Assessment of thermal stress in a street canyon in pedestrian area with or without canopy shading

Riccardo Paolini[a]*, Andrea G. Mainini[a], Tiziana Poli[a], Lorenzo Vercesi[a]

[a] *Politecnico di Milano, Architecture, Built environment and Construction engineering Department, Via Ponzio 31, Milano 20133, Italy*

1. Introduction

In built environments a plurality of microclimates is generated by the different way the atmosphere interacts with man-made and natural surfaces and objects (i.e. buildings and infrastructure, vehicles, people, etc.), and, as widely reported in the Literature, in summer conditions, especially in case of weak circulation (i.e. lack of wind) urban areas are often affected by heat islands effects, resulting in higher air temperatures compared to those in an adjacent non-

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* Corresponding author. Tel.: +39 0223996015; fax: +39 0223996020.
E-mail address: riccardo.paolini@polimi.it

urban area, especially during the night. High albedo materials and green roofing are commonly referred as effective techniques for mitigating heat islands, but few options are available for mitigation interventions below the rooftop level, and, especially with high rise buildings the mitigation effect of green roofing and cool roofs is reported to be minimal at local scale [1] (while a large scale deployment of cool and green roofs surely provides a contribution a meso-scale and then at global scale). In this work we focus on a possible mitigation technique at urban canopy scale, that may be applied on a single street canyon and provide a sensible benefit without the need of a large deployment. Thus, we try to quantify the impact of the mitigation strategy of canopy shading,

While with high buildings' height to street width (*H/W*) ratios the urban roughness is high, and the air circulation weak but the solar access is limited, in case of low *H/W* ratios (e.g. lower than 0.5) the air circulation, for many urban contexts, is still poor since the wind velocity is largely reduced by the urban texture as a whole and the canyon has very high solar access, with limited shading of the building surfaces, and, especially of the street pavement, which is normally made of low reflective materials such as asphalt or concrete. More in detail, as numerically demonstrated by Harman during the day, especially between 10 and 16 am, the turbulent sensible heat flux (Q_H) increases with decreasing H/W, with the highest values with *H/W* below 0.5. During the night, instead, the situation is inverted, with the highest radiative cooling for canyons with *H/W* lower than 0.5, thus yielding to negative values of Q_H. As a consequence, the potential temperature, daytime, is maximum for canyons with *H/W* lower than 0.5, and decreasing with increasing *H/W*, while during the night is lower for canyons with low *H/W* ratios. Moreover Grimmond and Oke [2] observe that the sensible heat flux decreases with increasing urbanization, as measured in North American urban areas.

To address the evaluation of possible local countermeasures to overheating street canyons, we modified existing urban canopy parametrizations to include the presence of a tent providing shade, and to allow for a one-year simulation, supporting decision making based on thermal comfort considerations.

2. Model description

Starting from existing urban canyon parametrizations (UCP) [3,4,5,6,7] we developed a modified version of canyon model with opposite buildings of same height, with the street element divided into five sections (while all the models in the literature consider just one geometric element for the street). Then, to assess the mitigation potential of light and temporary structures providing canopy shading we included the possibility of adding a tent over the street (Fig. 1), and computing the surface temperatures by means of a heat and moisture transport (HMT) dynamic finite difference model (WUFI 5.2). In the modified UCP we included up to six reflections of both short-wave and long-wave radiation within the canopy with the radiosity method (i.e. considering purely lambertian surfaces, thus diffuse reflection). The impact of rain – thus a sudden cooling due to henthalpic balance, and then evaporative cooling – on built surfaces, which are normally porous and water absorbing, is considered, although further developments are necessary to include a robust calculation of wind-driven rain on building façades.

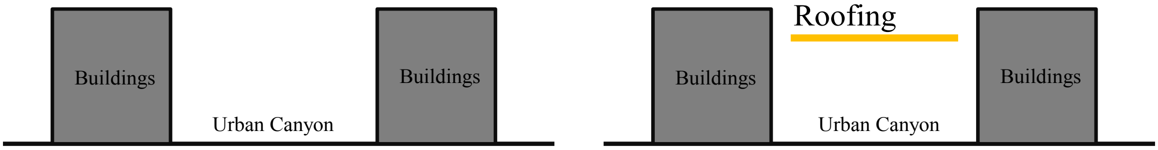

Fig. 1. The two situations considered: an urban canyon without canopy shading, and a street canyon with a tent positioned at rooftop level.

Both the UCP and the HMT model are initialized with weather data (in this case the UCP is used offline, but it should be linked to a meso-scale climate model), then the UCP calculates the microclimate conditions, while the HMT model computes the surface temperatures of roofs, street elements, and façades.

The two models are coupled and run iteratively up to convergence. This coupled model computes short-wave and long-wave incident radiation on each surface after multiple reflections, fluxes of turbulent sensible and latent heat, wind velocity and relative humidity, and the air temperature within the urban canyon, below the tent (Fig. 2).

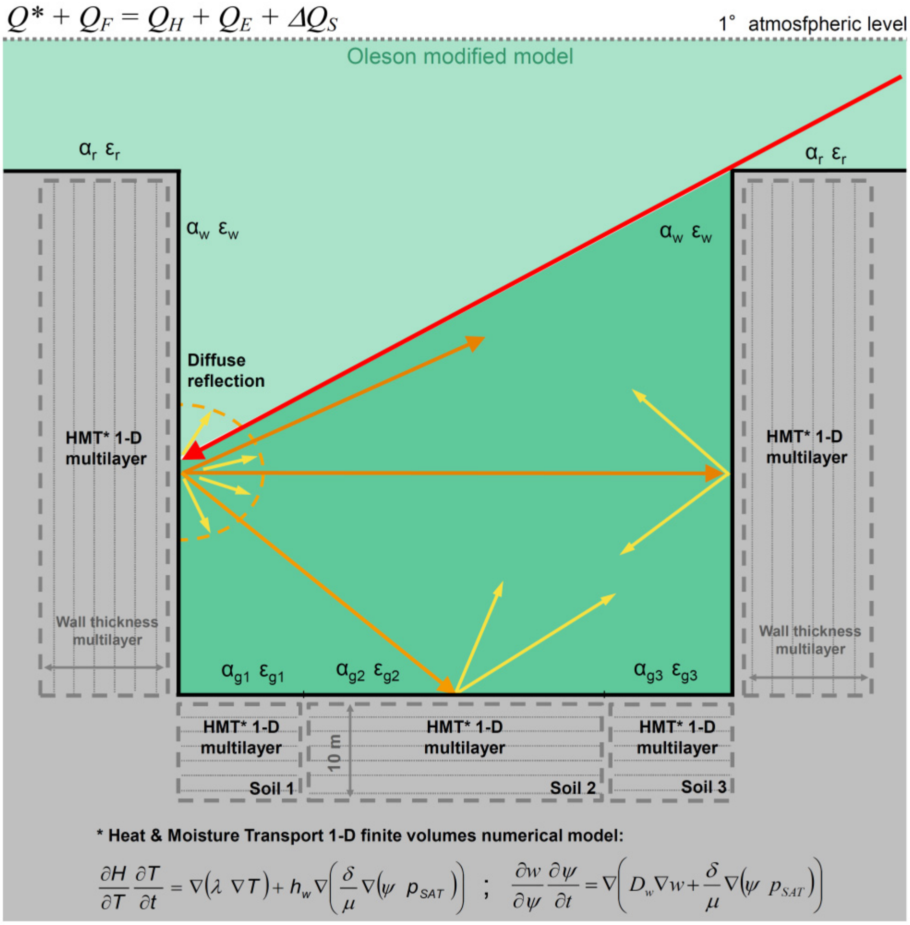

Fig. 2. Scheme of the urban canopy parametrization coupled to a 1-D heat and moisture transport model.

3. Urban canyon microclimate conditions: with and without canopy shading

We considered an urban canyon with height to width ratio equal to 0.18 (building height equal to 10 m and street width equal to 55 m), north-south oriented, and in a second configuration we introduced a tent 35 m wide, placed at rooftop level over the street. Thus, in this case, the tent does not completely close the urban canopy, allowing the turbulent sensible heat to be partially released laterally.

First, we modeled the canyon as it is, without shading provided by tents, then we modeled the same canyon with a tent positioned at rooftop level over the canyon, with solar transmittance equal to 0.05, solar reflectance equal to 0.80 and thermal emittance equal to 0.90 (Fig. 3). Considering a peak day (June 26), we observed a good agreement – within 1°C at 14:00 – between the results of the CFD simulations and the results of the 2-D canyon model. In the considered case, the air circulation is weak with or without tent (the average wind velocity in Milano is less than 1 m s-1, and for only 16% of the hours in one year the wind velocity exceeds 2 m s-1. Thus, adding a canopy shading does not alter significantly the air circulation, while reducing the solar access is crucial for mitigating the microclimate at canopy scale, especially considering the pavement surface temperatures.

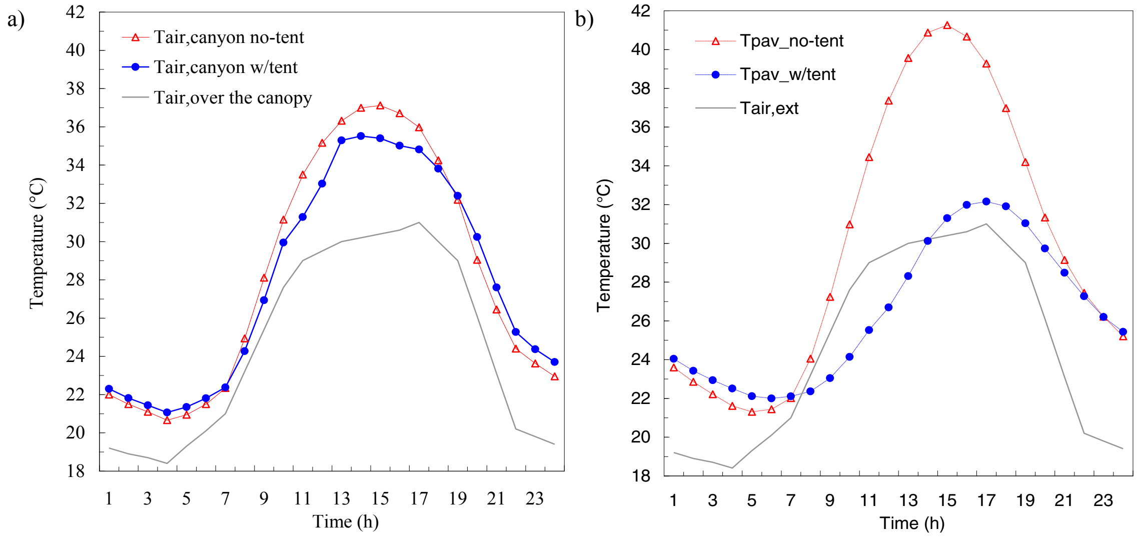

Fig. 3. (a) Air temperature for June 26th below the tent with and without tent; (b) surface temperatures of the street pavement in the central section (section below the tent) with and without the tent.

4. Evaluation of thermal comfort and thermal stress mitigation strategies effects in an urban canyon.

In outdoors the great and sudden variability of environmental conditions, and in particular solar radiation, severely affect the perceived thermal comfort of people. The intensity of the perceived solar radiation also depends on sun positions and users body orientation. The comfort improvement potential of different shading strategies, like technical textile structures for roofing, where also investigated with a particular attention on the optimization of the solar reflection, absorbance and transmittance properties of shading surfaces.

In hot weather conditions the influence of the shading position, surface temperature and transparency are noticeable and affect the comfort perception of users. Increasing solar transmittance of shading surfaces, request the evaluation of alternative comfort control strategies like increasing air circulation and decreasing of surface temperature of surroundings.

MRT in the Urban canyon, is hourly calculated in accordance with the heat balance of an irradiated body conditions[8]. The dependence between the sun position and the receiving body surface is taken into account, the sky temperature is computed and adequate angle view factors[9,10] for long wave radiation are computed in accordance with Fanger. In Fig.1a and b is presented the comparison between two different thermal comfort conditions evaluated for a generic urban canyon and for the same canyon with a membrane layer used as a roofing to reduce solar radiation and consequently solar gains on building walls inside the canyon and on the ground plane. The Urban Heat Island effect is considered.

The outdoor comfort conditions presented in this example are evaluated with the Universal Thermal Comfort Index (UTCI) evaluated with Rayman Pro [11] and plotted to present the results hourly for every day of extended summer months. The equivalent Tair comfort temperature is presented and compared to standard temperature range assessing different thermal comfort ranges (Fig. 4).

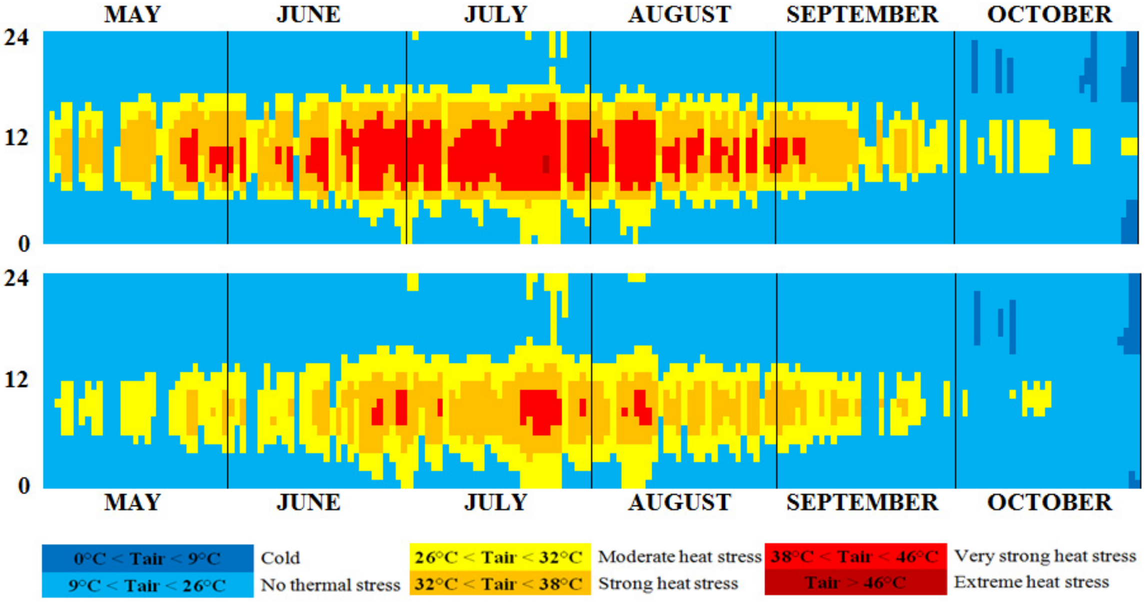

Fig. 4. (a) On top, equivalent canyon Tair evaluated with UTCI, (b) on bottom, equivalent canyon Tair evaluated with UTCI with a membrane roofing over the canyon. Reflectance of the ground ρ =0.2 and transmittance of the roofing τ = 0.05.

5. Concluding remarks

Among urban microclimate mitigation options, canopy shading is the one capable of limiting the solar access of large urban canyons, namely with height to width ratio of less than 0.5. However, existing urban canopy parametrizations do not allow for taking into account the presence of tents over the canopy.

To assess the mitigation potential of canopy shading, starting from existing urban canyon models, we developed a variant model, including the possibility of adding tents (of different width) over the street at rooftop level. Moreover, we coupled the model to a finite volumes 1-D transient heat and moisture transport numerical model (WUFI 5.2) to compute the surface temperatures of the canopy surfaces. The two models are coupled and resolved iteratively up to convergence. To achieve a first assessment of the coupled model performance, we carried out 2-D CFD simulations by means of FLUENT-ANSYS for a peak day condition, finding an agreement within 1°C of air temperature in the canopy in peak conditions. Then we performed simulations with the coupled UCP-HMT model forced with one-year weather data, computing the microclimate conditions, and then assessing the thermal stress conditions (from May to October) by means of the Universal Thermal Comfort Index (UTCI) evaluated with Rayman Pro. We conclude that canopy shading with tents having low solar transmittance and high solar reflectance (of more than 0.80) is effective in reducing the solar access of street canyons, since it limits the incident solar radiation on the street pavement, that is the main element influencing the air temperature and the thermal comfort perception of large canyons. Whether tents with very low solar transmittance (of less than 0.10) may provide an "indoor sensation" to people, increasing the solar transmittance of shading surfaces, requests the evaluation of alternative comfort control strategies like increasing air circulation and decreasing of surface temperature of surroundings. However, in the standard condition there is a lack of air circulation underneath the tent and within the urban canopy, so shading devices that do not prevent air recirculation (namely convective mixing of the air from the canopy with the air above the canopy) should be addressed in future developments. Also, in future work, we will include the possibility of opening the tent over the canopy during night hours.

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