) using the turnbuckles, missing in the current version of the prototype.

During the experimental campaign the two shading devices proved to be able to resist to the modest urban wind in Milano. Further efforts could be devoted to identify the wind load resistance of the structure.

4.2.2 Thermal comfort test

The MRT trend in open field and under the two prototypes is shown in Figure 4 and Figure 5 for a representative day of the first and second part of the monitoring campaign respectively, named day 1 and day 2. As already explained, during the first part of the campaign, and thus on day 1, the single membrane device is over grass and the double membrane device is over the cement pavement, while they are exchanged during the second part of the campaign, and thus on day 2. In both cases the advantage of sun shading is evident, as both shading devices largely decrease the MRT with respect to the open field unshaded situation. It can be noticed from Figure 4 and Figure 5 that the grass surface remains always cooler than the cement surface, up to about 5°C more, probably because evapotranspiration occurs more effectively. As expected then, the ground surface conditions are not fair under the two prototypes. However, it is found that MRT below the double membrane device is always lower than under the single membrane, both when the latter is over the cooler ground surface (day 1, Figure 4) and when it over the warmer ground surface (day 2, Figure 5). In other words, the double membrane device performs better whatever the kind of ground cover, as it is more clearly shown in Figure 6, where the MRT data of the single membrane device plotted against the MRT data of the double membrane device remain generally above the bisector of the chart, with comparable trends in both days. The MRT difference is equal on average to 3.1°C with a maximum of 4.6°C during day 1, while it is on average 2.5°C with a maximum of 5.4°C during day 2.

By analyzing the temperature of the membrane surface facing downwards in each prototype, it was found that they do not differ significantly and systematically, namely sometimes the single membrane surface is the coolest but often the situation is reversed (Figure 7). Indeed, thermal energy radiated by the membrane surface towards the ground and the person depends on the membrane temperature but also on thermal emissivity, so that the temperature alone does not define the radiative heat transfer between the membrane and the underlying person.

Figure 4: Monitoring data in a representative day of the first part of the campaign ("day 1")

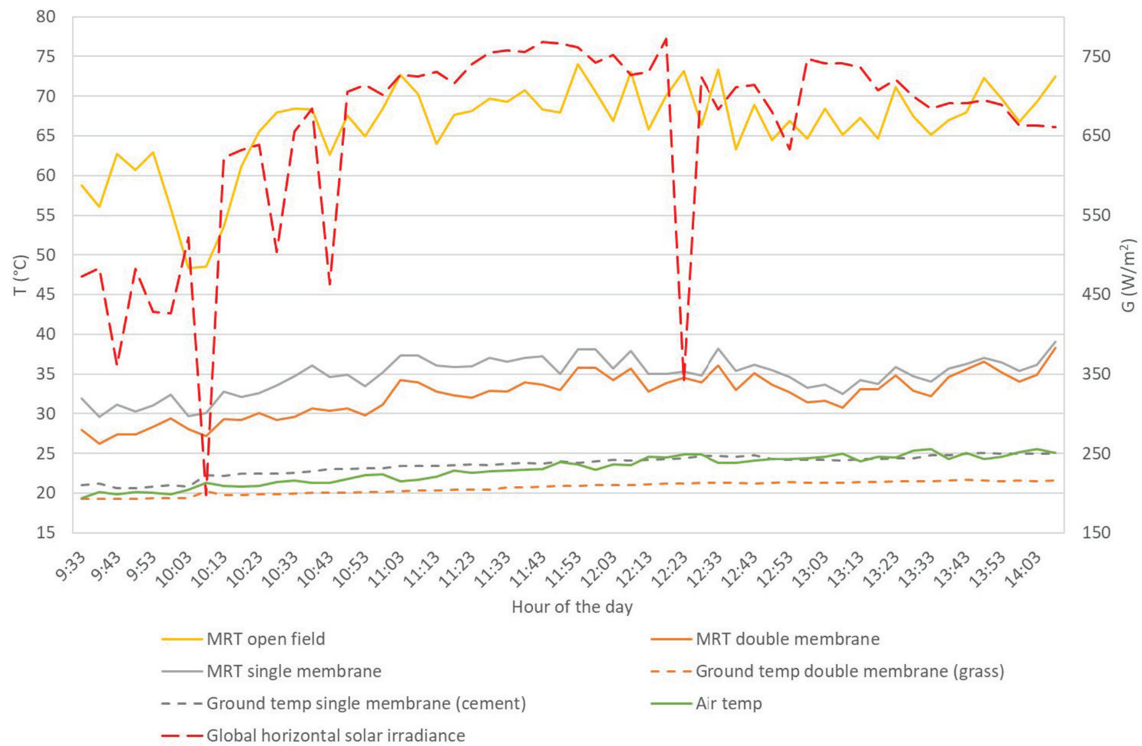

Figure 5: Monitoring data in a representative day of the second part of the campaign ("day 2")

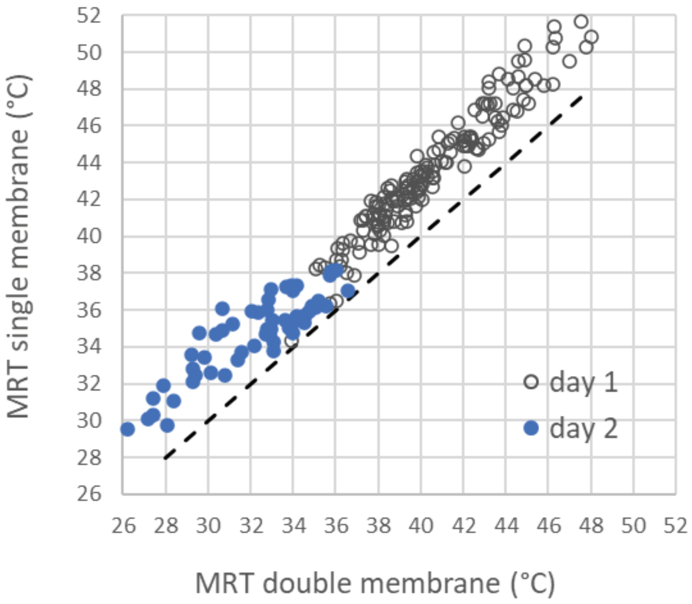

Figure 6: Mean radiant temperature below the single membrane device versus the same under the double membrane device (days 1 and 2)

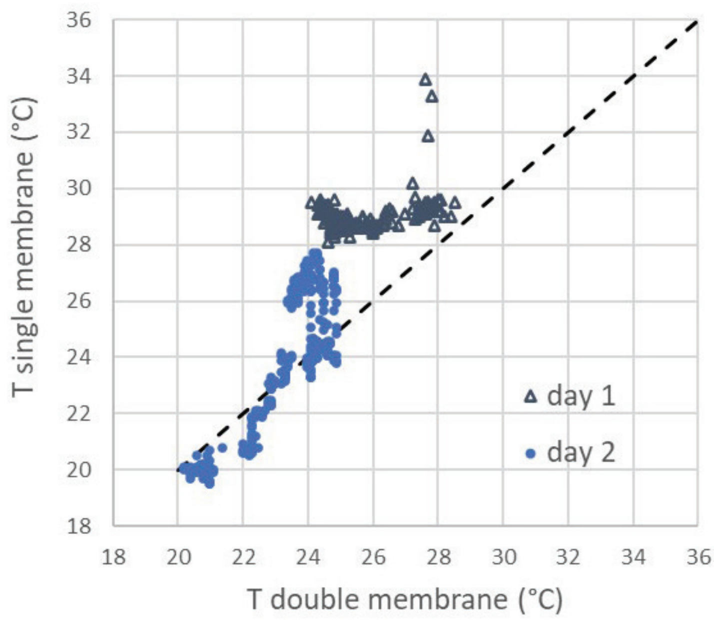

Figure 7: Surface temperature of the membrane of the single layer device versus surface temperature of the bottom membrane of the double layer device (days 1 and 2)

Conclusions

The research designed and developed a flexible solar shading device for mitigating heat stress during summer in open urban spaces. Testing the prototypes allowed to identify some key aspects able to ease the installation and dismantling phases, such as the opportunity to equip the membrane corners with redundant connections, and the necessity to pre-couple and tension the two membrane kits before raising at the design height. Moreover, the experimental campaign allowed to verify that a double membrane configuration featuring a low emissivity surface towards the ground is able to reduce significantly the Mean Radiant Temperature with respect to a single layer configuration based on a standard white membrane. Further developments of this study will investigate to which extent the better performance of the double membrane device is due to the adoption of two layers or to the use of a low emissivity membrane. To this purpose, field tests will be performed on different shading devices configurations and membrane materials, thanks to the modularity of the designed devices. Moreover, a simulation model is being developed, allowing to analyse the energy balance of the shading devices and to generalise the experimental results.

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References

R. and A.C.E. American Society of Heating (2001), ASHRAE Handbook Fundamentals, SI Edition.

Göppert, K., Paech, C. (2015), High-performance materials in façade design: Structural membranes used in the building envelope. Steel Construction, 8(4), 237-243.

Johansson E., Thorsson S., Emmanuel R., Krüger E. (2014), Instruments and methods in outdoor thermal comfort studies – The need for standardization. In: *Urban Climate*, vol. 10 (pp. 346–366).

Kántor N., Chen L., Gál C. V. (2018), Human-biometeorological significance of shading in urban public spaces—Summertime measurements in Pécs, Hungary. In: *Landscape and Urban Planning,* vol. 170 (pp. 241–255).

Knippers, J., Cremers, J., Lienhard, J., & Gabler, M. (2011), Construction manual for polymers + membranes: materials, semi-finished products, form-finding, design. Basel: Birkhäuser Verlag.

Paolini R., Mainini A., Poli T., Vercesi P. (2014), Assessment of thermal stress in a street canyon in pedestrian area with or without canopy shading. In: *Energy Procedia*, vol. 48 (pp. 1570 – 1575).